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The use of bridging analogies in encouraging conceptual change in the teaching and learning of momentum and kinetic energy in Physics

by

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A thesis presented in fulfillment of the requirements for the degree of Doctor of Philosophy

2010

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Kenneth MacMillan

Date: 9th August 2010

Acknowledgements

I would like to express my thanks and appreciation to each of the students who volunteered to participate in this study and for their patience and willing co-operation during the interviews. I would also like to express my appreciation to their parents for allowing them to participate in the study. The assistance of Mr Andrew Donaldson, who cross-checked a sample of the interviews and Dr Ivan Ruddock of the Physics Department of the University of Strathclyde, who gave valuable advice and encouragement are also much appreciated. Janet, my wife, was a real encouragement and source of support to me, particularly during the times when I was struggling with aspects of the research and write-up. Finally, I wish to express my sincere appreciation, in particular, to my supervisor Professor Tom Bryce for his invaluable support, encouragement, help and advice throughout the course of this research.

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Abstract

Momentum and kinetic energy are two deceptively simple ideas which are often mis-understood and confused with one another, as well as other related quantities in Physics. This qualitative, grounded theory study consists of three parts. Firstly, students' understanding of momentum and its conservation, and kinetic energy and its non conservation in most collisions was assessed using a 'check-up' questionnaire which was administered to one hundred and twenty one 16-18 year old students from five different comprehensive schools in the Glasgow area who were studying for the Scottish Higher examination in Physics. The second section of the study involved the development and use of two bridging analogy sequences which were devised in an attempt to help students to (1) understand why momentum is conserved when a small object collides with a large, apparently 'immoveable' object; and to (2) help students explain why kinetic energy is lost in an inelastic collision while momentum is conserved. Both of the bridging sequences were used in conjunction with semi-structured, think-aloud interviews, which utilised Socratic questioning to assess the level and type of conceptual change experienced by sixty volunteer students (thirty per sequence, representing a range of ability in Physics) as they worked through each sequence. The sixty, fully transcribed interviews were then analysed using open, axial and selective coding to ascertain how the thinking of these students developed throughout the interview and how it matched up with the propositions of several conceptual change theories that were examined. Using the findings from the second part of the study, the third section consisted of an analysis of the conceptual change evidence. This supports the notion of a unifying principle of connectivity. Finally, arguments relating it to the theoretical stances, and to effective teaching and learning practices, are developed.

Chapter 1
Introduction

This thesis examines upper secondary school students' understanding of the topics of momentum and kinetic energy. It also critically evaluates current conceptual change theories using qualitative data obtained from semi-structured, think-aloud interviews with volunteer participants, all aged between 16 and 18 years, who were studying Higher Grade Physics in five non-selective, comprehensive schools in the Glasgow area of Scotland as they worked through one of two specifically created bridging analogy sequences. Prior to their participation in the study, all of the students had been taught about momentum and kinetic energy by their own class teacher as part of the 'Mechanics and Properties of Matter' unit of the Higher Grade syllabus.

The study consisted of two parts. In the first, 121 volunteers completed a 'check-up' questionnaire which was designed to analyse their understanding of the conservation of momentum and conservation, or non-conservation, of kinetic energy in several scenarios that became progressively more difficult to explain correctly. The second part of the study used semi-structured, think-aloud interviews to analyse a sub-set of 60 students' thinking and learning as they interacted with one of the two bridging analogy sequences which are also discussed in detail in the methodology. A bridging analogy sequence consists of a set of inter-related analogies that progressively moves from easier, concrete analogies, to more abstract, but technically accurate analogies of an intended 'target' situation, for which a model or explanation is being sought. The two sets of analogies had been specifically created to examine the extent to which they were effective in helping students to gain a better understanding of the concepts of conservation of momentum and elastic and inelastic collisions. Specifically, one of two possible situations was explored by the students using one of the bridging analogy sequences. The first was where an object collides with a much larger, supposedly 'immoveable' object. The second sought to examine why kinetic energy is not conserved when two objects come into physical contact with each other but is conserved when the collision does not involve actual contact, but instead consists of a 'force at a distance' when the identical poles of two magnets on the vehicles repel each another.

1.1 The physics of momentum and kinetic energy.

The terms ‘momentum’ and ‘kinetic energy’ are two physical quantities that have specific meanings for physicists. Both initially appear to be basic and straight forward concepts. However, there are levels of difficulty and complexity associated with both that have been widely reported in literature as causing students great difficulty in truly understanding them and reconciling the difference between them. In particular, their conservation (or in the case of kinetic energy, more typically non-conservation) in collisions is a source of confusion and difficulty. These problems are compounded by the fact that everyday usage of the word ‘momentum’ in particular, is markedly different from its meaning to physicists.

In order to allow all potential readers to more fully appreciate the basis and reasoning behind the material in this thesis, it is necessary to start by briefly outlining some of the basic concepts and theories regarding the terms ‘momentum’ and ‘kinetic energy’ as used in physics. This will serve as an introduction to those who are not familiar with these topics and as a reminder of the most salient points for those who are more conversant with them.

Momentum is defined as the product of mass and velocity ($p = m \times v$). It is a vector quantity, meaning that it has both a magnitude and a direction. The amount of momentum in the universe is thought to be fixed, which leads to the law of conservation of momentum, which states that the total momentum present before and after an interaction between objects is the same. In many cases (including the content statements for the Higher Physics syllabus in Scotland) this law is stated with a proviso that conservation of momentum only occurs in situations in which no ‘external’ forces are acting. The imposition of this caveat has been found to lead to confusion in the minds of students as they are poor at identifying what is meant by an ‘external’ force in many everyday situations. For details of this, see the discussion of the research review carried out by Grimellini-Tomasini, Pecori-Balandi, Pacca and Villani (1993), and a study (which is not part of this thesis) by Bryce and MacMillan (2009), in the literature review that follows.

By applying a force to an object, it is possible to change its momentum. The change in the object's momentum is related to the *magnitude*, *direction* and the *duration of the applied force*. The relationship between these variables is that the product of the applied force, and its duration, is equal to the change in the object's momentum, Δp. This is summarised by the equation, $F \times t = \Delta p$. Newton's Third Law states that when two objects (A and B) interact, they exert equal and opposite forces on one another. More precisely, if object A exerts a force on object B, then object B exerts an equal force in the opposite direction on object A. This law can be demonstrated in situations involving recoil, such as when one stationary ice-skater pushes against another stationary skater. The push exerted by only one of the skaters results in both individuals moving in opposite directions, where the relative speeds of each skater are dependant on the ratio of their masses.

A direct consequence of Newton's Third Law is that momentum must be conserved in every interaction between any two objects, regardless of the relative sizes of the objects involved. This can be explained using the equation discussed above, which interconnects the applied force, time and change in momentum of an individual object. It shows that equal forces, applied in opposite directions, for equal amounts of time, must result in changes in momentum for both objects that are equal in magnitude, but opposite in sign to one another. In other words, the synergy will result in one object gaining a certain amount of momentum, while the other object reduces its momentum by the same amount. For this reason, it is often stated that momentum is 'transferred' from one object to another when they interact.

Kinetic energy is the energy associated with moving objects. It too is related to the mass and the velocity of the object by the equation, $E_K = ½ mv^2$. In common with all other forms of energy, it is a scalar quantity, meaning that it has no direction. Although energy as a whole is always conserved, usually through a process of transformation from one form to another, kinetic energy is often not conserved in an interaction between objects. The amount of kinetic energy that an object has can be altered by doing 'work' on it. The amount of 'work' done on an object (which is an amount of energy) is related to the force applied to the object and to the displacement over which the force is applied. The equation for calculating the amount of ‘work done’ (E_W) on an object is $E_W = F \times s$. By doing work on an object it is possible to either increase or decrease its kinetic energy, depending on the direction of the applied force in relation to any pre-existing movement of the object. When work is done, energy gets converted from other forms (such as chemical energy) into kinetic energy or vice-versa.

In the literature review which follows this introduction, it is demonstrated that there is wide acknowledgement (Driver et al., 1985; Lawson and McDermott, 1987; Driver et al. (1994), Olenick 1997; Bryce and MacMillan, 2009) of the difficulty involved in clearly enunciating the difference between the momentum and kinetic energy of a moving object, and therefore the distinction between them is often poorly understood. Indeed, the historical development of the two concepts has been arduous, at times highly contentious, and closely inter-connected. While the equations for each clearly differ, and one quantity is a scalar while the other is a vector, it is difficult to succinctly express the qualitative differences between the two measurements, as both are essentially about ‘mass on the move’ and depend on the mass and velocity of a moving entity. Arguably, the difference between them only becomes clear when the movement of the object is *changed*. Momentum is linked to the time that it takes to alter the movement of the object (since $F \times t = \Delta p$), while the kinetic energy is related to the displacement through which the object’s velocity is changed (because $E_W = F \times s$).

1.2 Types of collision.

There are two types of collision that are distinguishable from one another: ‘elastic’ collisions, in which both momentum and kinetic energy are conserved; and ‘inelastic’ collisions, in which momentum is conserved but kinetic energy is not conserved. Kinetic energy is not conserved in inelastic collisions because of the effects of contact between the two objects involved. When the objects strike one another, vibrations are initiated in each. As a consequence, some work is done internally since a force is applied that results in a displacement of molecules. Consequently, some kinetic energy is converted into a combination of heat and sound energy, which requires a net loss of kinetic energy in the system. Truly elastic collisions (in which kinetic energy is completely conserved) are rare as they require one of three special conditions to be met. The first option is that there is no actual contact between the objects. This occurs in ‘collisions’ between sub-atomic particles where electrostatic forces between the particles cause interactions at a distance and therefore no physical contact takes place. The second possibility is in interactions between ‘perfectly rigid’ objects. In this case, since no vibrations can occur, there is no displacement of particles and therefore no internal work is done, resulting in non-conversion of energy into other forms. The third possibility involves the use of theoretical ‘super’ rubber balls that return entirely to their original shape after a collision. When this occurs, no net displacement of material has happened, and so there has been no work done, meaning that any transient energy changes are converted back into kinetic energy.

The foregoing material has been included at this introductory stage to briefly and simply outline the key points in the physics associated with momentum and kinetic energy. These ideas constitute some of the learning outcomes in the physics syllabus that the students who participated in the study were studying. The later methodology chapter of the thesis analyses the design of the two newly created bridging analogy sequences that were utilised in this research. At that stage, the relevant physics is re-visited in more detail in order to justify the reasoning behind the design of each sequence.

1.3 The aims of the research

The detailed research questions for this study are stated and analysed in the methodology chapter of the thesis. However, in summary, there were two main aims for this study. The first aim was to ascertain the effectiveness of bridging analogies in helping students to better understand collisions in terms of the conservation of momentum in all collisions, and the non-conservation of kinetic energy in 'inelastic' collisions. The second aim was to investigate the mechanism by which conceptual change occurred as the students interacted with the bridging sequences during the think-aloud interviews. This was carried out in order to determine the extent to which the existing conceptual change theories (that are discussed in the literature review) are evidenced and borne out in the transcribed interview data. A degree of unification of the existing conceptual change theories was attempted and evidence for the overarching theoretical stance was sought in the qualitative data, and reported and discussed in the findings and discussion chapters. Finally, the case for adopting the proposed theoretical stance is argued in the discussion chapter of the thesis. A brief overview of the approach adopted in this study to meet each of these aims is summarised below, along with a short synopsis of the main arguments that are developed in the thesis.

1.3.1 Addressing conceptual difficulties using bridging analogies

It will be shown in this thesis that students often have difficulty in believing and understanding that momentum is conserved in many everyday situations, including where an object is observed to be slowing down as a result of frictional forces, or where an object collides with a large, apparently 'unmoveable' object. The existing perceptions of a sample of 121 students in terms of momentum and kinetic energy for several scenarios was investigated using the 'check-up' questionnaire, that was administered by the students' own teachers in class time. The students' written answers were analysed to ascertain common themes and patterns in their responses. It will be argued that many of the difficulties that the students experience are a consequence of their failure to perceive the system that they are analysing in global enough terms; their 'system' view consists of only the single object that they are considering or of the two objects that they can see interacting in some way. Students often fail to take into account that momentum can be transferred to very large objects (such as buildings or the earth) when smaller objects collide with them or, in the case of frictional forces, rub against them. They fail to take cognisance of the idea that, because of their much larger relative mass, these bigger objects do not change their velocity enough to enable the tiny movement, caused by the interaction, to be perceived. One of the bridging analogy sequences was developed in an attempt to address this difficulty.

The second bridging analogy sequence was created to assist students to understand why momentum is always conserved, while kinetic energy is 'lost' in 'inelastic' collisions, but is conserved in 'elastic' collisions (in which there is no physical contact between the colliding objects). This was achieved by encouraging students to explore the mechanism through which kinetic energy was converted into sound and heat during several similar collisions which resulted in physical contact. In addition, the reason why both kinetic energy and momentum are conserved in 'elastic' collisions was investigated. The design of the constituent analogies for both sequences, and the reasoning behind the progression from one analogy to the next is discussed and explained in the methodology chapter of the thesis.

The bridging analogies were found to be effective in helping many of the students to better understand the situations that they addressed. The ways in which progress occurred, as well as the reasons for it were analysed. Some students did not make much progress using the analogies or, in some cases, became confused as a result of their use, partly because there was a deliberate strategy deployed whereby they were not told whether or not they were developing their thinking in the direction of the 'accepted' answer. The reasons for the students' difficulties were explored, and found to centre on their relative inability to make adequately robust connections between successive analogies in the sequence, and/or between the analogies and the initial real-world 'target' situation for which an explanation was being developed.

1.3.2 An examination of the nature and mechanism of conceptual change

The conceptual change theories that are currently posited perceive learning as a process involving the construction of ideas from a constructivist, rather than behaviourist, psychological stance. All but one of the theories argue that students build up a body of knowledge, or views of the way in which the world around them operates, by developing or changing the models or systems that exist in their mind. The mental structures that change or develop in the learner's mind are variously referred to by the different theories as paradigms, mental models, explanatory models, framework theories or cognitive structures. Most of the theories suggest that conceptual change involves a process of refining or altering some pre-existing, assumed theory about the way in which things work which is developed experientially from a very young age. However diSessa's 'conceptual ecology' theory (which is outlined in the literature review) argues from a very different perspective by suggesting instead that people start with 'knowledge in pieces' and build increasingly complex mental structures from these constituent pieces. One theory, known as 'category re-assignment', invokes an entirely different perspective from all the others as it does not see conceptual change as a building process. Instead its exponents imply that conceptual change involves changing the category that a concept or entity is associated with incorrectly in the mind of the student, to the correct category - for example from the category of a 'substance' to the category 'process'.

In this thesis it is argued that all of the existing learning theories can be unified by positing that learning involves a process whereby connections are made between ideas. This can involve either making connections for the first time, or a process whereby pre-existing connections are altered or replaced. In this latter case, conceptual change would be deemed to have been successful where the newly developed links were more accurate or robust, and therefore enabled the student to more precisely or confidently predict and explain the way things 'work' in the real world. The transcript data was analysed in order to discover whether or not this claim could be substantiated and exemplified from the students' thinking patterns that were made evident through the use of the non-directive, think-aloud interview technique, referred to as ‘guided analogical reasoning’. This method was non-directive in the sense that the participants were simply encouraged, by careful questioning, to state and explain their thoughts at each stage of the sequence of analogies. They were deliberately not given any indication regarding whether or not their ideas matched the thoughts of physicists until the end of the process. This allowed them a high degree of freedom to develop their thinking and theoretical stance in the direction of their choosing, guided only by a deliberate strategy of encouraging them to think about their perceptions of the similarities, and differences, between components of the sequence and the scenario being investigated.

1.4 Outline of the following thesis chapters

In the chapters that follow, the literature pertaining to the teaching of momentum and kinetic energy learning, as well as students' understanding of the topics, will be critically analysed. The methodology employed in this study will then be explained and justified. This study draws heavily on qualitative rather than quantitative methods that were extensively used in all of the previous studies. The reasoning behind this shift in approach, and the philosophy behind the techniques that are employed are outlined in the methodology chapter. The findings from the analysis of the 'check-up' questionnaires and the fully transcribed think-aloud interviews are then reported on before being probed in detail in the discussion chapter.

Chapter 2

Literature Review

2.1 Overview

There are three constituent parts to this study. These are the use of *bridging analogies* as a possible method for teaching and learning about *momentum and kinetic energy* in physics, and an examination of the *theory* and the *process* of *conceptual change*. This literature review starts by examining previous studies in the area of momentum and kinetic energy. Several theories regarding the process of conceptual change are then critically examined. Finally, an overview of the types, uses and purposes of analogies in the existing literature is given.

2.2 Previous studies of momentum and kinetic energy.

Momentum is a topic in many introductory Physics courses for students of about 14 years-old and upwards across the globe. There have been relatively few studies in this area of the Physics curriculum to date. Most have involved either the administration and analysis of a test; or a teaching and learning sequence used in conjunction with pre- and post-testing, resulting in purely quantitative results; while a few have more mixed methodologies which have yielded both quantitative and qualitative data.

In this review, the previous research studies that have been undertaken will be analysed. Three of the previous studies (Backhouse, 1964; Singh & Rosengrant, 2003; Grimellini-Tomasini, Pecori-Balandi, Pacca & Villani, 1993) examined students' understanding and misconceptions regarding both momentum and kinetic energy, or conservation of energy, while several pieces of research have studied just momentum (Raven, 1967; Williams 1976; Graham & Berry, 1996; Papaevripidou, Hadjiagapiou & Constantinou, 2005). Of those that focused specifically on momentum, two studies attempted to delineate the relevant sub-concepts and place them into rank order by difficulty (Graham & Berry, 1996; Williams, 1976), while two suggested alternative teaching sequences (Raven, 1967; Graham & Berry, 1996). A further two articles (Lawson & McDermott, 1987; Pride, Vokos & McDermott, 1998) discuss the related areas of momentum and impulse. Only one of the previous studies (Olenick, 1997) specifically looked into the views of teachers regarding the topic of momentum.

The recurring message from all of the studies is that students find these topics conceptually difficult. Despite this, several researchers mentioned later report that students are successful in answering numerically-based examination questions about momentum or energy and its conservation, without necessarily having a good grasp of the underlying physics. For example, Touger, Dufresne, Gerace, Hardiman and Mestre (1995) maintain that practice in solving lots of (numerical) problems is not an efficient means for helping students to organize their knowledge but instead, students would gain more benefit from practice in writing qualitative explanations as part of regular instruction, which is a view shared by Arons (1997). Papaevripidou et al. (2005) argue from their pre-test results, which they administered to 20 students prior to carrying out a computer modelling exercise on 1-D collisions, that 13 and 14 year old students treat calculations about momentum conservation as ‘meaningless algorithms’ (p. 95) which they merely apply to collision problems. In their study regarding students’ understanding of energy and its conservation, Goldring and Osborne (1994) reported from their questionnaire results for a sample of seventy five 16 and 17 year olds that: “Many pupils who were able to solve numerical problems showed a lack of understanding of fundamental concepts, and were not able to solve qualitative problems or reveal declarative knowledge” (p. 29). This was confirmed when they subsequently interviewed a cross-section of the participants and found that “many pupils could recall statements without comprehending their meaning” (p. 27).

The earliest study in the field, by Backhouse (1964), sought to ascertain students’ understanding of momentum and kinetic energy. He designed and administered a test to 147 students from seven different independent and maintained secondary schools in England whose ages ranged between thirteen and nineteen years. The test was intended to analyse four aspects of students’ understanding of momentum and two aspects of kinetic energy, as follows:

1. Momentum is measured by the formula mv.
2. Considering motion in a straight line, momentum is a directed quantity.
3. Momentum is conserved on impact
4. Momentum is a vector quantity.
5. Kinetic energy is lost on impact
6. Kinetic energy is a scalar quantity measured by the formula $\frac{1}{2}mv^2$

Backhouse (1964) found that the success rate was age-related to some extent as the 20 students in the sample who were over eighteen years-of-age outperformed the other ages while the 23 students who were under sixteen years-of-age were the least successful. However there was no clear age-related advantage between candidates in the sixteen to seventeen and seventeen to eighteen year age ranges. Backhouse (1964) observed that 10% of the students made no mistakes in the questions which required an understanding of momentum, while 33% were completely successful with regard to the smaller number of questions on kinetic energy. He suggested that some of the errors could have been due to students misreading or misunderstanding the questions rather than not comprehending the aspect that was being tested.

The results clearly demonstrate that students find momentum and kinetic energy difficult to understand, with the latter appearing to be less problematic. However, the usefulness of the study to practising teachers is limited as a result of its restricted design and methodology. Firstly, the six topics studied were framed in very factual, rather than analytical terms. Consequently, the students appear to have been primarily tested on their ability to recall facts about momentum and kinetic energy rather than examine their analytical and comprehension skills regarding the underlying physics. They were asked to explain their reasoning, but since this was a written test, any possible evaluation of the students' thinking was restricted to what they wrote down. Two of the areas which were examined are very similar. Being able to recognise that momentum is a 'directed quantity' is not significantly different from being able to identify that momentum is a vector. This lack of clarity and distinction between these two categories restricts the variety and volume of new and useful information that can be gleaned.

The results were purely quantitative and do little more than show the relative success rates of different ages of students at recalling specific ideas and sub-concepts about momentum and kinetic energy, although they clearly show that students often struggle with these concepts. The conclusion that older students generally out-perform their younger counterparts is not particularly surprising, since Piaget's stages of cognitive development suggest that students become more adept at abstract thinking as they mature. Perhaps the greatest short-coming of the study was that it did not identify, or analyse, the ways in which students conceive of momentum or the reasons why many fail to understand the ideas that were investigated.

A study by Singh and Rosengrant (2003) yielded more useful qualitative data. They designed a multiple-choice test consisting of twenty-five questions on the topics of energy and momentum, of which fourteen items examined the students' understanding of energy, while eleven questions probed the students' comprehension of momentum. In the process of developing and piloting the test items, they administered various earlier versions of the test to over 3000 university students and conducted thirty-four, one-hour-long interviews.

The test was used as a post-test, after instruction had been delivered on linear kinematics and dynamics, with a total of 1356 students. It was also administered as a pre-test with 352 students, and as a post-test with a total of 336 of the same students from a university in the United States of America. The sample size is impressive, however it is unfortunate that the actual study did not also involve student interviews as this would have given more insight into students' thinking and reasoning. This meant that, in common with most of the other previous studies, the findings of this research were limited as it was only possible to analyse the students' written responses to set questions.

By comparing the pre- and post-test results, Singh and Rosengrant (2003) showed that the course of instruction improved the conceptual understanding of some, but not all, of the students. The results also highlighted that many students lacked a coherent understanding of energy and momentum concepts and that they had some difficulty in applying them in different situations as between 15% and 75% of the students gave the wrong answers to each of the twenty five questions, even after instructive intervention had been given. They reported that the difficulties encountered by the students were often caused by a tendency to focus on surface features and being distracted by irrelevant details. In particular they found, in common with several previous researchers, that students had significant problems in using the conservation principles of energy and momentum appropriately in many of the situations presented to them.

In an improvement over the work of Backhouse (1964), the test results were analysed on an item-by-item basis in order to identify specific areas of difficulty. Three common problems experienced by students when trying to understand and apply the concept of momentum and its conservation were discovered that mirror those found in several of the other studies.

1. Students had difficulty in understanding and applying the idea that momentum is a vector quantity and instruction was largely ineffectual in remedying this difficulty.

2. Many students operated on the premise that momentum was conserved for each object in a system rather than being conserved by the system of objects as a whole.

3. A sizeable proportion of students thought (incorrectly) that the size of the force exerted by an object hitting a surface was related only to the initial velocity, rather than its change in velocity and hence its change in momentum. Interestingly, an examination of the pre- and post-test data shows that this misconception appeared to become more prevalent after the course of instruction had been undertaken.

Grimellini-Tomasini et al. (1993) reviewed several pieces of research, including several of their own studies as well as several of those discussed in this review, which examined the conservation laws in mechanics. The data in the review had been collected using a number of techniques in the various studies including questionnaires, interviews, essays, tests and recordings of classroom discussions. They came to a number of interesting conclusions and gave a helpful summary of some of the intuitive or ‘spontaneous’ ideas expressed by students about collisions between various combinations of masses, which were at variance with correct ‘disciplinary’ physics. These are highly relevant to the focus of this study. Firstly, they noted from the range of studies that students often failed to make connections between their everyday experiences of collisions and the physics that they learned in the classroom. In particular, students were found to be poor at: recognising regularities in experimental results; making comparisons between initial and final states of a system; and recognition of invariance in certain quantities. Making these connections, comparisons and observations were, they argued, instrumental in allowing physicists to initially deduce and clarify the accepted 'disciplinary' principles and laws. Secondly, students often failed to use the terms that they had been taught or used them in such a way that their understanding of the meaning was shown to be highly ambiguous or confused. The concepts of momentum and energy were found to significantly overlap in students' minds, as discussed by Lawson and McDermott (1987) and by Bryce and MacMillan (2009) in an article that is not part of this thesis. The conceptual overlap between these ideas was found to cause common difficulties in understanding and interpreting collisions, particularly in relation to the two conservation laws. Thirdly, in common with several of the other studies, Grimellini-Tomassini et al. (1993) identified that many students struggle to understand the vectorial nature of momentum. Students often used a vector sum to find directions while applying an algebraic sum to find the magnitude of the momentum for an object involved in a collision.

Confusion regarding what constituted an 'isolated system' in the minds of the students, and which objects were or were not included in such a system, was seen as a fourth contributory factor in students' misconceptions. This was found to be particularly problematic in situations where frictional forces were seen to be causing the non-conservation of momentum, depending on how the 'system' was defined. In these situations, the researchers reported that students often abandoned the idea of conservation of momentum or blamed the results on poor accuracy of the experimental readings. In common with Singh and Rosengrant (2003), they found that students intuitively tended to describe collisions in terms of single objects or events (which Grimellini-Tomassini et al. (1993) referred to as a "local view") rather than comparing the initial and final states of a system. Consequently, students were found to commonly refer to causes and effects and talked in terms of developments in time, rather than invariance of quantities over time. Grimellini-Tomassini et al. (1993) concluded that in order to overcome students' difficulties, successful teaching strategies should promote opportunities for students to verbalise their thinking, look for patterns or regularities in experimental results, and explicitly examine the before, during and after phases of collisions.

Of those studies that only examined momentum, arguably the most surprising result was produced by Raven (1967) who argued that children as young as five have an intuitive feel for the concept of momentum, despite not knowing the term, or its scientific meaning. Furthermore, he showed that this intuitive feel for momentum was not dependent on them having previously mastered the concepts of speed or conservation of matter. He conducted a study in which the acquisition of the concept of momentum in 160 children in the age range of five to eight years was examined. A test consisting of six tasks was administered. The tasks, presented to each student in a random order to control for the effect of learning, were designed to assess their understanding of individual sub-concepts of momentum. None of the tasks involved calculations but relied instead on the students' intuitions. The first two tasks examined the students' conceptual understanding of mass and speed. Task one assessed their ability to deduce that matter is conserved even when its shape changes. The second item was designed to ascertain how well they could differentiate between the speeds of two objects that were travelling through two different lengths of tube in the same amount of time.

The third and fourth tasks were intended to examine the students' intuitive feel for the links between momentum, mass and speed. In the third task, the students observed two tennis balls, which contained different numbers of masses being pushed at the same speed into two identical boxes. They were then asked to describe how they would alter the mass of either tennis ball in order to move both boxes through the same distance. The fourth task used the same pre-prepared tennis balls and boxes. On this occasion the students were asked how they would change the speed of each ball in order to make both boxes move the same distance.

Tasks five and six were designed to investigate students' intuitive understanding of conservation of momentum in explosions and collisions. In particular, they were probed to find out if they could deduce the inter-relationships between mass and momentum, and between speed and momentum. In the fifth task, boxes (hiding different numbers of bricks) were placed on two identical dynamics trolleys which were then exploded apart. Both trolleys were stopped when they collided with equidistant bricks. After watching this, the students were asked to state which box contained the greater number of bricks, and give a reason for their answer. Two colliding dynamics trolleys were used in task six. Initially, one trolley collided with an identical, stationary one, which then moved off at approximately the same speed as the initial velocity of the first one. Then different numbers of bricks were added to either of the trolleys and the students were asked to postulate on the post-collision speed of the second cart, relative to its speed in the initially observed collision.

Raven (1967) found that performance improved with age and that the highest percentage success rate by all of the age groups was achieved in tasks 5 and 6. Since each of the students attempted the tasks in a random order, their ability could not have been attributed to them learning about momentum as a result of carrying out the tasks in a structured, logical, sequence. It should be noted however that the students' understanding was very much at an intuitive level, which lacked the precision or formality required of students in physics exams.

Task	Age in years			
	5	6	7	8
1. Conservation of matter	43%	53%	88%	93%
2. Speed	3%	5%	18%	45%
3. Proportional use of mass	30%	43%	80%	93%
4. Proportional use of speed	8%	25%	50%	93%
5. Momentum and mass	77%	88%	100%	100%
6. Momentum and speed	73%	80%	100%	100%

Table 2.1: Percentage of students (by age) getting each task correct. (Adapted from Raven, 1967)

Raven (1967) suggested that the results, shown in table 2.1, called into question the way in which momentum should be taught. Consequently he asserted that the order should follow what he termed the ‘psychological sequence’ rather than the ‘logical sequence’ (see table 2.2) if it is to be most effective.

Logical sequence of teaching	Psychological sequence of teaching
Conservation of matter	Momentum
↓	↓
Speed	Conservation of matter
↓	↓
Proportional use of mass & speed (momentum held constant)	Proportional use of mass & speed (momentum held constant)
↓	↓
Momentum	Speed

Table 2.2: Raven’s ‘logical’ and ‘psychological’ sequences for teaching momentum.

Raven's research suggests that young children have an intuitive feel for the effects of changing the mass and speed of objects in collisions and explosions. However, the study can be criticised on a number of fronts. Firstly, the children were deemed to have succeeded in a task if they gave the 'correct' answer and were able to give one valid reason for their answer. However the lack of in-depth analysis of the children's thinking and reasoning, beyond a single plausible explanation, limits how certain one can be regarding their true perception and level of understanding of any of the given scenarios.

A second set of possible objections arise from the assumption that being able to give a correct response in tasks 3, 4, 5 and 6 along with a plausible reason (which would have been highly unlikely to have included the term 'momentum' since the children had never been formally introduced to it) was synonymous with an understanding of the concept of momentum. An alternative explanation for this could be that the children were actually displaying an intuitive grasp of one or other of the related, but not identical, concepts of force or energy, rather than momentum. Confusion between these inter-related concepts is commonly reported in research studies of students' conceptions, like those discussed by Driver, Guesne and Tiberghien (1985) and Driver, Squires, Rushworth and Wood-Robinson (1994). In another study, which is not part of this thesis, Bryce and MacMillan (2009) examined the content of a range of textbooks written specifically for the various physics syllabuses in the UK. A detailed analysis of the ways in which the books introduced, explained and tested students' understanding of momentum and kinetic energy was undertaken. These studies all discuss that students of many different ages are confused about the distinctions between force, energy and momentum. The assertion that the participants in Raven's study intuitively grasped the concept of momentum is also questionable as there was a clear indication from the results of task 2 that they were especially poor at distinguishing between the speeds of different objects, which could be argued to be a pre-requisite for correctly interpreting the observations in tasks 4 and 6 in particular.

The claim that children understood the concept of momentum if they could identify how the mass or the speed of a moving object affected the distance moved by the object into which it is collided (tasks 3 and 4) is flawed. The distance that the object moves is primarily linked to the force exerted in the collision and the kinetic energy of the incoming object, as work done = force × distance.

Task 5 pre-supposed that the children appreciated that both vehicles in the explosion experienced equal and opposite forces. The results certainly suggest that many successfully made links between the mass and speed of objects after experiencing a force but this does not necessarily mean that they have a feel for the concept of momentum. It is quite plausible to suggest an alternative explanation, which at least some of the children may have had in mind (Driver et al., 1985) was that the slower movement of the more massive objects was because such objects are harder to move, as they require more force (or energy) in order to initiate movement. A similar potential difficulty exists when considering the results for task 6 when the mass of the second vehicle was altered. In the other circumstances examined in task 6, where the mass of the first vehicle was increased, the observation that this change increases the post-collision speed of the second cart could readily have been conceptualised by the students in terms of more massive objects exerting more force or giving more energy to an object that it collides with, rather than necessarily making the connection between the speed and the momentum of an object.

Since these arguments show that it is possible that the students were actually demonstrating an intuitive feel for the effects of force or energy rather than momentum, Raven's suggestion that the teaching sequence should begin with momentum and end with speed seems to be somewhat questionable. As discussed previously, this approach is particularly problematic since his results strongly indicate that their understanding of speed is deficient. The potential danger with his suggested approach is that it could mask the existence of alternative conceptual frameworks (like those discussed above) or misunderstandings which lead to confusion about the true meaning of momentum (as opposed to force or energy) until a proper understanding of mass conservation and speed had been developed.

Two of the previous studies, by Graham and Berry (1996) and Williams (1976), sought to delineate the sub-concepts that constitute an understanding of momentum and to put these sub-concepts into rank order by difficulty. However both studies came to very different conclusions about the relative difficulty of several of the sub-concepts. Graham and Berry (1996) categorised students' understanding of momentum into four different stages. They administered a test, which consisted of twenty questions, in the form of a postal questionnaire. It was returned, fully completed, by a total of 549 students, all of whom were seventeen and eighteen-year-olds from several schools in the South-West of England. Each of these students had already studied momentum, impulse and conservation of momentum in class lessons as part of their courses in GCE Advanced Level (Applied) Mathematics.

Although the sample size provides a good cross-section of people, the use of only a postal, written test restricts the researchers' ability to examine the true nature, extent and range of students' difficulties in understanding momentum. Although errors and misconceptions in the respondents' answers could be examined from their written responses, the underlying thinking and reasoning could not be interrogated beyond what was written. This inevitably meant that the researchers had to apply a degree of interpretation in order to categorise each answer, which could not be verified or corrected by the respondents. Had the study involved an interview with at least some of the students, it would have been possible to explore, confirm or clarify what they thought, meant and really understood much more readily. Two criteria were applied in order to decide the level that a particular student had attained. A student had to have passed all of the previous levels before they were considered to have passed the higher level. The second criterion was that students were considered as having achieved a certain level if they achieved the pass mark, which was defined to be as close as possible to, but not exceeding, seventy percent for the five or six questions which were set to assess each level.

While the requirement to have gained success at a previous level in order to be assessed at the subsequent one is commendable, the use of a pass mark to infer that a prescribed level of understanding had been achieved can be criticised. A student who gained a score of 70% in answers to only five or six questions which assessed competence at each level was judged to have attained that level of understanding. However, since they were permitted to get up to 30% wrong, this would mean that they could have conceivably harboured a number of over-looked, or even undisclosed, important gaps or errors in knowledge and understanding. This is particularly possible in the case of the over-populated level 2. The four stages of understanding that Graham and Berry devised from their results are outlined below in table 3.3 in terms of student performance criteria for each stage.

Level	Performance criteria
0	Little or no coherent understanding.
1	Recognise the importance of mass and speed. Compare the momentum of different objects moving in the same direction.
2	Model simple situations where the mass of a moving body changes. Recognise that momentum is a vector quantity. Recognise that momentum is the product of mass and velocity. Understand and apply the principle of conservation of momentum, when motion is restricted to one direction. Understand and apply the impulse-momentum equation, when motion is restricted to one direction.
3	Understand and apply the principle of conservation of momentum in two dimensions. Understand and apply the impulse-momentum equation in two dimensions.

Table 2.3: Graham and Berry's (1996) four levels of students' understanding of momentum.

Although there is an obvious progression of difficulty between the ideas in the different levels, the way in which that they have been assigned to one or other of levels one and two can be criticised as rather arbitrary. Level 2 in particular seems to be over-populated with a large mixture of concepts which could be considered to vary considerably in their level of difficulty. Further sub-division, in terms of the conceptual demands that items place on students, would arguably make this study more useful to practitioners.

From their sample, they found that most of the students were at level one or two with a small number at level 0 and a relatively small 'top-end' who were operating at level three. The percentages of students placed at each level are shown in table 3.4.

Level	Percentage of students	Pass mark
0	6	---
1	42	4/6 (67%)
2	38	4/6 (67%)
3	14	3/5 (60%)

Table 2.4: Percentage of students at each level and pass mark for each level. (Extracted from Graham and Berry, 1996)

The difficulties typically encountered by students at each level were described. These insights are particularly illuminating, as they show how students' understanding of momentum progresses as they improve through the different levels. Students at level 0 were found to have a very confused view of momentum. In particular they tended to have a very heavily speed-dominated view of the quantity. The researchers found that this led many students to ignore the mass of an object when trying to deal with problems involving momentum.

Those students who had progressed to level 1 were judged to have grasped the fundamental idea of momentum and were able to recognise situations in which it was appropriate to calculate it, and how to do so. However they had difficulties in three specific areas. In common with the findings of other studies, a sizeable proportion of the students failed to recognise or treat momentum as a vector quantity; they tended to think of momentum as the product of mass and speed, rather than velocity. Consequently, they had difficulty in justifying why the momentum of an object changed when its direction altered. In terms of their understanding of the impulse-momentum equation, it was judged from their written statements that many of the students struggled to relate the product of force and time to the change in momentum of an object. They also struggled to apply the principle of conservation of momentum in problems involving collisions, particularly in situations where there had been a change of mass.

The concept of momentum being the product of mass and velocity posed no real problems for level 2 students. They also coped well with the principle of conservation of momentum and the impulse-momentum equation in situations in which the motion occurred in a straight line. It was also found that these students struggled in problems where the direction of motion changed due to an inability to recognise the need for, or cope with, manipulating the vectors in the problem. When faced with such difficulties, the data showed that the students resorted to using intuitive ideas, which resulted in vague and imprecise responses.

Graham and Berry (1996) argued that the way in which momentum is typically taught contributes to the failure of many students to grasp the vector nature of momentum. They suggested that teachers and many textbooks typically introduce the concept and analysis of momentum using only one-dimensional situations, and then introduce two-dimensional problems as an extension towards the end of the teaching and learning process - a greater emphasis on momentum as a vector from the outset would be more beneficial in their opinion.

In the other study designed to rank momentum sub-concepts and examine the growth of students' concept of momentum, Williams (1976) administered a test to seventy-two 'O' level students. The test instrument consisted of a set of five written questions, each of which had sets of sub-questions. Two of the questions were descriptive in nature, while the other three were numerically based and required a calculation for some parts of the question and description for others. The descriptive questions required the students to consider changes to the initial conditions given in the question and to articulate their views on how these changes would alter the outcome. The test was administered verbally and each student's responses were audio-taped and transcribed. The results were analysed by examining the transcripts of the interviews for evidence of students' understanding of the various sub-concepts of momentum that Williams (1976) had defined. From this data, he empirically devised an order of difficulty for the sub-concepts, in order to produce what he referred to as a 'scale of understanding for the concept of momentum' which is summarised in table 2.5 below.

On carrying out an analysis of his scale, in comparison to Piagetian levels of intellectual growth, Williams (1976) found that 'concrete operational' thinking was required to reach level two on his scale, but that 'formal operational' thinking was a pre-requisite to progress to levels three and beyond. When compared with the scale developed by Graham and Berry (1996), Williams' scale is much more detailed in several respects. In particular it is interesting to note that he delineated the understanding of the vector nature of momentum much more clearly. As previously discussed, the scale developed by Graham and Berry (1996) suffered from having level 2 too densely populated with concepts, which reduced its ability to distinguish between students' levels of understanding as effectively.

Level	Understanding exhibited by student
1	No understanding of momentum (p).
2	Momentum, $p = m \times v$ and simple calculations by rule. Mass (m) as inertia and the vector nature of velocity (v) are not understood.
3	Change in momentum, $\Delta p = F \times t$ and simple calculations by rule. Changes in momentum are associated with forces but the influence of the time is not appreciated.
4	Total momentum, p = constant. Limited to situations where the total momentum is not zero or where the vector nature of momentum does not need to be considered. Mass is inversely proportional to velocity can be argued.
5	Total momentum, $p = 0$ in situations involving explosions. The vector nature of momentum is understood, but only intuitively.
6	Change in momentum, $\Delta p = F \times t$. Changes in momentum can be discussed in terms of both force and time.
7	Total momentum, $p = 0$ in situations where p must be considered as a vector. The explosion process is understood in terms of Newton's Third Law, with the interacting forces giving rise to the momentum changes.
8	All of the previous levels are understood and in addition the effects of a change in direction and the vector nature of momentum are fully appreciated.

Table 2.5: Williams' scale of understanding for the concept of momentum. (Adapted from Williams, 1976)

Williams (1976) also used the transcript data to carry out a 'principal components analysis', from which he deduced that three major concepts contribute to an understanding of momentum. The first of these is the law of conservation of momentum, applied to collisions and explosions. The second is the vector nature of momentum when applied in one dimension to collisions which involve a change of direction for one of the colliding bodies and the third is using the rule momentum = mass × velocity. In his final conclusions he advocates that, in order for the acquisition of the concept of momentum and its conservation to be most successful, the teaching and learning sequence should follow the same order as his scale of understanding.

A study by Lawson and McDermott (1987) and a follow-up piece of research by Pride et al. (1998) both examined the links between student understanding of momentum and the related concept of impulse. In a study of 28 undergraduate students in the University of Washington, Lawson and McDermott (1987) used tutoring interviews to assess two groups of students' ability to relate the concepts of change in momentum and impulse (force × time) as well as work (force × displacement) and kinetic energy. The student group consisted of 16 students who were doing a non-calculus physics course and 12 students who were undertaking an honours course in Physics that did involve the use of calculus. All of the students had completed an introductory mechanics course, which included material on momentum and energy.

The students watched two dry–ice pucks, of different mass, being blown by a steady air current on a 'frictionless' glass table between two lines before being left to move freely across the remainder of the table. They were then asked two questions and asked to give reasons for their answers. Firstly, they were asked whether the pucks had the same, or different, momentums during their free-motion after crossing the second line. The correct answer to this question was that the puck with the larger mass had the greater momentum as it crossed the second line because its impulse was greater; its larger mass meant that it was being accelerated for a longer time (at a lower rate) by the same force as the lighter puck. The second question asked them to compare the kinetic energies of the two pucks as they crossed the second line. Since they were pushed by the same force through the same distance, their kinetic energies would be identical. If they answered either question incorrectly, or they inadequately justified their answer, they were then given two hints by the interviewer. The first hint was to draw the students' attention to the fact that both pucks were subject to the same constant force for the same distance. If this did not result in a successful answer, they were then asked if they were familiar with the terms 'impulse' and 'work' and if they felt that these could be applied to the situation that they had observed. If they were then still unable to answer the initial question successfully, then the interview was concluded. This arguably abrupt approach could be criticised on two fronts. The rather vague nature of the hints given would not necessarily have helped many of the students to resolve, or even necessarily reveal, their difficulties. The hints given pre-supposed that the students had merely forgotten the relevant pieces of information, but did not help them if in fact they misunderstood the underlying concepts. Secondly, the decision to only allow these two hints before the interview was terminated meant that potentially useful data regarding the students' difficulties and misconceptions could have been missed. By allowing further discussion, it may have been possible to glean more details of students' reasoning and could have helped some of them to gradually deduce the correct answer.

The findings for the momentum task showed that the students found the task of linking impulse and momentum conceptually difficult as only 25% of the honours students could give a correct and adequately justified reason before any intervention by the interviewer. Even after both of the interventions, only 67% of the honours students and 6% of non-honours students got the answer and reasoning correct. These findings suggest that both Williams (1976) and Graham and Berry (1996) were justified in assigning the linkage between impulse and changes in momentum to higher difficulty levels in their conceptual schemes.

Prior to any intervention, 58% of the honours students and 50% of the non-honours students deduced incorrectly that the momentum of each puck was identical. The most common justification for this was that the more massive puck had a slower velocity, which compensated for its greater mass, so that the product of mass × velocity in each case would be the same. The other common incorrect reason given was that since the force on each puck was the same, the change in momentum would be the same. Clearly, the equally important effect of the time was ignored by the students who gave this answer.

Lawson and McDermott (1987) noted that many of the non-honours students were prone to deducing that the momentum and kinetic energy of an object were the same. They found that the reason for this confusion was that both quantities are based on a combination of mass and velocity. Only the honours undergraduates had successfully learned that the kinetic energy is dependent on the square of the velocity, unlike momentum.

The work of Lawson and McDermott (1987) was followed up by Pride et al. (1998). They developed a tutorial scheme that was designed to improve students' understanding of the work–energy and impulse–momentum theorems. The same questions as the earlier study were used as a pre-test, but in the form of a written paper, which they administered to 985 physics undergraduates studying on honours courses, not all of whom had received a lecture on momentum and impulse. Those who had not received the lecture were told that the momentum of an object is equal to the product of its mass and velocity. They found that only 5% of the students could correctly answer and justify the momentum-impulse question in the pre-test, in which they were given no help. There was no significant difference in the success rate of those who had covered momentum in their lectures when compared with those who had not. The written responses in this second study highlighted that the students commonly used the same incorrect reasoning patterns as had been prominent in the interviews in the first study.

Pride et al. (1998) devised a tutorial lesson which they used in an attempt to help students to reason their way to an answer more effectively. This consisted of two tasks on a worksheet. The use of a tutoring worksheet meant that there was no face to face or verbal interaction between the researchers and the students. This had the advantage of ensuring that all of the students were given identical help and information. However, the lack of interactive feedback meant that students who did not fully understand the worksheet were potentially not helped.

The first task encouraged the students to analyse the motion of the puck in the pre-test scenarios by constructing an algebraic representation. They were also asked to consider fictionalised dialogues in which the commonly used compensation arguments were encountered. It was found that the students were then better at recognising the erroneous lines of argument. The second task involved the analysis of two demonstrations. The first showed a ball following a curved path when it was given an initial push horizontally along the top of a slope. In the second, the ball was set rolling up the slope at an angle, which meant that it followed a parabolic trajectory that reached the top of the slope. This resulted in a situation where a change of direction was involved. A worksheet was used to lead them through the algebraic process of deducing that the kinetic energies and the magnitudes of momentum at the bottom of the slope were identical in both scenarios. However, it also led them to see that the change in momentum was different in each case due to the change in direction of the initial and final momentum in the second scenario.

The post-test scenarios were almost identical to those used in the pre-test. The only difference was that both pucks were blown for the same amount of time rather than the same distance. Consequently, the momentum of both pucks was identical, but their kinetic energies differed. Pride et al. (1998) found that the post-tutorial test results showed a marked improvement from 5% (in the pre-test) to 50% of the students giving a correct answer and explanation for similar questions about momentum.

The first task on the worksheet would have been helpful in correcting misconceptions associated with the pre and post test questions and would therefore account for the improvement in the students' post-test performance. However, the second set of tasks involving the demonstrations of the ball on a slope seem to be a rather strange choice and could be argued as having being somewhat counter-productive. Potentially, the numerous differences between these and the test scenarios would make it unlikely that many students would deduce useful connections.

A study by Olenick (1997) is the only one that has examined the views of Physics teachers and reports that many regard this topic as being conceptually difficult for their students. Around 100 American high school physics teachers were surveyed to find out which topics they regarded as being problematic for their students. The most common misconceptions and difficulties demonstrated by students were also identified. Difficulties with a number of topics, including momentum and its conservation were reported. Some of the reported misconceptions regarding momentum were as follows:

1. Momentum is not a vector.
2. Conservation of momentum applies only to collisions.
3. Momentum is the same as a force.
4. Moving masses in the absence of gravity do not have momentum.
5. Momentum is not conserved in collisions with “immovable” objects.
6. Momentum and kinetic energy are the same.

A series of pre and post-discussion tests were given to the participating teachers. From the results of these it was discovered that that there were also problems with the teachers’ understanding of some of the topics that they had highlighted as areas of difficulty for students.

As can be seen from the discussion above, previous research has been successful in identifying several difficulties that students encounter when trying to learn about momentum and kinetic energy. In three cases, the research has culminated in some useful suggestions regarding the most effective teaching order, based on a process of ranking the relative difficulties that samples of students have encountered. The main limitation of all of the previous work is that it has been quantitative in nature, focussing on ascertaining the proportion of students who demonstrated particular difficulties in their understanding. Even in the case of the ‘tutoring interviews’ carried out by Lawson and McDermott (1987), the intention was to find out the proportion of students who could successfully complete the given task, with or without the pre-determined ‘tutoring’ interventions. An opportunity was missed in that study to use the interview in a more qualitative manner to explore the students’ thinking and reasoning. What has not been demonstrated by any of the existing research is the way in which students develop their understanding of these topics as they think through practical situations as they encounter them. The present study therefore deliberately seeks to use a qualitative approach in which think-aloud interviews are used to enable students' thinking and reasoning to be tracked and analysed as they interact with one of two bridging analogy sequences (which have never been used in the context of momentum or kinetic energy before). The two analogical sequences were custom designed to assist students to gain an understanding of two scenarios that were highlighted by previous research as being particularly problematic: explaining how momentum is conserved in a collision with an apparently 'immoveable' object, and the non-conservation of momentum in inelastic collisions.

2.3 Conceptual change

Vosniadou (2008) outlines some of the current areas of controversy in conceptual change thinking and research that have been debated over many years. These debates began with the introduction of the 'classical approach' of conceptual change introduced by Posner et. al. (1982) which took its inspiration from the idea of Kuhn (1962) that as science progresses certain crisis points arise regarding sets of shared beliefs, assumptions and commitments and practices (which he called paradigms). At these points the crisis is resolved by a revolutionary change which he named as a 'paradigm shift'. Vosnaidou (2008) summarises the main debates as being in terms of cohesion versus fragmentation; sudden, revolutionary versus much more gradual, evolutionary change; spontaneous change which comes about as part of natural cognitive development versus instruction-produced conceptual change; the role of different mechanisms such as additive enrichment, radical changes in the learner's schema or categories, or mental model building and revision techniques.

Even the definition of conceptual change is not entirely agreed upon. Vosniadou (2008) describes the classical view of conceptual change in terms of a paradigm shift in which new concepts become "embedded in a different theory, have different interconnections to other concepts, and apply to different phenomena" (p. xiv). However, her own definition would be a process involving synthesis of different mental models through a gradual process. Clement (2008), on the other hand, considers conceptual change to have occurred when "new cognitive structure is created" (p. 418). He goes on to emphasise that this involves a change that is structural or relational in nature rather than simply a change in the surface features of a learner's thinking. Yet another opinion is offered by Chi (2008) who perceives it as a process whereby a student shifts an idea from one ontological category to another, while diSessa (1993) sees it as a process involving the interconnecting of basic pieces of knowledge into more complex structures.

Keil and Newmann (2008) add a word of caution to the debate by suggesting that not all changes to an individual's thinking can be classed as true conceptual change. In their estimation there are other surface rather than deep change possibilities, such as ‘conceptual elaboration’ or ‘shifting relevance’. For them, true conceptual change involves either a change to a concept’s internal structure, or a change occurs in its relationship with other concepts in a manner that is central to its meaning. They also make the specific assumption that any conceptual changes are likely to be domain specific, in that the student will not apply changes that they make in the physics domain of their conceptual structure to their biological domain, for example.

2.3.1 Misconceptions or alternative conceptions

It would be common practice, from a constructivist perspective, for teachers to begin a teaching sequence by taking cognisance of their students’ existing ideas and knowledge.

However, Driver (1983), Driver et. al. (1985) and Driver et al. (1994) have summarised a great deal of research which suggests that pupils’ pre-conceptions can be very stable, in that they hold strongly to their prior ideas or conceptions despite being presented with what the teacher believes to be compelling evidence for the new, better concept. This is a concern as it calls into question how much real learning is going on in classrooms, as demonstrated by genuine conceptual change, as opposed to pupils simply rote learning their teacher’s explanations and ideas in order to pass exams, without actually believing and understanding the ideas for themselves.

Maloney and Siegler (1993) conducted research which indicated that students often complete courses in Physics with competing conceptualisations; they still retain their informal understandings alongside their newly acquired, formal understandings, the latter not having replaced the former. Touger et al. (1995) also observed that students’ conceptualisations compete with one another, rather than being resolved. Some of these ideas are ‘spontaneous’ (intuitive) and may contain misconceptions, ideas chosen selectively, or illogicalities; some are ‘disciplinary’ in that they are a result of theory in the accepted physics.

Driver et al. (1985) also state that students' use of these pre-conceptions in coming up with interpretations and explanations is often incoherent, in that they often contradict their own predictions and switch from one explanation to another, for the same phenomenon. They can be quite content with these rather ad hoc interpretations and explanations as, in their minds, they appear to work well in predicting the outcome of everyday, practical situations. Nonetheless, from the teacher's perspective, they are misconceptions. Touger, Dufresne, Gerace, Hardiman and Mestre (1995) concluded that, to be able to apply physics knowledge to real-world problems, "… bridging is needed between everyday phenomena and ordinary language representations on the one hand, and formal physics concepts and mathematics on the other" (p. 265).

The ways in which misconceptions are seen to form is also a matter of considerable debate. Many researchers (for example Biemans et al., 2001; Bliss and Ogborn, 1994; Mason, 2001; Mildenhall and Williams, 2001; Vosniadou et al., 2001) suggest that 'misconceptions' are ideas or theories that students pre-form prior to instruction. Chi. et al. (1993) argue that misconceptions are the result of students having an incorrect fundamental view of 'how things are' (ontologically). On the other hand, Rowlands et al. (2007) align themselves with Strike and Posner (1992) and Champagne et al. (1982), in arguing that students' conceptions are situation-specific and are produced impulsively when they say that "... we cannot *assume* that a misconception is formed prior to its revelation. It would be better to assume the converse: that misconceptions are spontaneous, they are evoked ('constructed') rather than revealed." (p. 25). Rowlands et al. (1999) suggest that this spontaneous formation of the misconception is overtly influenced by the student's perception of some dominant feature in the situation or question. This was highlighted by Viennot (1985) who cites a number of studies which found that there was a common belief in the idea that the force acting on an object is proportional to its velocity when students were presented with questions in which the motion of an object was the primary feature and was presented diagrammatically or verbally rather than in a more analytical form. Furthermore, she reports that such responses have been found to be more common if the student cannot identify a 'well-known' force which could explain the object's motion and so they tend to invent forces which are consistent with the idea that force is proportional to velocity. Consequently, Rowlands et al. (2007) perceive that these dominant features result in some prior experiences (as opposed to well conceived theories) influencing the learner's ideas. They postulate that this occurs when the student bases his/her thoughts on what Stinner (1994) calls 'personal kinetic memories', such as having to push a heavy box in order to keep it moving.

Rowlands et al. (2007) also discuss the usefulness of 'schema theory' (c.f. Howard, 1987) in accounting for the formation of misconceptions by spontaneous reasoning and their intransigence to subsequent change. They suggest that learners develop a personalised 'world view' which comprises of a group of expectations about how things are organised or work. This system acts as a filter through which individuals organise their thinking and learning.

Viennot (1985) shares similar views, perceiving misconceptions primarily as 'intuitive reasoning'. She indicates that many people 'share a common intuitive explanatory scheme for phenomena' (p. 432) and that this 'intuitive physics' demonstrates that they work with 'a partially self-consistent stock of concepts and relationships' (p. 432) in their minds, which they are often unaware of, and therefore regularly fail to notice or challenge the discrepancies between the official view of physics and their own ideas and thinking. Essentially, Rowlands et al. (2007) argue that learners are reluctant to abandon their personal network of ideas. This, they argue, accounts for the well documented tendency of students to completely ignore new conceptions or to change their schema in anomalous ways.

However, not all preconceptions are misconceptions as pointed out in a study by Clement, Brown and Zeitsman (1989) in which they argue that certain preconceptions are useful 'anchoring' or starting points for basing learning on pupils' intuitions. Such preconceptions are used as the base example for a series of inter-related analogies known as 'bridging analogies'. The strategy employed in the present research involved the construction of a set of bridging analogies specifically for the topics of momentum and kinetic energy.

2.4 Conceptual change theories

Duit and Treagust (2003) give a useful overview of some of the currently held theories regarding conceptual change. Posner et al. (1982) see it in terms of '*accommodation*' of an old idea, while Chi, Slotta and de Leeuw (1994) consider it to be a matter of '*category re-assignment*'. In studies by Brown and Clement (1989) and Brown (1994), conceptual change is described in terms of achieving '*abstract transfer*' or '*explanatory model construction*'. Vosniadou (1994) considers it to be the result of '*theory transfer*' involving either the revision of a person's 'specific' or more deep-rooted 'framework' theory. Tiberghien (1994) thinks of conceptual change as being a type of '*modelling*' task, which can result in either 'semantic' conceptual change, involving changes to mental structuring, or more deep-seated 'theoretical' conceptual change. Another common explanatory theory is that conceptual change comes about as a result of cognitive conflict, which is articulated by Limon (2001) and Caravita (2001) among others. Ausubel (2000) favours a theory which he calls '*assimilation*'. On the other hand, diSessa (1993, 2002 and 2008) describes a process which he calls '*conceptual ecology*'. Several of these theories will now be examined in some detail.

2.4.1 'Accommodation'

This is a commonly used 'classical' conceptual change theory that was developed by Posner, Strike, Hewson and Gertzog (1982) from Piagetian ideas using their research on students' understanding of special relativity. According to Piaget, there are two types of conceptual change. The less difficult is where a student uses their existing concepts to deal with new situations, which is called 'assimilation'. In the more radical process, referred to as 'accommodation', the student is required to reorganise or replace their existing central concepts or 'paradigms' as Kuhn called them.

In order for accommodation to occur Posner et al. (1982) argue that four conditions need to be met in the mind of the learner. Firstly they need to be *dissatisfied* with their present conceptions. Then the new conception must be seen to be *'intelligible'*. Next they need to perceive the new concept as being *'plausible'* which finally results in it being thought of as *'fruitful'*.

In common with other theories such as modelling and theory transfer, Posner et al. suggest that accommodation will only occur in situations where the students have tried and failed to assimilate the new idea into their existing structure. This results in students experiencing a level of dissatisfaction with their existing ideas and personal theories about the way things work – the student then perceives their existing theories as being unable to solve the problem with which they are faced. The intelligibility of a new idea is then seen as being of primary importance in moving towards a new way of thinking. This means that the student must be able to see how both new and prior experiences can be more intuitively explained by the new idea and so existing theories must be perceived as less understandable than the new one. Plausibility, which is seen as the next step by Posner et al. (1982), requires that the learner can see how the new stance solves the problems which their prior one could not cope with. In essence, the new stance needs to be more believable than the first because it is solves problems, but it still needs to be compatible with prior knowledge and experiences. Finally, the new concept needs to be capable of being fruitful in that it is able to be extended into other areas or be able to explain other things.

This conceptual change theory has the advantage over many of its competitors of describing a more detailed mechanism for conceptual change. Its popularity possibly stems from its discussion of the thought processes which the student undertakes as they decide whether or not to move towards the accepted way of thinking which their teacher is trying to establish. These thought processes can be tracked and analysed in research studies where think aloud interviews are utilised such as Posner et al.'s (1982) own study, or by Bryce and MacMillan (2005). The difficulty with the theory as it stands, according to Clement (2008), is that it discusses the conditions and effects of change rather than the mechanism by which a student moves from one stage to the next. It can also be criticised as implicitly assuming that the learner engages in a great deal of reflection. The current research seeks to examine this change mechanism and make the students' reflective processes much more explicit.

2.4.2 'Theory Transfer' or 'Restructuring'

Vosniadou (1994) describes her idea of 'restructuring' or 'theory transfer' as an attempt to explain the nature, rather than the process, of conceptual change. According to this stance, deep-seated naive '*framework*' theories about the world are formed in early childhood, which constrain an individual's interpretations about the way in which the world around them operates. These broad 'framework' theories in turn strongly influence '*specific*' theories that a person constructs regarding a particular object or event in given subject domains or situations through an iterative process of modification.

In common with several other theories, conceptual change is considered to involve embedding new concepts within larger theoretical structures, which by their nature and presence, constrain the way that learning occurs. Vosniadou (1994) discusses two conflicting views of how the knowledge acquisition process occurs. One possibility is that small units of knowledge (referred to as 'atomistic concepts') are connected in the mind of the students on the basis of perceived similarity into increasingly complex conceptual structures, but she argues that "similarity is insufficient to explain how atomistic concepts are grouped together to form categories" (p. 46). Instead, she suggests, in common with others (such as Murphy and Medin, 1985 and Vosniadou and Ortony, 1989), that learning has more to do with the existence and function of an individual's explanatory, naive 'framework' theories within which new concepts become embedded from infancy to form increasingly complex mental models.

In this theoretical stance, conceptual change involves moving from an initial model towards a final 'scientific' model via successive 'synthetic' models that are generated during cognitive functioning and seek to preserve the essential structure and behaviour of the idea or object that they represent in the learner's mind. The models are seen as being dynamic and generative in that they can be mentally manipulated to provide the learner with explanations and facilitate predictions regarding new situations.

According to this theory, there are two types of conceptual change. The first is where new information is simply added into an existing cognitive structure in a process termed '*enrichment*'. This is thought to be straightforward in situations where the new idea is consistent with existing cognitive structures. Conceptual change is deemed to be more problematic when a new concept conflicts with an existing structure or model although, at times, the student may not be concerned by, or even aware of, these inconsistencies.

In the second '*revision*' process (which is considered to be more difficult), existing fundamental beliefs and suppositions (ie 'framework' theories) or specific theories are changed because the new information is inconsistent with them. The process of 'revision' is therefore more likely to result in misconceptions, by which Vosniadou (1994) means "an individual's attempts to assimilate new information into existing conceptual structures that contain information contradictory to the scientific view" (p. 45). From this perspective, misconceptions are not a consequence of disjointed ideas or thinking, but rather they are a direct result of a student's fundamental pre-suppositions and their attempts to reconcile these with new information to construct a synthetic model. The possibility of successful 'revision' occurring is made even more difficult because these 'framework' theories are constantly confirmed in their minds by everyday experiences and are therefore highly resistant to change since they constitute deeply entrenched views of the world and the way that it is perceived to operate.

Her argument that a student's existing naive 'framework' theories heavily influence the details of their developing mental models is significantly weakened by her inconsistent assertion that "it is assumed that most mental models are created on the spot to deal with the demands of specific problem solving situations" (p. 48). However she seems to contradict this by conceding that some mental models may come from previously useful models which are stored in separate structures and retrieved from long term memory when needed. The theory seems therefore to suffer from a lack of clarity regarding whether new ideas are primarily the result of spontaneous generation or heavily constrained by pre-existing theoretical structures.

2.4.3 'Modelling'

Tiberghien (1994) draws on several pieces of her own research to describe conceptual change as being a knowledge processing method which she calls 'modelling'. This term is more often used by behaviourists like Bandura (1986) to describe the process whereby learning occurs through observation. In this case, Tiberghien uses it to describe the *construction of a mental model* in the learner's mind. She suggests that a learner's mental models represent only some self-selected properties, objects, events or attributes of the reality that they seek to explain. She contrasts this with scientific models which primarily make reference to physical quantities and formulae. These learner models are thought to be constructed and altered during the learning process as the student seeks to interpret or predict the outcome of a particular situation that they observe or consider. She argues that "learning difficulties appear as a "gap" between the meaning constructed by the learner and certain aspects of physics knowledge, particularly concerning physical quantities, their relationships and their meaning in the framework of physics" (p. 71). It is only in the situation where a person changes their thinking at the level of their theories about the world around them that the greatest level of conceptual change occurs. A learner's mental model is considered to be an intermediary between their theoretical ideas and the real world observations.

In describing the various forms and levels of learning, she refers to an 'experimental field' which is concerned with measurements and facts about a real world situation. Her notion of a scientific 'model' is about relationships between physical quantities and is used to enable predictions and interpretations to be constructed, often through the use of mathematical formulae. A 'theory' is more abstract or general and is concerned with issues of causality, principles and laws about a situation.

Tiberghien (1994) maintains that learner's models (as opposed to the scientific models) are produced in an ad hoc manner and often change with each new scenario, despite the scientific explanation being the same in each case. This is thought to happen because the student very closely associates their model with their perception of specific objects and events, while the scientist relates their model more to the underlying physical quantities.

According to Tiberghien's modelling theory there are four types of learning, the most basic of which is considered to involve simply learning to make efficient use of *social rules*. In this case the theory is not understood but rules which the teacher has given the learner are followed as a mere recipe for solving examination questions but there is no ability to predict or understand real events. Where there is no change to either the underlying model or theory about a situation, the learning is referred to as an '*extension of the field of applicability*'. In this case, new events are simply added to the existing model.

In the case of '*semantic*' conceptual change the model is modified but not the underlying theory. The structure of the student's mental model, as well as their interpretation of the objects and events that are associated with it, can be significantly altered but the underlying theoretical assumptions are not. It means that the student gains the ability to interpret situations which would previously have been viewed as very different as having similarities. However, the change is restricted to the formation of new relationships between the model and real world events.

When '*theoretical*' conceptual change occurs, the student is considered to have altered both their model and underpinning theory – their view of the causality of a situation is restructured. They have gone beyond looking purely at objects and events to consider the actual physical quantities that are inherent within the situation. Their own theory has changed in such a way that it becomes better aligned with scientific theory.

Modelling theory is comparable with Vosniadou's theory in terms of the rank order of difficulty associated with different learning tasks. The level of difficulty associated with changing a students' theoretical stances as opposed to their interpretation (or model) of a specific situation is similar. What this theory lacks however is an analysis or discussion of the role played by an individual's underlying theory in the formation of the changing mental model. Tiberghien (1994) states that a student's personal theories are involved in their interpretation of a given situation, but she does not make it clear how she considers these personal theories and their 'models' interact during the learning process. This makes the modelling theory less powerful as it merely describes which types of conceptual changes are harder than others. It is also unfortunate that the process is called modelling since it articulates changes to not just the 'model' layer of conceptualisation but also to the 'theory' level. Duit and Treagust (2003) point to a number of researchers who suggest that students find the process of constructing a mental model difficult.

2.4.4 'Category re-assignment'

In this theory, put forward by Chi, Slotta and de Leeuw (1994), conceptual change is seen as a process whereby a particular idea or concept is transferred from one ontologically distinct category to another as a result of evidence and teaching that is presented to the learner. Three ontological categories are posited: *matter, process* and *mental states*. All entities belong to one of these categories. According to this theory, misconceptions are caused when students associate a particular idea or concept with the wrong category. It is argued that many scientific concepts such as heat, electrical current and force correctly belong to the 'process' category but instead many students wrongly perceive them as being an example of 'matter'. The example is given of the commonly discussed phenomenon of students thinking of force as an impetus that is given to a body and which gets used up as the object moves.

In order to exemplify the theory, they refer to data collected by other research studies covering a range of ages and stages of learner and claim that their theory allows contradictions in the results to be explained. However, they do not provide any examples of conceptual change occurring by their own definition, which seriously weakens the theory that they propose. Even in a more recent article, Chi (2008) gives examples of the types of changes that would constitute their idea of conceptual change, but fails to document direct examples of students changing from one category to another in order to exemplify this model operating in practice.

2.4.5 'Abstract transfer' or 'explanatory model construction'

The use of models and analogies is seen as being central to the working of 'abstract transfer' theory which was developed from a number of research studies, but those initially carried out by Brown and Clement (1989) and Brown (1994) were instrumental in its formation. Clement (2008) concedes that the term 'model' is used in a huge variety of ways by different commentators, which makes defining it very difficult. His own definition of a model is that it is "a mental representation of a system that focuses the user on certain features in the system and can predict or account for its structure or behaviour" (p. 418). Its usefulness in knowledge representation comes from its ability to represent useful interrelationships in a system rather than just being a collection of isolated facts.

Clement (2008) suggests that using a mixture of dissonance strategies and analogies is the most effective way of helping students to achieve conceptual change by an evolutionary process. Dissonance strategies include the teacher contrasting known misconceptions with the accepted scientific view or through the use of discrepant events, such as experimental results, demonstrations or summaries, which help the student to experience cognitive conflict regarding their current model and preconceptions

This theory suggests that '*model evolution*' is the key route by which conceptual change can be achieved. This involves using multiple teaching strategies such as seeking information, using analogies, the use of discrepant events and presenting explanatory models to learners. These methods are used repeatedly in an attempt to ascertain the current level of student understanding and to move it gradually towards the accepted scientific model. The use of analogies is thought to have two different purposes in refining the learner's cognitive model. The analogy can either help the student to enrich certain features of the model or help to build a more abstract relational structure to the evolving model.

2.4.6 'Assimilation'

Ausubel (2000) proposes a model of learning that has elements of both assimilation and accommodation from Piagetian ideas. He uses the term assimilation to describe a much more sophisticated process than Posner et al. (1982) did. His theory clearly refers to the existence of a cognitive structure in the mind of the students, which contains interrelated ideas which he calls 'concepts' or 'propositions'. He suggests that there are three different types of learning: *representational*, *conceptual* and *propositional*, all of which can be considered as being forms of assimilation. Representational learning involves activities like naming, where objects or events are assigned a symbol which conveys a meaning to the individual. Early 'conceptual' learning is seen by Ausubel (2000) to consist of the process of 'concept formation' while subsequent learning is seen in terms of 'concept assimilation', but in each case the act of learning is perceived as being inherently active. Even in the earlier situation where concept formation is occurring, the criteria by which a particular concept is defined in the child's mind are refined by experience and are developed through an active process of generating hypotheses, testing and generalising. He divides the most complex type of learning (propositional learning) into three types: '*subordinate*' or '*subsumptive*', '*superordinate*' and '*combinatorial*'. In 'subordinate' or 'subsumptive' learning, new ideas are said to be related meaningfully to more complex superordinate concepts in a student's existing cognitive structure. This learning is considered to be '*derivative*' if the new material simply supports or exemplifies existing ideas in the cognitive structure, but it is referred to as '*correlative*' if it extends, elaborates, modifies or qualifies previously learned propositions. 'Superordinate' learning occurs when a new proposition is perceived as being related to either individual or groups of lower level subordinate ideas which become subsumed under the new proposition in the student's cognitive structure. Finally, combinatorial learning describes a situation in which a potentially meaningful proposition is unable to be directly related to either existing sub- or super-ordinate ideas. Instead it is seen as being related to a combination of generally relevant content in the student's existing structure. Ausubel (2000) considers most propositional learning to be either subordinate or combinatorial in nature.

He makes a clear distinction between rote and meaningful learning, each of which he perceives to be at opposite ends of a continuum. In *meaningful learning*, the process of acquiring new knowledge or information results in a change in both the acquired idea and the aspect of cognitive structure with which it becomes associated (a change which is close to the Piagetian idea of accommodation). By contrast, *rote learning* only involves a simple bonding process between new information and an existing cognitive structure in which no actual changes to either occur. This is much more akin to the use of the term 'assimilation' as originally envisaged by Piaget and used by Posner et al. (1982). Ausubel argues that the process that occurs in meaningful learning contains a number of steps. The first step involves the learner in anchoring the learning material with certain pre-existing ideas in the cognitive structure. Subsequently the student works with the new and existing ideas in such a way that the meaning or understanding of each is altered in some way. Finally, the new material, meanings and understandings need to be linked to the original anchoring ideas in the student's memory. The result is that the new meanings become more stable and resistant to change or loss because they have been linked with an already stable anchoring idea.

2.4.7 Conceptual ecology

This theory stands out from the others in that it does not pre-suppose the existence of an intuitive model or theory which the learner adapts as conceptual change occurs. It came from research studies which involved interviews with undergraduate physics students by diSessa (1993). In a more recent article, diSessa (2002) claims that other conceptual change research suffers from a lack of "theoretical accountability concerning the nature of the mental entities involved and too little use of process data to support its theoretical view" (p. 29). However, the amount of research data that diSessa provides to substantiate his claims, in the articles that he has written explaining his theoretical stance, can be criticised as being rather sparse.

Conceptual ecology is very different from other theories as it starts from the premise that a person's understanding of the way in which things work, as well as the learning process, begins with many intuitive knowledge elements that are weakly organised, lack justification and are unable to resolve conflicts in the student's thinking purely on the basis of knowledge within the system. diSessa maintains that instead of replacing existing theories, the process of learning involves the development and refining of a systematic arrangement of knowledge and ideas from a starting point which involves numerous, small unconnected knowledge structures which he calls phenomenological primitives, or '*p-prims*'. During the learning process, some of the p-prims are prioritised over others and develop into a complex and *systematic knowledge* structure which are referred to as coordination classes.

In effect, diSessa argues that the learner begins the process of knowledge acquisition with 'knowledge in pieces'. The p-prims are recognised, or activated, by the student in various situations or systems that they observe in the world around them and can enable the person to explain some physical phenomena. According to diSessa, the use of these explanations is highly context dependent and learners therefore find it difficult to transfer ideas or knowledge from one domain, or subject, to another. He suggests that some p-prims can be self-explanatory in the sense that they represent "the way things are" in the mind of the learner but consist of only superficial interpretations of experiences and observations. However this line of justification sounds remarkably like the 'framework theory' that Vosniadou proposes or the types of intuitive mental models that Tiberghien and Clement describe. Indeed diSessa (1993) states that some p-prims "become the intuitive equivalent of physical laws" (p. 112), although he is at pains to state that they lack an explanation from within the individuals knowledge system and are used with no perceived need for justification.

2.4.8 Fragmentation vs cohesive, theory-like structure

As discussed above, there is an ongoing debate about whether students' preconceptions display fragmentation or cohesion. Most theories work on the premise that individuals have some form of coherent structure (which is described in terms of a model or theory) that has developed as a result of early experiences. This governs the manner in which individuals perceive the surrounding world to operate, although the exact nature and origin and production of this cohesion is a matter of debate among the different theories. The theory of conceptual ecology is the only one that suggests instead that an individual's mind contains unstructured pieces of knowledge or information, which become more structured and coherent through the learning process.

Blown and Bryce (2006) showed that studies on children's cosmologies have come to very different conclusions regarding this debate. They report that Nobes et al. (2003) "concluded that children's knowledge of the Earth was fragmented" (p. 1414) but they also quote the conclusion of Hayes et al. (2003) that there is "some degree of coherent structure within children's beliefs about the earth's shape and that such beliefs represent more than collections of fragmented facts" (p. 268). Blown and Bryce (2006) suggest that young peoples' thinking will potentially exhibit degrees of both fragmentation and theory-like coherence, but their analysis of substantial longitudinal/developmental interview data involving young people from several countries clearly showed a level of coherence in the students' thought processes. This finding was confirmed in a more recent article by the same authors (see Blown and Bryce, 2010) where coherence was explored across different modalities (young peoples' verbal explanations, their drawings and their models of cosmological events like seasons and eclipses). diSessa (2008) discusses this controversy, among others, as he defends his theory against various objections which are commonly put up against it. He argues that an individual may be able to demonstrate a coherent line of reasoning in a particular situation and yet have different and incoherent lines on other occasions, which he suggests demonstrates fragmentation of knowledge. He also argues that it is difficult, if not impossible, to assess the level of coherence in an individual's mind and so he suggests that those who advocate theory-like structures have no grounds on which to base their assertions.

2.4.9 Eliciting the mechanism of conceptual change

All of the conceptual change theories outlined above share the common view that learning involves a process whereby a person's perception or understanding of an aspect of the world around them is altered in some way. However the mechanism through which this learning is thought to occur is highly contested, given the number of theories that exist regarding it, even within the constructivist tradition alone. Each of these theories can, to greater or lesser extents, be criticised as lacking empirical evidence to back up their assertions regarding the process by which conceptual change occurs. They also fall short of enunciating a detailed mechanism by which conceptual change is thought to occur. In contrast, Posner et al. (1982) outline a process whereby a new idea is considered firstly as being more 'intelligible' than competing conceptions, then 'plausible' before it is seen as being sufficiently 'fruitful' to merit a change in a student's thinking. This is a useful starting point, but it falls short of explaining the ways in which a student reaches these conclusions.

This study utilised a qualitative technique of in-depth, think-aloud interviews, during which students engaged in 'guided analogical reasoning' (Bryce & MacMillan, 2005) as they worked through a set of bridging analogies. Tracking and analysing developments in each participant's thinking throughout the interview allowed the mechanism through which any detectable conceptual changes occurred to be made explicit and open to detailed scrutiny. This enabled the relative merits and veracity of the different theoretical stances to be assessed and led to a new way of conceiving the conceptual change process that brought together several elements of many of the existing theories.

2.5 Analogies

Physics teachers use analogies on a regular basis in an attempt to improve their pupils' understanding of the lesson content, whether that is a theory or new concept. Ogborn, Kress, Martins and McGillicuddy, (1996) have define an analogy as "a way of re-working knowledge" (p. 70). They see analogies as having a central role in learning and teaching as they state that "analogies and metaphors are always crucial in the thinking of new thoughts and the having of new ideas" (p. 72). This view ties in well with the intentions of conceptual change.

Literature on the subject of analogies suggests that there are three main types of analogy: '*close analogies*'; '*far*' or '*distant analogies;*' and '*bridging analogies*'. In the case of '*close analogies*', there is an obvious, direct link, between the analogy and the target, although they tend to be harder to interpret from a pupil's prior experience or intuitions than 'distant analogies'. In '*far analogies*', the analogy and the target are less obviously linked but the analogous situation is more commonplace and easier to understand because it appeals more directly to the pupil's existing intuitions. A '*bridging analogy*' acts as an intermediate stage between a 'close' and a 'far analogy'. This increases the likelihood of the analogical relationship being understood and useful in the learning process. In terms of constructivist theory, the use of bridging analogies could be compared with Vygotsky's concept of 'Zones of Proximal Development' in which he proposed that learning is most effective when it occurs in a series of small understandable steps which stretch the student's thinking each time in order to progressively develop that thinking. Often, this is achieved with the help of a teacher, who acts in the role of a coach or mentor, in order to encourage joint thinking and action regarding the concept or problem being considered. Structured assistance, like this, which occurs within the student's zone of proximal development, was called 'scaffolding' by Wood, Bruner and Ross (1976). This 'scaffolding', which may consist of a combination of mental and physical structures, is put in place by the teacher to support the learning process as new knowledge and skills are being built up. As the student becomes more skilled, the scaffolding which supports the learning can be gradually removed by the teacher until the student is able to function without it, on his/her own.

Heywood (2002) states that using analogies involves developing an understanding of abstract phenomena using concrete examples. However he cautions that it is unlikely that there will be one agreed interpretation of a particular phenomenon to which everyone subscribes. He therefore argues that the real benefit of analogies is their use in engaging pupils in the learning process, since developing meaningful explanations could be seen as the core enterprise of both scientific endeavour and learning science. In a similar vein, Kilbourn (2002) asks some very pertinent questions about the use of analogies in teaching. He asks whether the analogy plays an incidental role in the learning process since the conceptual changes that occur could possibly be explained as a result of simply spending more time thinking about a new situation by contemplating an analogical relationship with something else. He also asks whether an analogy should be merely roughly ‘sketched’ or ‘painted in detail’ in order to be most effective.

The use of analogies in encouraging conceptual change in the teaching and learning process of various concepts has been the focus of several previous studies (Baker & Lawson, 2001; Harrison & Treagust, 2000; Duit, Roth, Komorek & Wilbers, 2001; Treagust, Harrison & Venville, 1996, 1998). Within the field of mechanics, the teaching and learning of Newton’s Third Law by analogy has been studied by a number of researchers (Minstrell, 1982; Brown & Clement, 1989; Brown, 1992; Clement, 1993; Brown, 1994; Clement, 1998; Bryce & MacMillan, 2005).

The various studies by Brown and Clement made use of a set of bridging analogies which were designed to help students to believe in the existence of a reaction force when an object is placed on an inanimate object such as a table. Brown and Clement (1989) used four case studies of tutoring interviews to assess conceptual change while Clement (1993 & 1998) utilised experimental and control groups of classes and used pre- and post-tests to assess the level of conceptual change that had occurred. Minstrell (1982) used another strategy whereby several of the same analogies were introduced as part of a whole class lesson and gathered data by conducting straw polls of the class and through recording and transcribing the lesson.

Brown (1994) introduced the bridging analogies by giving pupils a series of written paragraphs with diagrams and assessed pupils' thinking and conceptual changes using a questionnaire, which was answered in sections after each paragraph had been read. He concluded that interviews would have yielded more detailed information about the pupils' thinking.

Brown (1992) interviewed students using three questions prior to them working through some material and four questions afterwards. One group was given an excerpt from a textbook, which included information on both the existence and the most widely accepted idea regarding the cause of the reaction force. The other group was given a series of seven short paragraphs that explained a series of bridging analogies, which again explained Newton's Third Law in terms of both the existence and the most widely accepted idea regarding cause of the reaction force. Using this methodology, Brown (1992) compared the use of analogical approaches with teaching a principle backed up by the use of examples, which were designed to show applications of the principle being taught. He concluded that where pupils held a misconception, analogical reasoning, which was used to draw upon and extend their existing valid intuitions, was more effective in producing conceptual change than simply presenting them with the scientific principle with supporting examples. From this he also concluded that analogical approaches are more effective because they encouraged an inductive process in the pupils' minds. Consequently they deduced a more general, abstract schema, which only included the most crucial and relevant details.

The study by Bryce and MacMillan (2005) built on these studies, involving the use of a very similar sequence of bridging analogies in the teaching and learning of action and reaction forces. This research was however different from previous studies as it used a qualitative methodology in which 'think-aloud' interviews were conducted with students as they interacted with the bridging analogy sequence. The results went further than those of the preceding enquiries in that it not only sought to find out if the analogies made the *existence* of the reaction force more obvious to students but examined the extent to which they could use the analogical sequence to deduce the *cause* of the reaction force for themselves, using only the sequence and without instruction by the researcher. The following conclusions were drawn from this work.

- Bridging analogies were effective in helping many students to achieve conceptual change in learning about Newton's third law both in terms of believing in the existence of a reaction force as well as deducing the accepted theory regarding its cause.

- The analysis of the students thinking provided some indication of how conceptual change was occurring through the use of the analogies. As advocated by Posner et al (1982), conceptual change appeared to occur when a new concept was firstly perceived as being 'intelligible', which then resulted in it becoming perceived as being more 'plausible' and then it became 'fruitful' (ie it became useful to the student as a way of explaining observable phenomena).

- Observable conceptual change occurred through the use of bridging analogies regardless of whether or not students had been previously taught the same concept using standard didactic teaching.

- Some students reported that, in their opinion, the use of bridging analogies was more effective than standard didactic teaching in causing conceptual change.

Treagust, Duit, Joslin and Lindauer (1992) carried out a study to examine the nature and frequency of analogy use by a group of science teachers and interviewed them to find out their views on the use and effectiveness of analogies. Venville and Bryer (2002) suggest that one of the most common reasons for the failure of analogies in teaching a new concept is where the pupil has limited prior knowledge of the base analogy. Several of the studies listed above used the classical 'accommodation' theory to analyse conceptual change. They showed the progression from intelligibility to plausibility and then fruitfulness but they stopped short of describing the micro-process by which each stage can be accomplished or how transitions from one stage to another can be achieved.

Tamim and BouJaoude (2000) and Patel, Magder and Kaufman (1996) examined the types of analogies that students generate for themselves when learning. Patel et al. (1996), who were studying their use in the learning of physiology, state that students use analogies to improve their explanations and understanding. They found that they were often used by students to facilitate clearer explanations, generating representations of a given situation, as a tool to help in bridging gaps in understanding, and in making links between ideas. People with a greater level of expertise in a particular area were found to be more likely to use analogies to assist them in articulating an idea and expand explanations, while less advanced users tended to use them more as a linking tool between ideas, often from different domains. In a similar manner, Tamim and BouJaoude (2000) described the students' use of analogies as a study and reasoning tool. In another study, Duit, Roth and Komorek (2001) describe the use of what they term 'observational sentences' in the generation of analogies and in analogical reasoning, whereby an analogy is generated as a result of a perceived similarity between two concepts. Iding (1997) conducted a study on the use of analogies in science textbooks and found that they were commonly used as a way of attempting to improve the clarity of explanations, and that they were often used in discussions extensively rather than simply being referred to in passing. The studies by Duit et al. (2001) and Iding (1997) both highlighted that careful use of analogies is necessary to avoid misconception being generated or perpetuated through their use.

2.6 The intentions of this study.

It can be seen from the preceding review that the topics of momentum and kinetic energy have not been extensively examined in the research literature and that these studies have been almost exclusively quantitative in nature. They have demonstrated that, although these topics at first glance may appear to be straightforward, they are in fact deceptively difficult for students to understand. Some of the studies have sought to delineate the sub-concepts and suggest an effective order for teaching them in order to improve student learning. These recommendations are based primarily on the relative difficulties of each of the sub-concepts, but they do not go nearly far enough in articulating the reasons for the difficulties that the students have, nor do they demonstrate how the students reason while they are in the process of trying to learn the ideas. This study sought to address this issue by using a qualitative methodology. The use of think-aloud interviews enabled the students' thinking processes, whether they are successful or otherwise, to be examined and interrogated.

Conceptual change theories abound, but as discussed above, many of them lack empirical evidence for their stance. Through the use of think-aloud interviews in conjunction with a set of bridging analogies, this study seeks to examine in greater detail than before, how conceptual change occurs as students make connections between different pieces of pre-existing knowledge, ideas and personal theories. Evidence of conceptual change, as suggested by the various theories discussed above, was looked for in the transcription data, in order to ensure that one particular theory was not favoured to the exclusion of others. An attempt was made to bring together the commonalities of each of the conceptual change theories by arguing that making connections is the overriding process which students are engaged in when their thinking undergoes conceptual change.

Analogies are widely used as a teaching, learning and explanatory tool, as demonstrated by the research which has been reviewed above. This study sought to provide a more in-depth, thorough and wide-ranging examination of the ways in which analogies can encourage conceptual change. Bridging analogies in particular have been shown to be successful in encouraging this process in several previous studies. It was therefore decided to devise a new set of bridging analogies which were custom-designed to encourage students to think through two scenarios which have been identified by previous research as being difficult for students to comprehend. In conjunction with the use of think-aloud interviews, the micro-process by which conceptual change occurs, as well as many of the difficulties and misconceptions that students struggle with, in the realms of momentum and kinetic energy were examined. The methodology by which this was achieved is discussed in detail in the following chapter.

Chapter 3
Methodology

3.1 Aims of the research

As a result of conducting the literature review above, two main aims were devised for the research study described in this thesis. The first was to analyse the effectiveness of bridging analogies in helping students to better understand the concept of conservation of momentum in collisions which involve large ‘immoveable’ objects, and to better understand why kinetic energy is not conserved in most collisions between objects. The second main aim was to analyse the ways in which learning and conceptual change occurs by analysing students’ thinking while they interacted with two bridging analogy sequences which were specifically designed to address these issues during ‘think aloud’, semi-structured interviews.

This qualitative study involved two phases of investigation. The first involved getting students to complete a ‘check-up’ questionnaire which sought to find out what they knew about momentum and kinetic energy and to ascertain what they thought the difference between these two quantities was, and to discover their reasoning concerning various collision and explosion scenarios that were outlined pictorially to them, particularly in terms of the momentum and kinetic energy of the system in question. This was carried out prior to engaging some of the students in interview in the next phase of the study. The second phase involved the analysis of sixty semi-structured, think aloud interviews that were carried out using two original bridging analogy sequences that were custom-designed to help students (i) to reason through what happens to momentum in a collision that involves an apparently ‘immoveable’ object, and (ii) to reason through why kinetic energy is not conserved in an ‘inelastic’ collision but is conserved when a collision is ‘elastic’.

The initial research questions for the study centred around how and why bridging analogies encourage conceptual change in the study of momentum and kinetic energy. However, as the research progressed, these questions evolved, giving the study a wider, more theoretical perspective in terms of the ways in which conceptual change occurs. This was examined through an analysis of students' thinking as they engaged with one of two specifically designed analogical sequences, in an attempt to back up, refute or find commonalities between some of the most popular conceptual change theories, as outlined in the literature review. The resulting set of research questions were as follows.

1. To what extent do bridging analogies help students to improve their understanding of the law of conservation of momentum?
2. To what extent do bridging analogies help students to improve their understanding of the physics of inelastic collisions?
3. How and why do bridging analogies result in conceptual change?
4. Which conceptual change theory (or theories) is/are at work during 'guided analogical reasoning'?
5. What can be discovered about the learning process from the use of 'guided analogical reasoning'?

The research questions start by seeking to discover what is happening in the specific case where bridging analogies are being used as a learning tool, before progressively widening the perspective in order to examine and enunciate what general principles can be demonstrated about the learning process through their use in conjunction with semi-structured interviews, which utilise Socratic questioning, to give an insight into each student's detailed thinking and learning strategies.

The first two research questions seek to examine the effectiveness of bridging analogies in helping students to understand two situations which often lead to misconceptions. These are (i) how and why momentum is conserved in a collision where one of the objects is so large that it is often considered to be 'immoveable' and (ii) how and why kinetic energy is not conserved in an 'inelastic' collision but is conserved in an 'elastic' collision, while momentum is conserved in both cases. Several of the previous studies that employed bridging analogies (for other concepts) have shown that they are effective in encouraging conceptual change in the context of Newton's Third Law (Minstrell, 1982; Brown & Clement, 1989; Brown, 1992; Clement, 1993; Brown, 1994; Clement (1998); Bryce & MacMillan, 2005.

However, the mechanism by which they achieve this has, as yet, not been clearly demonstrated or enunciated. Most of these previous studies have analysed students' progress in terms of Posner et al.'s (1982) ideas that conceptual change occurs when the learner considers a new idea to be more intelligible than an existing idea, which leads it to being 'plausible' and then 'fruitful' in solving problems or suggesting new ways of thinking. This progression was made particularly clear in the interview data that was analysed by Bryce and MacMillan (2005) in the case of action and reaction forces. However, what is as yet unclear is how a student makes these judgements. What criteria do students apply when trying to decide whether or not a new idea is more intelligible than their existing concepts or theories? What is the micro-process through which they move from one stage to the next?

The third research question therefore sought to interrogate the ways in which bridging analogies caused conceptual change. In order to answer this question, examples of conceptual change being triggered as the students interacted with the bridging sequences were looked for in the transcript data. The common features of these triggering scenarios were then compiled to suggest general principles of how and why conceptual change occurred.

As outlined in the literature review in the previous chapter, there are a number of theories about what happens to a learner's thinking and mental structures when conceptual change occurs. It was also noted that there was a lack of empirical evidence for some of the stances that were being put forward. The fourth research question addressed this issue by seeking to find which of the current theorised explanations have been evidenced in the interview data from this study.

The fifth research question further generalises the problem that question four seeks to address, and in so doing, forms the basis of the theoretical stance which underpins this research. Its focus is on discovering whether or not there are any overarching themes or ideas, evident in the transcript data, which could be used to unify (at least to some extent) the differing ideas from the conceptual change theories that are currently argued for.

In summary, seeking the answers to these five questions enabled several important issues regarding learning to be addressed. The details of the process by which bridging analogy sequences assist learning have been made more transparent. From a more theoretical and philosophical perspective, a greater understanding of the ways in which learning and conceptual change occurs have been addressed. Furthermore, addressing them necessitated analysing and attempting to synthesise the most important features of the conceptual change process that are argued for in the several theories advanced in this field. Each of these outcomes, individually and collectively, increases what can be known and understood about the learning process.

3.2 Philosophical and methodological considerations

The research is based on the philosophical approach to science education generally known as Constructivism. It is assumed that as students work through a set of analogies, they develop their personal theory about the way that momentum and kinetic energy are involved in the movement of objects in the 'real' world. The existing version of a student's personal theory and any changes to it can be assumed to have been affected by their interpretation of observations that they were making as part of the research procedure, as well as their own judgments regarding the relative (logical) merits or the correctness of one idea or explanation over another, based on their own internal criteria. Care was taken to avoid influencing their thinking by suggesting what the accepted answer was at any stage during the guided analogical reasoning process. The process was 'guided' in several carefully selected ways that were designed to elicit and develop the students' thinking without biasing them either toward or away from a particular answer. In particular: each student was encouraged to contemplate similarities and differences between prior analogies and the target situation; students were moved from one analogy to the next at a time decided by the researcher; thinking was probed in a manner that would encourage students to articulate their reasoning at each stage of the process; and any changes or inconsistencies in a student's ideas or reasoning were deliberately explored.

The approach in this study was not Empiricist or Positivist in terms of the definitions discussed by Nussbaum (1989) and Chalmers (1999) as it was assumed that knowledge is not ultimately provable by a series of carefully made observations. More specifically, this study does not fall into the Empiricist viewpoint since the senses were not assumed to have the primary role in decisions regarding the formation of knowledge in the mind of a student. Unlike the previous studies by Williams (1976) and Graham and Berry (1996) discussed in chapter 2, this study was not intended to result in a 'hierarchy of competencies'. Nussbaum (1989) states that Gagné had advocated this empiricist approach (from a behaviourist psychological perspective), whereby systematic inductive teaching (in which principles are gleaned from 'facts') is thought to guarantee successful learning. Nor was the study following a Rationalist perspective as it was not assumed that the power of the intellect alone would result in a 'correct' answer being deduced for a particular situation. Instead, knowledge has been assumed to be more personal in character. It is subject to falsification (as advocated by the philosopher Popper) or confirmation (which was emphasised by the philosopher Lakatos) through observation or experience and represents a 'best guess' by scientists or individual students, as to what is correct rather than a provable 'correct' answer.

This study has features associated with two different methodologies of qualitative research, these being grounded theory and case study. It has most in common with the grounded theory approach as its primary focus is to "develop a theory which is grounded in data from the field" (Creswell, 1998). However it also has features of a 'collective' case study project as it involved carrying out an in-depth analysis of a 'bounded system' of 60 volunteer participants responses when interacting with one of two bridging analogy sequences about momentum and kinetic energy. In particular it is an example of what Creswell (1998) refers to as an 'instrumental' case study since it highlights some issues that these students' struggled with as they tried to improve their understanding of these topics. In addition to this, the analysis of the students' thinking during the think-aloud interviews was instrumental in allowing an examination of ways in which conceptual change appeared to be occurring. Case studies normally involve the use of multiple sources of information. This project is therefore not a standard case study as the in-depth interviews were the main source of data along with a questionnaire which was designed to sample a larger cross-section of students' existing ideas about the conservation of momentum and the conservation (or non-conservation) of kinetic energy in various real-life scenarios that students find difficult to resolve in their minds. The method of data analysis used in the study was typical of a grounded theory approach (Strauss & Corbin 1990; Creswell, 1998). After fully transcribing the interviews, the data was submitted to a process of open coding, axial coding and then selective coding. More details are given of this in the data analysis section below. The student 'check-up' questionnaires were examined in order to identify common themes and descriptions, in line with a case study methodology.

Several previous studies of students' understanding of momentum and/or kinetic energy have used interviews as part of their methodology. As outlined in the literature review, Goldring and Osborne (1994) used interviews as a follow up to their main research tool which was questionnaires; Singh and Rosengrant (2003) used interviews in order to test the effectiveness of their primary research tool which was a questionnaire; Grimellini-Tomasini et al. (1993) used interviews as a component of some of their studies; Williams (1976) verbally administered his test and analysed the transcripts; while Lawson and McDermott (1987) used 'tutoring interviews' which were terminated when participants had been given two interventions in an attempt to assist his or her thinking. The present study used questionnaires prior to the interviews in order to determine what students already knew about kinetic energy and momentum and to examine their reasoning about momentum and kinetic energy in five situations. What is unique about this study is that it used semi-structured, in-depth, think-aloud interviews, in conjunction with specifically designed bridging analogies, as the *primary* source for gathering qualitative data. Rather than simply answering a set of entirely pre-determined questions, the students were encouraged to verbalise *their* thinking at each stage of the interview, through the use of Socratic questioning. Care was taken to avoid telling students what the accepted, 'correct' answer was at any stage. This meant that the students had freedom to alter their thinking in whichever manner seemed best to them. Using interviews in this way allowed the thinking processes of each of the sixty students, while they worked with the analogies, to be observed in the transcribed data and therefore made accessible for analysis.

3.3 The sample

There were one hundred and twenty one volunteers from the participating schools who answered the questionnaire for the first phase of the project. A total of sixty five secondary school students, aged sixteen or seventeen years, from five different comprehensive secondary schools took part in the in-depth, think-aloud interviews, although only sixty of these are included in the analysis due to technical difficulties which affected four of the interviews. Thirty students were interviewed and had their fully transcribed interview analysed for each of the two analogical sequences. Four of the participating schools were from two different Local Authority areas and had intakes which were drawn from mixed socio-economic status areas. The catchment area for the fifth school (a non-fee-paying local comprehensive school which operates out-with Local Authority control) consisted of a predominantly upper socio-economic status locale.

The interviews were carried after the students had completed the study of the Mechanics unit in the course. The range of possible results, from a grade A to those who failed the final national examination for the 'Higher' Physics course in Scotland (as well as those who dropped out prior to sitting the final exam) were represented in the sample for both analogical sequences. However, since the sample consisted of volunteers, it was not possible to ensure that the sample included equal numbers of students with each grade.

An analysis of the participants' final Higher Grade Physics results was carried out for those students who had participated in an interview. This was compared with figures obtained from the SQA (2007 & 2008) in order to check how representative the sample of interviewees was, in comparison with the national figures. Table 3.1 below shows how the final grade distribution for the sixty participants compared with the distribution of grades obtained by all of the Higher Grade Physics candidates across Scotland in the years 2007 and 2008, which were the years that the students' included in the sample sat their final exams.

Grade	National Candidates		Interview sample
	% gaining grade (2007) (n = 8580)	**% gaining grade (2008) (n = 8762)**	**% gaining grade (n = 60)**
A	26.3%	28.8%	25%
B	25.8%	24.3 %	28.3%
C	20.9%	21.0%	18.3%
D	9.3%	8.4%	1.7%
No Award	17.7%	17.5%	26.7%

Table 3.1: Distribution of grades in the Higher Physics exam of Scottish candidates in years 2007 and 2008 and distribution of grades in the Higher Physics exam for the sixty volunteer students in the interview sample.

It can be seen that the overall distribution of grades in the sample was similar to the national results for Grades A to C. In comparison with the national figures, the number of students in the sample who gained a Grade D appears to be very small, while those who gained 'no award' appear to be over-represented. However it should be borne in mind that the 'no award' figure for the study sample includes six students (10% of the sample) who withdrew from the course before sitting the final exam. The national figures do not include any of these candidates as only those actually entered for the exam appear in these statistics. The lower percentage of D Grades in the interview sample could be partly explained as being a consequence of students who withdrew from the exam because of their own school's policy on entering students who were considered likely to fail. It is possible that some of the sample of students who withdrew may have obtained a Grade D had they actually sat the final exam.

3.4 Approvals

Before the study could commence, several levels of approval had to be sought and gained. Initially ethical approval was gained from the University of Strathclyde's Faculty of Education Ethics Committee. Subsequently the approval of the Education Department for the two Local Authorities whose schools were approached was obtained, as well as the Head Teacher of one school in the study that was not in a Local Authority. Thereafter, the Head Teachers of a number of schools in each Local Authority were approached to ascertain whether or not they were willing to allow their establishment to take part in the study. Once this approval had been gained for an individual school, the researcher met with the head of each school's Physics Department to explain the ideas behind the study, the process involved and to outline the potential benefits of the research for both the students and the staff in their department. In every case the heads of department readily agreed to allow any of their students who volunteered to participate in the study. At this time, a mutually agreeable time was identified when the researcher could make a presentation to the students who were studying Higher Physics in the school. At that meeting, the process, required time commitment and potential benefits of participation in the project were outlined to the students, and volunteers were sought. Those students who indicated that they were willing to be involved in completing the questionnaire were then issued with two letters with attached consent forms. One gave their parents/guardians information about the project and the questionnaire and sought their written permission for the student's involvement. The second letter reminded the students of the details that had been outlined during the presentation regarding the questionnaire and sought their written consent to be involved in the sample. Those students who also indicated that they would be willing to be interviewed as part of the sample for the second phase of the study were given two further letters and consent forms, one for their parents / guardians and another for themselves giving information to, and seeking written consent from, both parties. Copies of the letters and consent forms are given in appendix 1. Once the consents had been returned, the head of each school's Physics Department decided on a suitable time to administer the questionnaire to their students. Separate interview appointments were arranged with those students who had consented to take part in the second phase of the study. The interviews were conducted across a total period of one year. Most of the interviews were carried out between February and June of one academic year. A small number of additional interviews had to be conducted during the subsequent year to replace interviews from the first batch that were not useable as a result of technical difficulties, such as having sections missing from the recorded data.

3.5 The design of the study

As outlined above, the final design of the study consisted of two parts. Initially, an introductory lesson plan had been devised to precede the other parts, but it was decided to omit this from the final design for several reasons which are discussed below. However, it was decided that although potentially useful, trying to get participating schools to agree to use the lesson plans as well as take part in the other two parts of the study would have been problematic. This lesson, which is outlined in appendix 8 may form the basis of a future piece of related research.

3.5.1 Phase 1: The pupil 'check up' questionnaire

A pupil 'check up' questionnaire was designed in order to sample a wide range of students' ideas regarding momentum and kinetic energy. A copy of the final (post-pilot study) check-up is in appendix 2. It was administered after students had received teaching on these topics in the Higher Physics syllabus. In addition to being useful in terms of this research study, the questionnaire was intended to provide potentially useful information for the teachers in the Physics departments that participated in the project. It provided an indication of students' grasp of the topic or brought to light some of their conceptual difficulties. These insights could then be used formatively by the teachers to improve their students' mastery of the topic. The first short section invited students to define both terms in their own words and to state what they thought the difference is between them. Subsequent questions investigated students' views on, and understanding of, the conservation of momentum and the conservation, or non-conservation, of kinetic energy in several increasingly complex, real-life situations, several of which they were asked to compare, which were as follows: two ball-bearings colliding; one initially stationary skater pushing themselves away from another, or pushing away from a brick wall; a ball being dropped into a container of sand and stopping; a car crashing into a brick wall, or two cars crashing head-on with one another; and a bullet being fired into wood and becoming embedded, or thick rubber from which it bounces. Scenarios two, four and five were based on questions originally posed by Epstein (2002). A deliberate decision was taken to make the questions as open as possible in an attempt to gain an insight into their existing ideas in the given scenarios without influencing their thinking.

3.5.2 Phase 2: Semi–structured, think aloud interviews & bridging analogy sequences.

Two separate sequences and interview protocols were devised, and refined as a result of the pilot study (see below). Both sequences and sets of interview questions were designed to examine an area that previous literature had highlighted as being problematic for students: the idea of momentum being conserved when an object hits a large 'immoveable' object; and explaining the difference between 'elastic' and 'inelastic' collisions, particularly in terms of the non-conservation of kinetic energy in the latter. Members of the University of Strathclyde's Physics Department were consulted to ensure that the explanation that was being worked towards in each sequence was an accurate reflection of the accepted physics.

3.5.3 The target situations

A 'target' situation is the name given to the 'real-world' scenario that students are intended to understand more accurately by interacting with the set of connected bridging analogies. In the case of momentum conservation in collisions involving an 'immoveable' object, the situation was outlined pictorially to the participants, but the target situation of the differences between elastic and inelastic collisions was examined experimentally by the students, using PASCO dynamics carts.

Collisions involving 'immoveable' objects

The target situation chosen for a collision with an apparently 'immoveable' object was a car crashing into a large brick wall or building. The two pictures that were shown to each student are shown in figure 3.1 below.

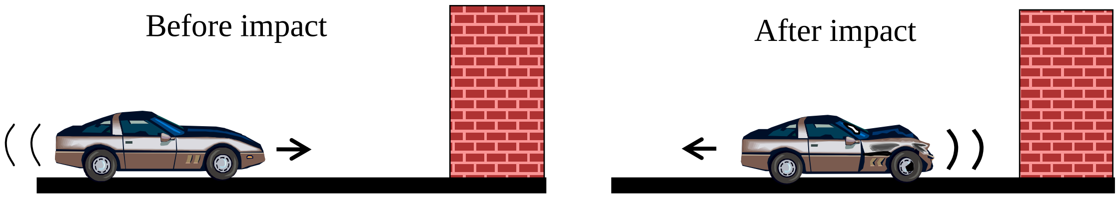


Figure 3.1: 'Target' situation of a car crashing into an 'immovable' brick wall and rebounding.

Initially the student was shown just the 'before impact' picture and asked to describe what they thought would happen when the vehicle struck the large brick wall, or building, at a reasonably high speed of around 50mph. When they had responded they were shown the 'after impact' picture and invited to comment on whether or not they felt that it gave an accurate depiction of what would happen. They were subsequently asked to state what they thought would happen to the momentum of the car as a result of the collision.

Olenick (1997) identified that there is a common misconception among students that momentum is lost in collisions with large objects. The accepted explanation for justifying that momentum is in fact conserved in such a collision is that the momentum is transferred to the 'immovable' object which has a very large mass and therefore moves very slowly and imperceptibly after the collision; it remains approximately at rest. This is however a very difficult concept for many students to grasp as they tend to have a very selective, 'localised' view concerning the objects that constitute a 'system', rather than taking a 'universal' perspective on the range of objects between which momentum is transferred and conserved; they tend to ignore large objects and fail to consider them as being part of a system of interacting entities (Bryce & MacMillan, 2009).

Elastic and inelastic collisions

In this instance, the target situation was comprised of a linked pair of initial hands-on experiments and the connected analogical sequence was designed to enable students to believe and justify the commonly misunderstood concept that momentum is conserved, while kinetic energy is not conserved in an inelastic collision. As discussed in the earlier literature review, it is widely reported that students struggle to differentiate between the concepts of momentum and kinetic energy (Driver et al., 1985; Lawson & McDermott, 1987; Driver et al., 1994; Olenick 1997; Bryce & MacMillan, 2009). This in turn accentuates their difficulties in deciding, and explaining, their respective conservations and non-conservations in elastic and inelastic collisions. Before the analogical sequence was introduced and tackled, students worked through, and were asked questions about, the two target experiments (figures 3.3 and 3.4 below) which showed both types of collisions using two PASCO dynamics carts. In particular, they were invited to describe what they thought was happening during each type of collision in terms of conservation (or non-conservation) of momentum and kinetic energy. They were then asked to try to give a reason and explanation for the generally accepted theoretical position of the non-conservation of kinetic energy in the case of an inelastic collision. The PASCO carts and track that were used in this study may not be readily available in some school Physics departments to allow teachers to repeat this process exactly. However if this was not available, it would also be possible to use a linear air-track with identical vehicles instead to enable similar, almost friction-free motion to be achieved. The vehicles would require to have magnets (which are orientated to cause repulsion) attached at one end of each vehicle to allow the elastic collisions to be carried out.

The momentum (amount of 'mass on the move') stays constant before and after each type of collision since the contact forces on both carts are equal in size but opposite in direction (in accordance with Newton's Third Law) and act on the carts for equal amounts of time. Consequently, the gain in momentum of the second vehicle is equal to the reduction in momentum of the other; momentum is transferred from the first vehicle to the second. However in the case of the inelastic collision, some kinetic energy gets transformed into heat and sound energy due to slight vibrations being initiated in the colliding objects as a result of their direct contact with one another. In order for a collision to be completely elastic (no loss of kinetic energy) there would have to be no physical contact between the objects, hence no such vibrations would occur. This is understood by physicists to be the case for ‘collisions’ involving sub-atomic particles.

The PASCO carts contain internal magnets at one end, which can be used to ensure that the carts do not actually come into contact with one another. The other end of each cart has a pair of Velcro pads attached to it, which can be used to make the carts stick together on contact if required. When the carts are therefore ‘collided’ magnet to magnet (figure 3.2), the collision is as near to being completely elastic as possible. With this experimental set up, the first cart stopped immediately and completely as a result of the collision. The velocity of the second cart after the collision was virtually identical to the initial velocity of the first, since there were very small frictional forces between the wheels of either cart and the track. The equality of the two carts’ velocities before and after the collision was readily observable and accepted by the students.

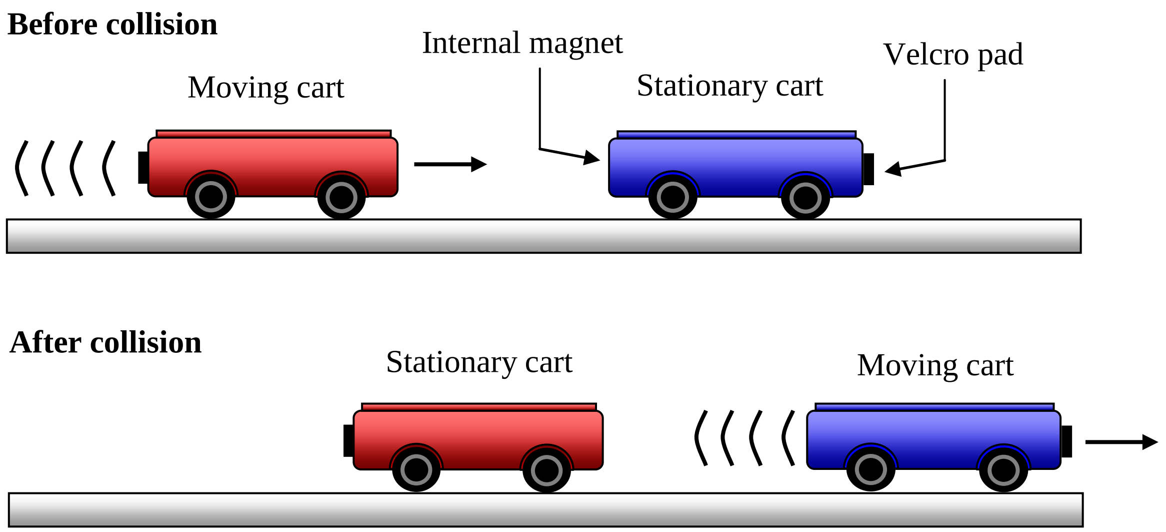


Figure 3.2: ‘Target’ situation of an elastic collision between two PASCO dynamics carts

An inelastic collision between the two PASCO carts (figure 3.3) was produced by turning one cart around so that its magnet no longer faced the other cart, but the side with a Velcro pads attached to it did. Consequently, the two carts came into physical contact and sound was produced during the collision. Only one vehicle was turned round so that both Velcro pads did not come into contact with one another and stick together. This was thought to be undesirable as students often express the idea that inelastic collisions are the result of objects colliding and sticking together. The experimental set up was deliberately configured to avoid reinforcing this idea. Both carts are intended to be identical, other than their colours, and so theoretically, only the second cart should have moved after the collision. In practice however, although they were very similar, the carts did not have completely identical masses and consequently both moved after the collision, the first having slowed down considerably. This anomaly did not appear to trouble the students and the discussion about the conservation of momentum was not impeded.

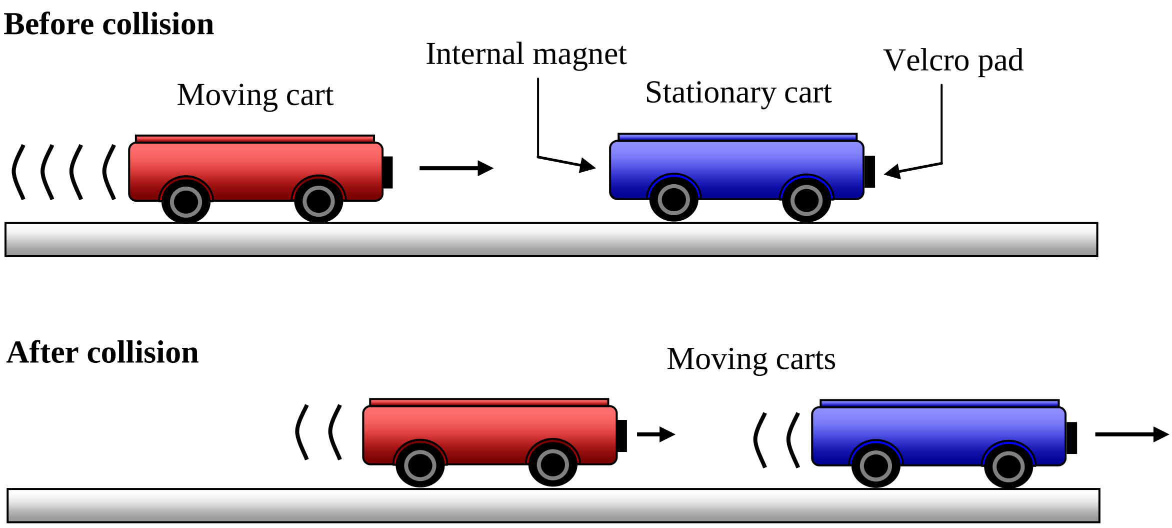


Figure 3.3: 'Target' situation of an inelastic collision between two PASCO dynamics carts

An analogical sequence was developed in an attempt to help students to work out for themselves the currently accepted theoretical explanation for the 'immoveable' object scenario, and another sequence was designed to address the difficulties involved in understanding the non-conservation of kinetic energy in inelastic collisions. Think-aloud interviews were used to allow an examination of the students' thinking processes during the reasoning exercise. The two sequences are shown in figures 3.4 and 3.5 below, while the sets of interview questions that formed the basis of both sets of interviews are now discussed.

3.5.4 Interview protocols

The interview questions that formed the basis of both sets of interviews were devised to ensure that the structure of each interview followed a similar basic pattern as well as making sure that the initial preamble to each interview was standardised. The interview schedules for each scenario are given in appendices 3 and 4. The questions were used as a starting point for each part of the discussion, although follow up questions were asked depending on what each student gave as responses.

Each interview started by asking the students to explain what they knew about momentum and kinetic energy and what their definition of each was. They were also asked to describe what they thought the difference between these quantities is. They were then asked to consider the target situation and were asked a number of questions that were designed to elicit their ideas about, understanding of, and reasoning for the way that the target situation operated, particularly in terms of any underlying physics principles that they knew. Once this had been explored and prior conceptions elicited, the analogical sequence was worked through. Each analogy involved the student in carrying out a 'hands-on' mini experiment using easily obtainable equipment. (For details of the apparatus used, see below where each analogical sequence is described in some detail). The questions that were used while working with each analogy were similar and therefore formed a cyclical pattern of interrogation each time. Students were asked to state whether or not they thought that conservation of momentum was occurring in each analogical situation. In the case of the elastic / inelastic sequence they were also asked whether or not they considered kinetic energy to have been conserved. They were subsequently invited to state how confident they felt about being correct about conservation, or non-conservation, on a scale of 1 – 6. A six point scale was used to avoid the students simply picking the central value which is a potential hazard with scales involving an odd number of values.

After carrying out the experiment and describing what they thought had happened, they were asked to explain what they thought had happened in terms of any underlying physics. The student was then asked to state how confident they were that their explanation was correct on the same 1 – 6 scale as before. This process allowed any changes in a student's theories to be examined, as well as the monitoring of any progression or regression in their level of belief in their theory. Students were also quizzed to ascertain what similarities or differences, if any, they perceived between the analogy that they were working on and the previous one, and between each analogy and the target situation. This encouraged students to think of things that each analogy had in common with its predecessors and to make links between the analogy and the target situation, while also helping them to realise that analogies are never exact matches with the situation that they seek to mirror in some way. Before moving on to the next analogy, they were asked to enunciate their current ideas about the physics involved in the target scenario.

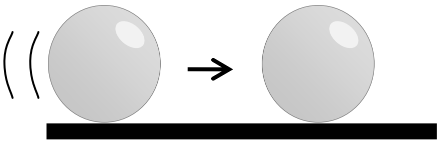
Once all of the analogies had been worked through, students were asked to rate which analogies they felt were the most useful in coming up with their final explanation for the target situation. They were also asked to state what they thought of the bridging analogy sequence as a way of learning and thinking. Students were not told whether or not they had come up with the accepted explanation for the target situation until they had completed the interview sequence. However those who had come up with the accepted answer, and who had not used up the allotted amount of time in doing so, were asked to explain a related, but more abstract, 'real-world' example to examine whether or not they could transfer their apparent understanding to a new situation.

3.5.5 The bridging analogies

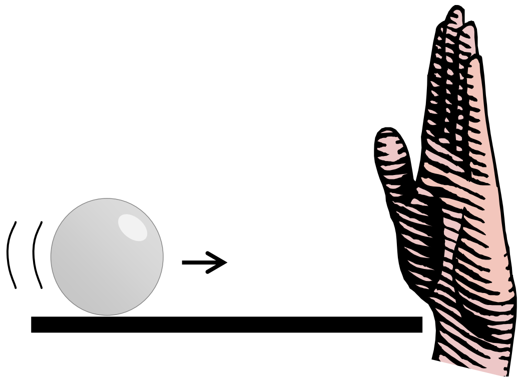
The equipment used in the mini-experiments of which each sequence comprised, included the following easily obtainable items: four identical ball bearings, a piece of stiff sponge, a piece of 'blu-tac', a small sponge ball, a tuning fork, a hammer, a small hard rubber ball and a water filled balloon. The only piece of apparatus that was specifically constructed for the 'immoveable' object experiments was a small L-shaped wooden jig which had a horizontal base section with a shorter upright section attached to it. The base had a small groove cut into it, along which the ball-bearings and the sponge ball could be guided. The wooden jig had been quickly and very cheaply constructed by a design and technology teacher in one of the participating schools with whom the researcher was friendly. All of the equipment was carefully chosen so that it would be possible for schools to follow the procedures outlined in this research study in order to teach students about conservation of momentum and the loss of kinetic energy in inelastic collisions, without having to incur great expense. Photographs of the equipment used in each of the analogical sequences are shown in appendix 9.

Sequence 1: The 'immoveable' object analogical sequence

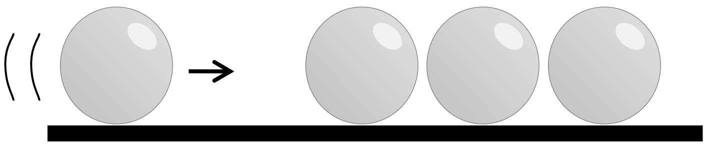
This analogical sequence (figure 3.4) was designed to encourage students to believe and justify that momentum is conserved when an object strikes an apparently 'immovable' object. The sequence was also intended to examine students' difficulties in identifying, justifying and correctly comprehending the vector nature of momentum.



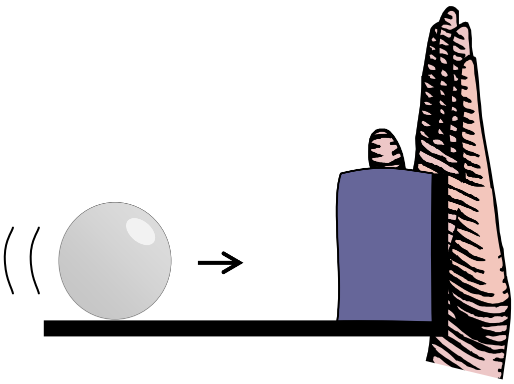
1. Ball running into identical ball.



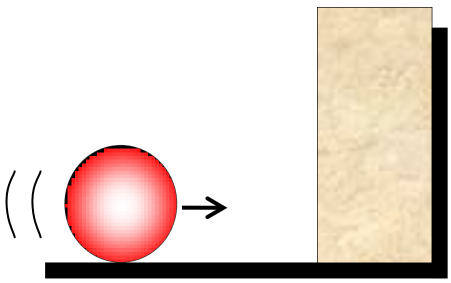
2. Ball running into hand and stopping.



3. Ball running into a set of identical balls.



4. Ball running into blu-tac and stopping.



5. Sponge ball running into sponge and rebounding.

Figure 3.4: Bridging analogy sequence for explaining conservation of momentum when an object runs into a large 'immoveable' object. (Note: All pictures show situation **before** impact).

In designing this sequence, a deliberate decision was taken to include no quantitative work. This was done for two reasons. Firstly, it ensured that the students were forced to think about reasons and justifications for asserting that momentum is transferred and conserved. Secondly, it encouraged the students to think about the concept of momentum at a deeper level, rather than simply 'hide' behind the potentially rote learned 'number-crunching' procedures that they may have been taught in order to get them to successfully answer the most common types of examination questions on the topic (Bryce & MacMillan, 2009; Papaevripidou et al., 2005; Goldring & Osborne, 1994). In each of the analogies a ball-bearing was used to ensure that any effects due to friction were minimised, while at the same time also ensuring that the equipment used in the interviewing process was both easily transportable from school to school and was not unwieldy or noisy, as would have been the case if a set up involving a linear air track had been used to reduce the effects of friction. Only linear momentum was considered and none of the students raised the issue of rotational momentum, which they had not been taught about. A small, simple wooden jig was constructed which had a groove in which the ball-bearings ran, but it also had an upright section at the end against which 'blu-tac' and a sponge could be rested for the last two analogies.

The first analogy was intended as an anchoring analogy. It was considered likely that students would have previously encountered a very similar situation, probably involving the use of dynamics trolleys or linear air track vehicles, when they were taught about momentum in class. They should therefore readily deduce that the momentum of the first ball would be completely transferred to the second as it has the same mass and moves off, observably at the same speed as the incoming ball which stopped on impact. This situation also had the advantage of keeping the reasoning to motion in only one direction which previous research has shown is a concept which is much more accessible to students.

The second analogy gave the students an opportunity to have a personal 'experiential' link as the momentum of the ball was transferred to their hand. If the ball chosen has sufficient mass, and therefore sufficient momentum at low speed, they are able to feel their hand being moved backwards very slightly, which should emphasise the transfer of momentum. Since their hand is free to move, but won't move very much, it was hoped that it would trigger the process of thinking about 'immovable' objects for some students. As with the first analogy, it continued to involve reasoning in only one direction.

The third analogy involved collision between the same ball-bearing with three identical ball-bearings, each of which was set up with a very small gap between them. This analogy was intended to help the students to deduce that the momentum from the ball bearing that they pushed was passed from one ball to the next without loss since the last ball is observed to move off with the same (approximate) speed as the initial ball struck the second. This simulates the transfer of the car's momentum through the bricks of the wall or building, without there being any loss of momentum or apparent motion of the individual bricks in the wall. This analogy was however limited by the fact that the last ball-bearing moves off when the momentum is transferred to it, unlike the bricks in the wall that are held in place by the mortar.

The ball bearing was then collided with 'blu-tac' while the student placed their hand at the back of the wooden jig in the fourth analogy. Touching the upright section of the wooden stand during the collision enabled the student to feel the slight motion that the stand exhibited. 'Blu-tac' was chosen as it had the ability to trap the ball when it collided with it, in order to keep the students thinking about motion in one direction. It also had the advantage of being relatively easily deformed by the ball. This was intended to introduce the possibility into the students' thinking that there may be some movement (even if only at a particle / molecular level) or deformation, however slight, in an apparently 'immovable' object when it is struck by a considerably smaller object.

A relatively dense piece of sponge was used in the final analogy in order to provide a bridge towards the hard surface which is being alluded to in the target scenario. The sponge was intended to enable students to see that there could be a movement and deformation in an object which is not obvious to the naked eye, but that is nevertheless present. Due to its compressibility and elasticity, the sponge will also cause the ball to rebound. This introduced motion in more than one direction and hence explicitly challenged students' understanding of the vector nature of momentum. Much of the previous research has strongly indicated that students find scenarios like this significantly more cognitively challenging, which is why the earlier analogies did not involve this situation. The use of a sponge ball introduced a link to the more realistic situation in which the incoming object deforms on impact. However it had the disadvantage that the deformation was only temporary, for the duration of the impact. In this analogy the student was deliberately not permitted to touch the wooden stand which enabled them to observe that the whole stand, including the running board beneath the ball, moved as a result of the impact. The significance of this observation in the mind of the student was explored to see if they could make the conceptual leap to realise that, ultimately, the momentum of the car is transferred to the Earth. As a last step the students were asked to remove the sponge which was resting against the upright section of the stand and simply run the sponge ball into the wood. This most closely simulated the hard surface which the wall or building presents to the incoming car in the target situation.

Sequence 2: Elastic and inelastic collisions

The analogical sequence that followed on from the target experiments, which were described above, is shown in figure 3.5 below. The sequence was designed to help students to explain why kinetic energy is lost in an inelastic collision but not in an elastic one. As with the other sequence, no quantitative information was involved so that the principles would be of paramount importance during the discussion with the student.

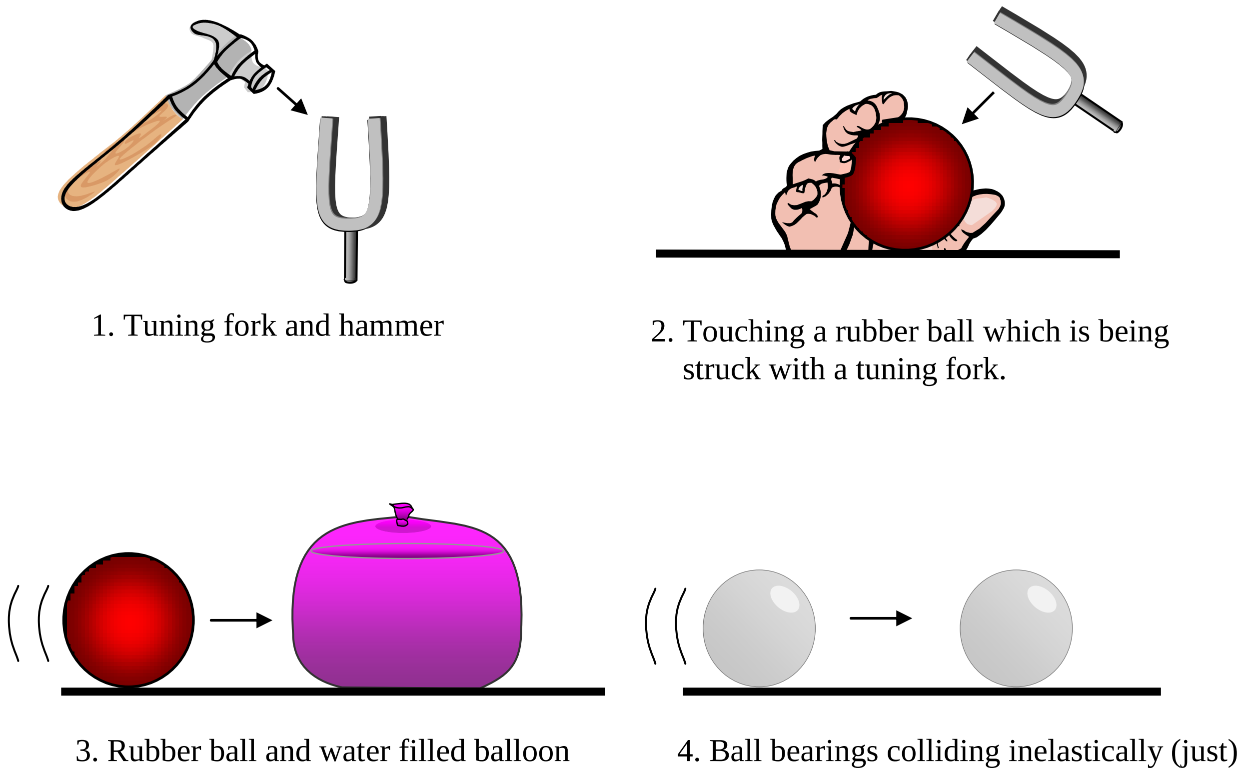


Figure 3.5: Bridging analogy sequence for explaining the non-conservation of momentum in an inelastic collision.

The first analogy was considered to be an anchoring analogy as it was thought that it would be reasonably apparent to the students that the tuning fork makes a sound when it is struck because it vibrates, which students were encouraged to experience by touching it lightly using their fingers. This scenario draws upon ideas that they had been taught in previous courses regarding the link between sound and vibrations.

In the second analogy, the same tuning fork was used to tap a rubber ball that was being lightly touched by the student. Students were able to feel that there were vibrations set up in the rubber ball. The tuning fork and the ball produced a small amount of sound as a result of their vibrations and the students were asked to lightly touch the tuning fork again to confirm that it was indeed vibrating as a result of its collision with the ball.

The third analogy used the same rubber ball that the student had just identified as vibrating when it was struck in the previous analogy. In this situation, the rubber ball was rolled into a water filled balloon that was seen to vibrate upon impact. A small sound was heard at this time. This analogy was designed to reinforce the idea that vibrations in each object caused sound (and heat energy) to be released, resulting in the loss of kinetic energy in the inelastic collision.

The final analogy made the jump to a situation which was much more akin to the target situation of the two trolleys. A steel ball-bearing was rolled into an identical one and the student was asked to explain what they thought was happening to the kinetic energy in this collision. By this stage they were thought likely to have picked up on the common feature of each of the previous analogies that sound energy (and some heat energy) was being dissipated as a result of vibrations in the objects, even if those vibrations could not be seen or felt in this case. Therefore they should be able to deduce that kinetic energy was being lost in this collision.

3.6 Pilot study

Both the questionnaire and the analogical sequences were piloted with six students who were studying the Scottish Higher syllabus in Physics in one of the schools that had agreed to take part in the full study. The students who took part in the pilot represented a range of ability from Grade A to Grade C. Both the pre-conceptions questionnaire and the bridging analogy sequences were trialled with these individuals. All six completed the questionnaire while three students were interviewed using each of the analogy sequences.

A number of changes were made to the check-up questionnaire and both analogical sequences as a result of the piloting process. The changes to the check-up questionnaire were as follows. Some of the questions were re-phrased or removed as they were felt to be slightly ambiguous by the students. Questions regarding different sized ball bearings were shortened and subsumed into the first scenario in order to reduce the overall length of the questionnaire. In the car scenarios, a question was added about likelihood of injury in each type of crash to ascertain whether or not students can see that the change in momentum is the same in either case.

The sequence about the car crashing into the 'immoveable' brick wall was re-designed considerably. The overall number of analogies was reduced to shorten the sequence by removing two examples, one of which caused confusion (judging by feedback from the students) while the other was thought to add little to the usefulness of the sequence. One new analogy was added to the middle of the sequence. This consisted of the ball-bearing running into a row of three identical ball-bearings. This was introduced between the analogy of the ball running into the hand so that it stopped and the situation where the ball ran into the 'blu-tac' and stopped as it was hoped that it would help to introduce the concept of momentum being passed from one part of an object to another.

The sequence used to promote thinking about inelastic collisions in the pilot study had involved striking a small desk bell (of the type used in hotel receptions) with a small hammer as the first analogy. However the students in the pilot group were unable to unequivocally feel the resulting vibrations in the bell. For this reason it was decided to replace the bell with a tuning fork. This had several advantages. As well as making the vibrations more tangible, it made the link between the first and second analogies more obvious to the students since one object in the first analogy that had already been established as vibrating was used in the second situation, therefore increasing the likelihood of successful bridging between the two situations. The sequence about the inelastic collision was also shortened by removing the last two analogies in which different sizes of rubber and then steel balls were collided inelastically. These two situations were replaced by a single scenario in which two identical steel ball-bearings were collided as this has a greater degree of similarity to the situation of the identical PASCO carts colliding inelastically.

3.7 Data analysis

The pupil 'check-up' questionnaires were analysed and common themes, difficulties, misconceptions and descriptions were identified and compared. All sixty interviews that were included in the sample were fully transcribed. Thereafter, open coding was undertaken to decide on categories of information which the interview data contained. Following this, axial coding categories were developed by examining several of the transcripts in order to ascertain conditions, contexts, actions or consequences for each of the open codes. This process was continued iteratively until all possible conditions or consequences were identified. Finally, selective coding was undertaken to show inter-relationships between the core category of conceptual change and the other categories that were examined. The coding categories were used to develop an interview analysis sheet for both sequences (which are shown in appendices 5 and 6). The analysis sheets include details of the student's final higher grade as well as the coding grid for the interview sequence that the student followed. In each case, the open codes are shown in the grey boxes on the grid and the axial codes are listed beneath each open code. The order of the sections in the grid follows the same order as the interview schedule in that it starts by analysing the student's preconceptions, then the manner in which they interacted with the bridging analogy sequence. An analysis of the students' views on the analogical sequence as a learning tool is then carried out before finally examining how they answered the questions about the extension scenario. Each of these four sections of the analysis grids is discussed in detail below.

3.7.1 Section 1: Student preconceptions

The first section of the grid allowed an analysis of the student's preconceptions about momentum and kinetic energy to be recorded as a series of either ticks, short comments, or occasionally, a short quote that was lifted from the transcript. Where a comment or quote is entered on the grid, the transcript was annotated in such a way that the relevant section of the interview could be easily identified at a later date.

3.7.2 Section 2: The analogical sequence

Section two constituted the majority of the analysis that was carried out. In this section of the grid, the interview was analysed as each of the sections of the analogical sequence was worked through. The axial coding categories were developed to enable a student's responses to be entered as a tick against the appropriate response for the target situation (T), each of the analogies in the sequence (1, 2, 3, 4, 5), and when they were asked to give a summary of their final answer for the target situation (TF) after completing the analogical sequence. The transcript had the appropriate phrase or section highlighted when an entry was made in the table and the highlighted section was annotated so that it could be linked with the corresponding tick in the table. In the case of the immoveable object sequence, the student's ideas regarding conservation of momentum (for both the analogy and the target) were tracked at each stage of the interview in three domains: (i) the level of system that they were considering as being applicable (i.e. single objects, the system of the car and wall, or at a more universal level by including the ground in their considerations) (ii) the significance of any change in direction, in terms of whether or not they felt that this meant that there had been a change in the object's momentum and (iii) their belief rating (on a scale of 1 – 6) to indicate how convinced they were about the conservation, or non conservation, of momentum in the analogy and the target situation at each stage of the process. They were told that a rating of 1 meant that they were very unsure that they were correct, up to a 6 which meant they were really certain that they were correct. A six point scale was chosen for this to ensure that they could not simply 'play safe' by choosing the mid-point in the range at each stage. Each student's ideas regarding the conservation of momentum and kinetic energy for each analogical scenario and the target were tracked in a similar manner for the inelastic collision sequence.

Categories of open code in the remainder of section 2 (from which the axial, sub-categories of student responses were developed) included student theories about the target situation at each stage of the interview, types of thought process (ThProc) that were evident at each stage, various aspects of reasoning associated with the use of the analogical sequence, evidence of conceptual change (ConCh) from the different theoretical perspectives and change triggers (ChTrig) that could be seen to cause conceptual change to have happened..

The student's theory regarding the target situation for each of the two sequences was tracked as they tackled each analogy to see if and how their understanding and thinking was changing as they engaged with the analogies. This was considered an important tool in deciding whether or not conceptual change was occurring. The sub-categories of theory were devised so that a tick could be entered in the row of the table that corresponded to what the student was stating at any given stage in the interview. The theoretical stances are listed in the analysis table in increasingly complex order from the least accurate to the one nearest the idea accepted by physicists as being the most accurate. Therefore a student who was gradually making progress in terms of their theoretical stance would have a set of entries that moved progressively down this section of the table. The only exception to this would be a student whose theory did not fit into any of the existing categories and so had an entry made in the 'other' row, in which case the student's theory was briefly summarised in the table. The students were asked to self-assess their belief rating in their theoretical stance at each stage on the same scale of 1 to 6. The belief rating was used as another means to assess whether or not conceptual change was occurring, in line with the theoretical position advocated by Posner et al. (1982) which was discussed previously in the literature review.

The next sub-set of entries in section 2 allowed the general type(s) of thinking that each student was displaying during each cycle of the interview to be categorised and compared. In each case the appropriate section of the transcript was highlighted and annotated with the appropriate code from the analysis table (ie ThProc a, b, c, d, e or f). The sub-category of 'confused' was included as it was found that some students became unclear in their thinking at some parts of the interview and it was felt that it was useful to find out if there were any common points at which this happened in either sequence.

The ability of a learner to perceive similarity between a situation and an analogy is seen as being key in the process of analogical reasoning (Vosniadou & Ortony, 1989). It was therefore important to analyse the similarities and differences that the participants perceived at each stage between both the target and the preceding analogy. Vosniadou and Ortony (1989) discuss two types of similarity that are defined by many writers; *surface* and *deep similarities*. They define a 'surface' similarity as one in which the similarity that is perceived is limited to simple, descriptive properties of the two situations. On the other hand, a 'deep' similarity extends to less obvious properties of a situation which are at a more theoretical level, in terms of similarities regarding the way that the two situations 'work' or 'are'. The relative success of each student in perceiving these two types of similarity were therefore tracked. Likewise the number of differences that each student felt were noteworthy between each analogy and its predecessor, or the target, was noted (and each example was highlighted on the transcript for categorisation purposes) to see if this had a bearing on the success or otherwise of the student in making progress in terms of their learning and thinking. The number of differences that each student mentioned as the analogical sequence progressed was followed in order to find out if they began to ignore these differences as being largely irrelevant, when they could see that they had little or no bearing on the use of the analogy in formulating their thinking.

The ability of the student to use the analogy to explain the target situation was assessed in the next sub-section of the analogical reasoning analysis. This was also based on the ideas of Posner et al. that conceptual change is evidenced by an increasing ability to explain a situation. It was therefore thought important to track this ability with each of the analogies in order to monitor any progress. Explanations were assessed on the basis of whether or not they were considered to be at a 'surface' or 'deep' level, using similar criteria to those for the similarities discussed above.

The conceptual change (ConCh) categories became the core categories for the study as they were at the heart of the aim of discovering how and why learning takes place, and the role played by analogies in this process. They were developed to enable evidence of conceptual change, as well as the triggers that promoted it, to be extracted from the interview data. Rather than simply examining if and how the analogies helped students to understand the concepts of momentum and kinetic energy better, they allowed an analysis of the way(s) in which learning and conceptual change were occurring at a psychological level to be carried out. They also enabled the development of the students' thinking to be tracked during the interview. When the analysis of a student's comments made it evident that there had been a change in their theoretical stance during a particular analogy, a tick entry was made in the analysis sheet against the type(s) of conceptual change for which evidence was found at each stage of the interview, and the corresponding section of the transcript was highlighted and annotated with the appropriate conceptual change code (eg. ConCh a, b, c, …). If the transcript data suggested that a particular type of conceptual change mechanism was *possibly* enabling progress to be made, but it was not demonstrated clearly enough to warrant a tick, a question mark was entered in the table in the appropriate cell to show that there was *potential* evidence for it. There were also examples of students becoming more confused, clearly failing to achieve conceptual change, or indeed made negative progress in this regard by going back on what they had previously stated. If the data strongly suggested a reason for this, the corresponding change category was marked with a cross to indicate the nature of the problem that the student was experiencing. The set of ticks and crosses therefore enabled identifiable types of, and reasons for, success and difficulty in achieving conceptual change to be monitored. One example of a fully analysed and annotated transcript for both bridging analogy sequences has been included in appendix 10.

The role of constructing and modifying increasingly complex and realistic mental models is a key feature of most of the existing conceptual change theories which were discussed in the previous chapter. The conceptual change coding categories in the table (ConCh a, b, c, …) were associated with each of these theories. This enabled evidence for each of the theories to be looked for in the transcripts. For example, one of the areas which underwent close scrutiny was in regard to whether the dominant process of conceptual change was *adding* new ideas or features to an existing mental model, or *altering* the way in which the mental model is constructed and works in the light of new ideas or information. The analysis of this 'conceptual change' data enabled links to be made both with, and between, different theoretical stances. Table 3.2 below, shows how the different sub-categories of conceptual change, for which evidence was sought in the transcript data, were linked to the current theories of conceptual change. Conceptual change criteria were developed to assist in deciding whether or not one, or more, of these particular types of conceptual change had occurred. The criteria that were applied are shown in appendix 7. Each of these criteria was based on the theoretical position that is advocated by the proponents of each stance.

Type of Conceptual Change Evidenced (ConCh)	**Conceptual Change Theory Links**
a) Replacing central concepts to deal with new phenomena	Accommodation (Posner et al.)
b) New material simply supports or exemplifies existing ideas	Assimilation: Derivative (Ausubel)
c) Extension, modification or qualification of existing ideas	Assimilation: Correlative (Ausubel)
d) Ideas become subsumed under the new proposition	Assimilation: Superordinate (Ausubel)
e) Change in acquired idea & associated cognitive structure	Meaningful Learning (Ausubel)
f) Reorganising only within current context	Conceptual Ecology (di Sessa)
g) Complex system building – from bits of knowledge	
h) Target enriched with new concrete features	Explanatory Model Construct. (B&C)
i) New events simply added to existing model	Modelling (Tiberghien)
j) Model only modified (specific objects & events level only)	
k) Model and underlying theory modified	
l) Social rules only (doing what the teacher has told them to do)	
m) Use of only existing concepts to deal with new phenomena	
n) Existing theory enriched	Theory Restructuring (Vosniadou)
o) Revision of specific theory (objects & properties level only)	
p) Revision of framework theory ('how things are')	
q) Category change from matter to process	Category Re-assignment (Chi et al.)

<table>
<tr><td>r) Connections made between new thinking and:</td><td rowspan="6">Accommodation (Posner et al.)
Assimilation (Ausubel)
Conceptual Ecology (Di Sessa)
Explanatory Model Construct. (B&C)
Modelling (Tiberghien)
Theory Restructuring (Vosniadou)</td></tr>
<tr><td>(i) Analogy</td></tr>
<tr><td>(ii) Existing mental model</td></tr>
<tr><td>(iii) Prior experience</td></tr>
<tr><td>(iv) Prior learning and knowledge (Physics)</td></tr>
<tr><td>(v) Prior learning and knowledge (other subject)</td></tr>
</table>

Table 3.2: Links between types of conceptual change that were sought and conceptual change theories

While conducting the interviews and examining the transcripts, it was noted that many students seemed to begin to make progress in their thinking and learning when they made a connection between what they were currently thinking and previous thoughts, teaching and ideas. The types of connections made by students therefore became of particular interest. This data was gathered in an attempt to discover whether or not this connecting process is a strong determining factor in successful learning. The making of such connections was also thought to be indicative of conceptual change having occurred. Several types of connections that had been identified in the transcripts were therefore included in the 'type of conceptual change evidenced' section of the categories (ConCh - row 'r', statements i - v). The ways in which this connecting process compares with (and possibly complements) previous conceptual change theories is examined in the discussion chapter at the end of the thesis.

A further sub-division of the 'conceptual change' category was deemed necessary. The change triggers (ChTrig) sub-category set was devised to enable the types of statements made by students that indicated what had caused them to change their thinking to be scrutinised. Whenever a student was deemed to have experienced conceptual change, the transcript was interrogated to ascertain what appeared to have triggered the change. As before, a tick was entered in the analysis table where evidence was found at each stage of the process. The transcript was highlighted and annotated with the appropriate code shorthand (eg ChTrig a, b, c, …) on each occasion, to allow detailed data to be quickly identified and interrogated.

3.7.3 Section 3: Review of the analogical sequence

The third section of the analysis grid enabled the thoughts of the students in relation to the effectiveness of the bridging analysis as a learning tool to be examined. In particular, the opinions of the students regarding the most effective analogies was sought in order to discover what particular features of analogies were both helpful and appealing to a range of learners. This section of the analysis grid was completed by initially entering the sequence number of the analogy (or analogies) that the student highlighted as being most effective or helpful to them in coming up with their final theory. Thereafter short comments or quotes were entered in the remaining boxes for reasons given. The thoughts of the student on how useful (or otherwise) they felt the sequence, taken as a whole, was in helping them to think and learn effectively was then recorded. Similarly comments or quotes were entered to record how the student perceived the use of the bridging analogy sequence in promoting learning.

3.7.4 Section 4: Extension situation

The final section of the analysis grid was linked to the last set of questions in the interview schedule that were designed to ascertain whether or not the student could use their new or changed thinking to explain a linked but more abstract question. Completing the grid involved noting whether or not the student successfully explained the extension situation and any other relevant details regarding how they tackled this. Several students did not get on to this final section of the interview as they ran out of time due to the inevitable constraints resulting from the interviews being conducted either during a lunch break or after school to avoid them missing classes in order to take part in an interview.

3.8 Reliability of coding

In order to ensure that the coding of the interviews had been carried out reliably, a sample of five transcripts, from each of the two analogical sequences, were analysed by another physics teacher. From the 'immoveable' object set of interviews those with students S1, 2, 4, 6 and 7 were cross-marked, while the interviews with S9, 10, 11, 12 and 14 from the inelastic sequence were checked. Both of the interview analysis tables were explained to the cross-checker and he was shown how the analysis had been carried out using one transcript from each of the analogical sequences. He was then asked to independently cross-check the sample of scripts in order to ascertain how closely his analyses matched those of the researcher. Among the 10 interviews that were cross-checked, a total of 134 conceptual changes, 93 change triggers and 195 thought processes were identified. Of these 422 items, all but three were agreed by the cross-marker, giving a 99.3% positive agreement tally on items that were identified by the researcher. The three examples where there was a variation of opinion were in interview 1. The cross-marker felt that one of the examples marked as confused thinking (ThProc a)) on page 4, could have been a case of the student simply trying to distinguish between momentum and kinetic energy; and it was felt that the researcher was inferring too much in a statement on page 17 from the use of the word 'guessing" when the statement was coded as ThProc h) [guessing] as it could be interpreted as a figure of speech. Likewise, the cross-marker felt that there was little evidence of a statement on page 25 being an example of ThProc c) [intelligibility]. These issues can be seen in the copy of the fully marked up transcript from the interview with student 1 in appendix 10, in which the researcher's annotations and coding can be identified along the cross-marker's annotations (which appear as purple ticks and comments beside the researcher's codes. A copy of one fully marked up transcript from the inelastic sequence is also included in appendix 10. Each of these discrepancies was discussed and a final decision agreed upon.

There were a total of five occasions where the cross-checker identified a piece of data that was missed by the researcher. On page 5 of interview 1, a conceptual change (c) [extension, modification or qualification of existing ideas] was thought to have been missed by the researcher, while on page 25 it was felt that the researcher had missed an example of ConCh (k) [model and underlying theory modified] and one example of a spontaneous generation of an idea (ChTrig (e)). In interview 4 the cross-checker felt that one example of ConCh (r) iv) [connections with prior learning and knowledge (Physics)] had been missed. While in interview 6, one example of ThProc (a) [confusion] was also felt to have been missed by the researcher. As with the discrepancies discussed above, the researcher and cross-marker then agreed on the inclusion, or non-inclusion, of each example.

Chapter 4

Findings 1: The 'check-up' questionnaires

The 'check-up' questionnaires (see appendix 2) were designed to ascertain how a sample of students (n = 121) defined momentum and kinetic energy as well as what they thought the difference between them was. The questionnaire also presented the students with five scenarios and they were asked to describe what they thought happened to the momentum and kinetic energy in each situation. The scenarios were devised to find out how students reasoned out different aspects of momentum, including ideas about whether or not conservation of momentum was considered to occur in each given situation, how changes in direction influenced student's thinking about momentum, and whether or not they could reason how transfer of momentum was influenced by the actions of one or more objects in a collision or explosion. The students' ability to explain what happened to the initial kinetic energy in each situation was also assessed. In contrast with the think-aloud interviews (the findings from which are reported in chapters 5, 6 and 7), the questionnaires were utilised to gain a more quantitative overview of students' existing understandings about momentum and kinetic energy. Sixty of the students who initially completed a questionnaire went on to participate in think-aloud interviews with one of the two analogical sequences. The interview enabled their thinking to be explored in more depth as statements that they made during the interviews could be followed up and explored in detail, which was not possible for the questionnaires.

The questions that were asked for each of the five scenarios were deliberately very open, as it was hoped that this would enable the students to state what they thought happened in each case without being guided down any particular route. It was also decided not to ask questions with simple 'yes' or 'no' responses as it was thought likely that some students might simply answer that part of a question without giving their reasoning. It will be seen from the findings described below that this strategy was relatively successful although some students stated that they found the questions hard. This is not surprising as they are not required to answer questions of this nature on a regular basis, even in examinations.

A total of one hundred and twenty one students filled in at least some parts of a questionnaire. These were answered by the students in class time under the supervision of their own class teachers as this allowed the participating schools the flexibility of being able to use the questionnaires at a time that was suitable for them as a diagnostic tool, without being restricted to times when the researcher could be present. Many of the questionnaires were however only partially filled in for one of three potential reasons. The first reason was that several of the students had evidently not had sufficient time to complete the questionnaire fully. One class group of students in particular were known to have been given a very short amount of time to complete the questions by their class teacher who was not willing to give them another opportunity. Secondly, it was apparent that many of the students were unsure of the answer to some of the questions, as they left them blank. As discussed in the methodology chapter, the questionnaires had been piloted with a group of six students with a range of abilities in order to ensure that both the recommended time-frame for completion was realistic and that the level and wording of the questions was appropriate. None of the students in the pilot group had struggled to understand the questions as they did not seek clarification from the researcher while answering them. They had been timed to see how long they took to answer all of the questions and the suggested completion time that the participating schools were advised of reflected the greatest time required by a member of the pilot group. Despite these undertakings, it was clear that a number of the participating students either had insufficient time to complete all of the questions, or they were unsure what to write. It was thought unlikely that students could not understand the questions themselves, as none of the pilot group had asked for clarification regarding the wording of any questions. Instead, it was thought to be more likely that they left certain parts blank because they were unsure what their answer should be as a consequence of uncertainty about the underlying Physics. The third possible reason for the non-completion of the set of questions was that some students worked through the questions much more slowly than had been anticipated. This could have occurred because they were not sufficiently motivated to answer them all, despite each of the students having volunteered to complete the task. However, the lowest number of respondents was in the final section of the questionnaire where sixty six students gave answers, but the number of students who answered each part of the questionnaire is given on a section-by-section basis below.

4.1 Momentum, kinetic energy and differences between them

The first three questions asked the students to define both momentum and kinetic energy and then to state what they perceived to be the difference between them. All of the students answered these three questions. The students' responses to these questions bore a great deal of similarity to the findings from the initial phase of both sets of interview sequences. Each of these issues are discussed in more detail in the analysis of the think-aloud interviews as they were also found to be prevalent there. The thinking of each student could be explored in more detail in context of the interviews, which was the reason for using them as the primary research tool in this study.

4.1.1 Momentum

In terms of the basic properties of momentum, it was evident from the questionnaire responses that they were not clearly remembered by the majority of the students. Only forty eight students directly stated that momentum was the product of an object's mass and its velocity, while another nine students wrote that the momentum was connected to the mass and the velocity of a moving object without explicitly stating the formula. Just twelve students either directly stated, or implied, that momentum is a vector quantity, while only five students stated that momentum is conserved.

Five students had a rather vague definition of momentum as the amount of motion or movement that an object had, while one student described it as "mass on the move". Twelve of the students had a very velocity-centred view of momentum as they only mentioned the speed or the velocity of an object in their definition. It will be seen in the analysis of several of the think-aloud interviews in chapters 6 and 7, and the analysis of one of the questionnaire situations in section 4.2.2 below, that this velocity-centric perception was confirmed as a common problem which hindered around a third of students' understanding of the concept of momentum and impeded their ability to comprehend the concept of conservation of momentum, particularly in a situation where one of the objects in a collision appears to be 'immoveable'.

Although it is true that the momentum and kinetic energy of an object and the force that acts upon it are all interconnected, the way in which they were perceived to interconnect in the minds of many students was often inaccurate. Five students thought that momentum was the energy that a moving object had. A total of twenty three students gave answers that implied that momentum was the same as a force; or was the force that an object carried with it as it moved; or was the force that it applied to other objects when it collided with them. Two students gave definitions which were essentially describing inertia as they stated that momentum was "something that carries you forward when you try to stop" and that it was the "ability to continue / carry on moving".

4.1.2 Kinetic energy

Only twenty five of the students explicitly gave the equation ½mv^2 for kinetic energy as part of their definition, while one student stated that the equation was mv^2. None of the students stated that kinetic energy was a scalar quantity as part of their comments in this section of the questionnaire, although several did state this as being a feature of kinetic energy in the next question, in which they were asked to state what they thought the difference was between kinetic energy and momentum.

Most of the students defined kinetic energy as being the energy associated with a moving object. Twenty five of the students had a slightly different view as they stated, using various phrases, that it was the energy that 'made' something move, rather than being the energy associated with an object that was moving. It could be argued from this that they were interpreting its role as being the same as a force as it implies that they felt that it was responsible for *producing* the motion, rather than being a way of quantifying its magnitude. A similar, but potentially more ambiguous definition, given by eight of the students, could be interpreted in two ways. They said that kinetic energy was the energy that was 'used to move objects'. It could be inferred that these students thought, similarly to the other twenty five students, that kinetic energy allowed motion to occur, or it could suggest that they were thinking kinetic energy was 'used up' when an object moved. Two students explicitly linked the kinetic energy with an object's momentum when they stated that that it was the "energy due to momentum" and the "energy that an object has for its momentum".

4.1.3 Difference between momentum and kinetic energy

Eighty students gave an answer to this question. Three of these said that they did not know, while forty other students were assumed to also have been unable to think of a suitable answer. Several of the students who did give a response were able to state genuine differences between the two quantities. Many students simply stated that their equations were different, while fourteen mentioned that momentum was a vector quantity, while kinetic energy was a scalar and a few answers simply mentioned that momentum is not a type of energy. Thirteen students were able to recall that momentum was conserved in collisions while kinetic energy is not always conserved depending on whether or not the collision was elastic or inelastic (with some students qualifying this by stating that the total amount of energy was conserved). Three students wrongly linked the law of conservation with kinetic energy rather than momentum.

Other answers showed that students had misconceptions regarding either, or both, concepts, many of which were related to the students' problems in defining the two quantities, as discussed above. In a commonly given answer, students related the momentum directly with force while stating that the kinetic energy was related to the speed, movement, or in some cases the amount of energy that the object had. One student related both concepts with force when she said "momentum is the force an object has, kinetic energy is given to an object to give it force and makes it move." Another student related the kinetic energy to the movement but linked the momentum to the inertia of the object when he stated that "energy is what makes it move, momentum keeps it going."

The dominance of the speed of an object in relation to students' understanding of momentum was evident in statements from several of the students, including the following:

> *"Kinetic energy determines how far an object can move, momentum is the energy that determines how fast something moves."*
>
> *"Momentum is speed and kinetic energy is energy."*
>
> *"The momentum is about the velocity but kinetic energy is about how the object moves."*
>
> *"Momentum is the speed of the object due to the kinetic energy acting on the object."*

The dominance of velocity in the thinking of another student was apparent when he stated that "kinetic energy is higher than momentum". This suggests that he had interpreted the fact that kinetic energy includes the square of the velocity, while the momentum does not, as evidence that the kinetic energy would always have a greater numerical value than the momentum for the same object.

Many comments showed that the students struggled to enunciate a difference between the two concepts and gave answers that did not really separate the two ideas, which led many of them to give incorrect answers. Three students stated that they thought that the momentum and the kinetic energy of an object were "proportional", although one of them added the caveat that this was true "until acted upon by another force". Other noteworthy examples of misconceptions, which demonstrate that students often pick up partly correct ideas, but mix them with other incorrect interpretations, are given in the quotes from several different students below.

> *"Momentum can be transferred, kinetic energy cannot."*
>
> *"Kinetic energy is the energy used in the momentum."*
>
> *"Momentum has control over kinetic energy."*
>
> *"Kinetic energy is when an object is moving, momentum is movement of an object when it's stopped using energy."*
>
> *"Momentum is the build up of energy. Kinetic energy is the movement energy creates."*
>
> *"Kinetic energy is the movement energy but the momentum is to do with the mass as well."*
>
> *"Kinetic energy is what gives [an object] velocity whereas momentum is mass multiplied by velocity."*
>
> *"Kinetic energy is movement energy. Momentum is to do with actual movement."*

"Momentum only occurs when there is a collision whereas an object can have kinetic energy by simply applying a force."

"Kinetic energy is asking what energy is required to move an object, momentum [is to do with] how it moves."

Many of the answers given by the students demonstrate that the difference between the two concepts is badly understood by the majority of students. Further evidence of this is provided and discussed in the findings from the in-depth interviews which are analysed in chapters 6 and 7.

4.2 Momentum and kinetic energy in five situations

After answering the three general questions, the students were asked to comment on five different situations in terms of momentum and kinetic energy. In each case the students were presented with a situation, or pair of situations, in pictorial form and asked to describe what they thought would happen in each in terms of momentum and kinetic energy. Unlike the analogical sequences in which the students actually carried out the experiments, these were thought experiments. The pairs of similar situations were presented in order to discover whether or not students perceived differences or similarities between them and to discover what these divulged about their understanding of momentum or kinetic energy. The answers given by students to each of these will now be outlined.

4.2.1 Situation 1

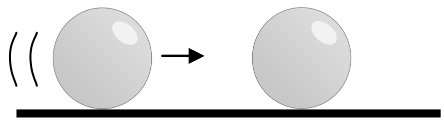


Figure 4.1: Steel ball colliding with identical stationary ball.

In this simplest scenario, students were asked to state what they thought would happen in this collision in terms of both momentum and kinetic energy. They were subsequently asked to state what difference, if any, they thought it would make if the first ball was replaced with one that was bigger or smaller than the other.

A total of ninety four students completed this section. Twenty students were not presented with this question as it was omitted by the school as a result of a photocopying error while another seven did not answer it.

Figure 4.2 shows a summary of the number of students' responses about what they thought happened to the momentum of the first ball-bearing as a result of the collision.

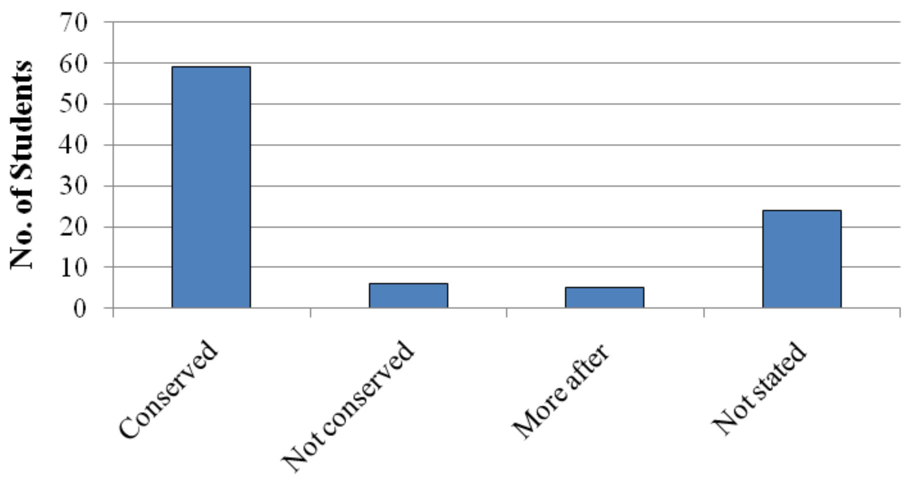


Figure 4.2: Number of students who stated various ideas about momentum for situation 1.

The majority of the students thought that the first ball would merely slow down as a consequence of the collision, while others thought that the first ball would come to rest. Fifty nine students explicitly stated that they thought momentum would be conserved in the collision. One student stated that the collision would result in a loss of energy when answering the question about momentum. Eleven students thought that momentum would not be conserved in the collision, although only one justified his answer by stating that this would be as a consequence of friction acting on the moving balls. Three of these students thought that there would be more momentum afterwards, while two others reasoned that this was because both balls moved after the collision and so there would be a greater total mass moving. Twenty four students did not indicate what they thought would happen in terms of the total momentum in the collision as they had all assumed that the first ball would continue to move and merely stated that the first ball would have more momentum before the collision than the second ball would have afterwards, since the second ball would not move away at the same speed that the first ball had struck it.

The students were also asked what they thought would happen to the kinetic energy of the first ball as a result of the collision. Figure 4.3 shows a summary of the responses.

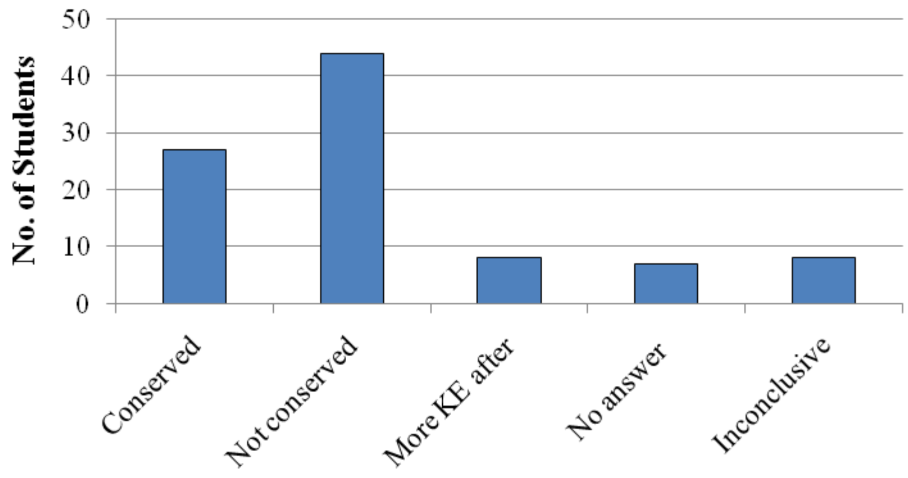


Figure 4.3: Number of students who stated various ideas about kinetic energy for situation 1.

Seven students gave no answer to the question about the total kinetic energy before and after the collision. Forty four students stated that the kinetic energy would be lost as a consequence of the collision with around half of these students stating that this would be as a result of the release of heat and/or sound energy in the collision. One student stated that the reduction would be a consequence of friction. A total of twenty seven students assumed that the kinetic energy would be conserved. Several of these students stated that this was because they thought that the collision was elastic. A few of the students however showed that they were incorrectly linking conservation of momentum and energy as they argued that the kinetic energy would be conserved *because* the momentum was conserved. Eight students argued that the total kinetic energy would have increased as a consequence of the collision. Three of these students justified this by stating that there was a greater total mass moving after the collision than before, while others argued in terms of other forms of energy being changed into kinetic energy. Eight students gave inconclusive answers because they simply described the two balls individually rather than discussing them as a system of objects.

When asked to explain what difference it would make if either ball was replaced with a larger one, very few students mentioned that a smaller incoming ball would rebound from a larger target ball, although most students realised that a larger incoming ball would slow down less if it hit a smaller target ball. None of the students enunciated what would happen in either of these situations in relation to momentum or kinetic energy.

4.2.2 Situation 2

In this situation the students were presented with a pair of similar situations which they were asked to consider and compare. In one situation a ball was shown being dropped into sand and in the second situation the same ball was shown being dropped on to a hard surface.

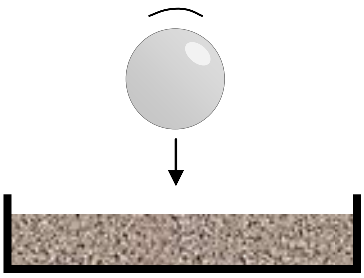


Figure 4.4a: Ball landing in sand

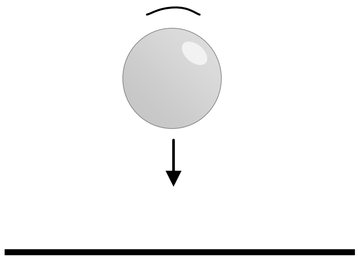


Figure 4.4b: Ball hitting hard surface

The ball that lands in the sand would stop, while the ball that hit the hard surface would bounce. As a consequence of its change in direction, the change in momentum of the ball hitting the hard surface would be greater than the one hitting the sand and stopping. These situations were presented to the students to ascertain whether or not they could interpret this difference correctly. A total of one hundred and seven students gave answers for this situation, although not all of the students answered all of the questions.

The answers given by the students when they were asked to describe what they thought happened in each situation in terms of momentum are summarised in the graph in figure 4.5 below. Figure 4.5a shows the number of responses from students in relation to the ball landing in the sand, while figure 4.5b shows the number of students giving each response when describing what would happen in terms of momentum of the ball when it struck the hard surface.

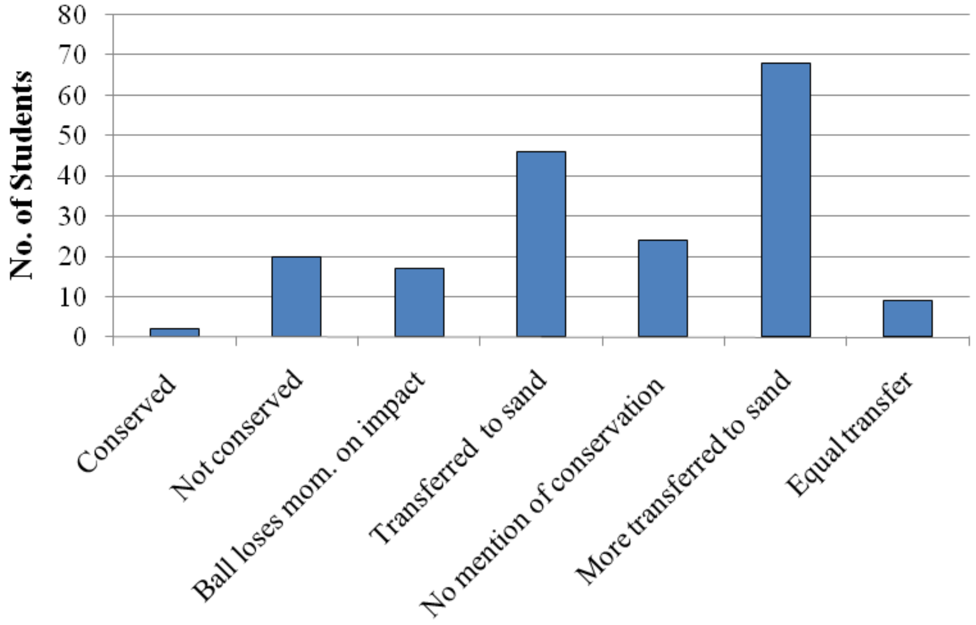


Figure 4.5a: Number of students who stated various ideas about momentum for situation 2a.

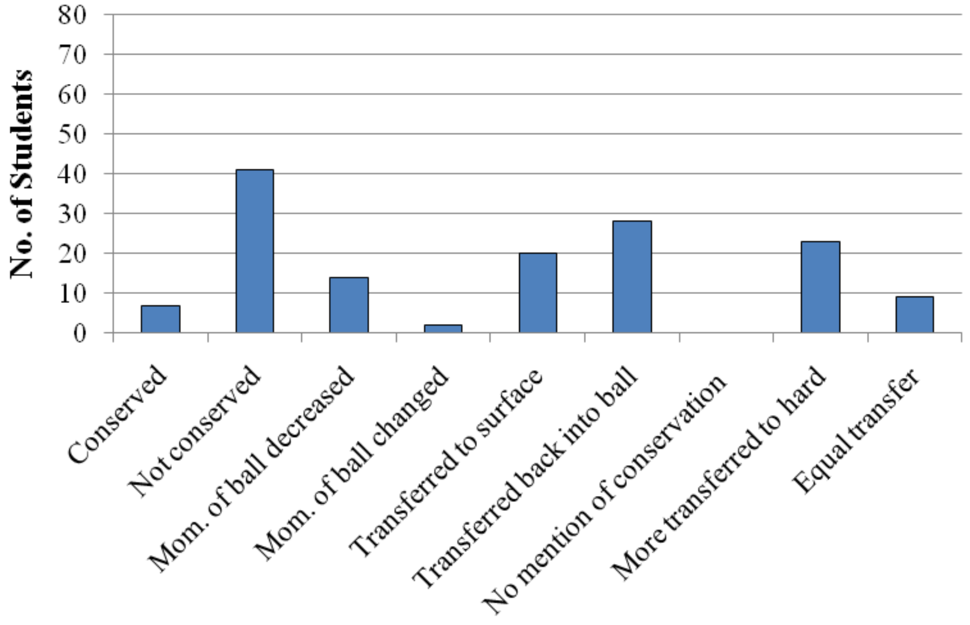


Figure 4.5b: Number of students who stated various ideas about momentum for situation 2b.

Only two of the students explicitly stated that momentum would be conserved when the ball hit the sand, while seven explicitly said that it would be conserved when the ball struck the hard surface, and only another four said that it would be conserved in both situations.

The students gave a range of answers about what they considered would happen to the momentum of the ball that landed in the sand. Forty six students stated that the ball would transfer its momentum to the sand on impact, while seventeen students stated that the momentum would be lost on impact. Eighteen of the students simply stated that the ball would lose all of its momentum without stating what would happen to it thereafter. Two students argued that momentum would increase on impact with the sand, one of whom justified their thinking by saying that this would occur because there was a sudden change in velocity.

There was a greater variety of answers concerning the momentum in the scenario where the ball struck the hard surface. Twenty of the students described the momentum being transferred to the surface through a series of bounces but they did not state whether or not they ultimately considered that momentum would be conserved. A total of twenty eight students said that the momentum would be transferred back into the ball again. Several students gave both of these answers. Thirteen students stated that the momentum of the ball would decrease as a result of a series of bounces while one went further and directly stated that the momentum of the ball would decrease until all of it was transferred to the hard surface. Thirty four students were of the opinion that momentum was lost in this scenario as they stated or implied that momentum would eventually be lost over the course of successive bounces. Two of these students justified this by saying that sound and heat would have been produced and another justified this by quoting $Ft = \Delta mv$. A further two students said that the momentum would be lost suddenly. Two students merely indicated that the momentum of the ball would have changed as it had experienced a force. Seven students actually thought that the momentum would increase because the ball bounced back up.

Sixty eight students thought that the ball that struck the sand transferred more momentum than the one that struck the hard surface, but only twenty three thought that the greater transfer was to the hard surface. A further nine students thought that the amount of momentum transferred in both situations was the same because both balls had the same initial momentum. Of the twenty three who stated that there was a greater transfer of momentum to the hard surface, none of them justified this in terms of the change in direction; some justified their answer by suggesting that it was demonstrated by the fact that the the ball bounced and some suggested that there was a larger force on the ball that rebounded but they did not justify their thinking. The most common reason given for the greater transfer to the sand was that the ball had stopped while in the other situation, it had momentum 'given back' to it. All of these perceptions clearly demonstrate that many students ignore the fact that momentum is a vector quantity in practical situations. They therefore miss the idea that a change in direction involves a change of sign in the value of the momentum, which in turn results in a larger change of momentum when the direction reverses.

Many students discussed the idea that kinetic energy was transferred to both surfaces while only some mentioned that kinetic energy would be transformed into other types of energy as a consequence of both collisions. It was apparent that several students misinterpreted the idea of an elastic collision as being one in which one of the objects rebounded. This often led these students to state that the kinetic energy was conserved in the situations where the ball hit the hard surface. This misunderstanding of the concept of an elastic collision meant that they did not consider the likelihood that some of the kinetic energy would be transformed into sound and / or heat energy.

4.2.3 Situation 3

In this situation there were two similar scenarios for the students to compare. In the first, two roller skaters pushed one another apart, while in the second scenario one of the roller skaters pushed against a wall.

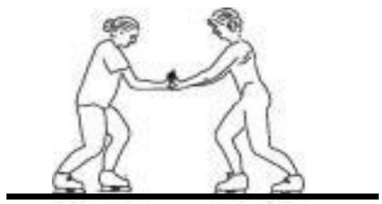


Figure 4.6a: Two skaters pushing apart.

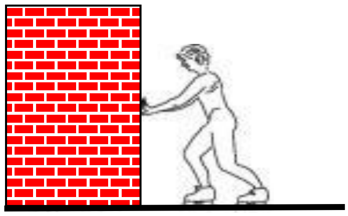


Figure 4.6b: Skater pushing against wall.

This pair of scenarios was designed to assess students' understanding of a simple 'explosion', in which objects that are initially at rest move apart in opposite directions. Many students were thought likely to wrongly assume that the two skaters who pushed against each other would move away from one another at a greater velocity than the single skater who pushed equally hard against the large wall. A total of seventy eight students tackled the questions in this section. The reduction in numbers was again partly caused by the error in photocopying in some papers in one of the participating schools. Figure 4.7 shows a graphical summary of the answers given about momentum regarding situation 3a where the two skaters pushed against each other (figure 4.7a) and situation 3b where the single skater pushed against the wall (figure 4.7b).

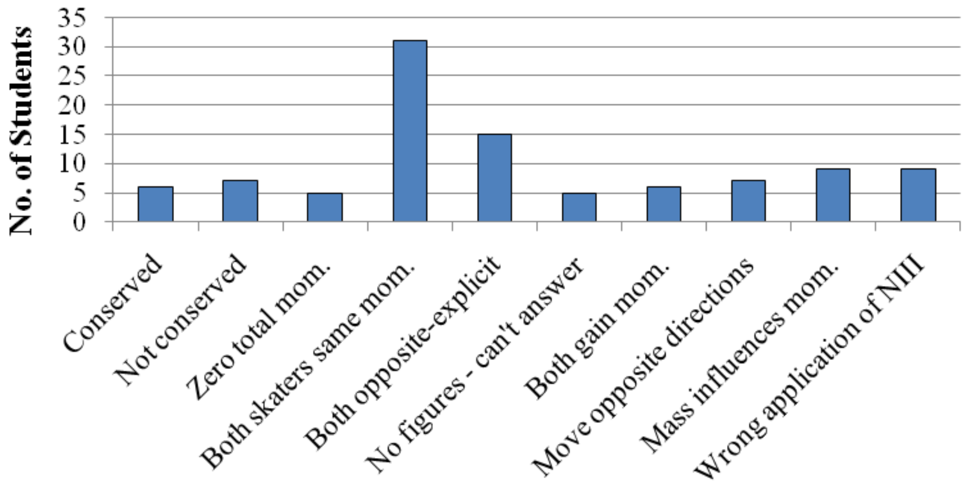


Figure 4.7a: Number of students who stated various ideas about momentum for situation 3a.

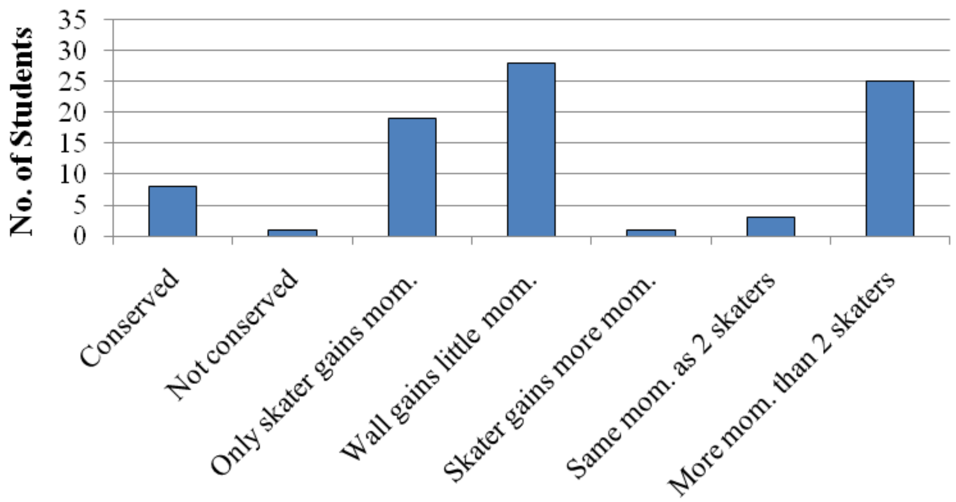


Figure 4.7b: Number of students who stated various ideas about momentum for situation 3b.

The lack of mass or velocity values caused five students to state that they could not make any predictions about the momentum. This suggests that these five students were not comfortable, or able to work, with general principles in order to reason out an answer to the questions. They were only willing to answer questions in situations where they were able to carry out calculations, which they were familiar with doing in a classroom setting. It was clear from the students' responses to both of these scenarios that many of them either disbelieved that the law of conservation of momentum applied in these circumstances or that they did not understand it.

In the answers for the situation where the two skaters pushed against one another, only thirty one of the seventy eight students stated that both skaters would end up with the same amount of momentum as each other, while only thirteen of these students explicitly stated that the momentum of each student would be in opposite directions. From this group, only six students explicitly stated that momentum was conserved in this scenario and only five students correctly specified that the two momentums would add up to zero both before and after the skaters moved. However, one of these students showed a lack of understanding which his initially correct statement had disguised as he stated that this would only be true if the masses and strengths of both skaters were the same as then there would be no movement. Four of the students specified that the acquisition of equal and opposite momentums by each skater was a consequence of equal forces being applied to each skater by the other. However, two of the students had a less accurate view of the reason for each skater getting equal and opposite amounts of momentum as they simply specified that the momentum would be 'split' between the two skaters. Two students implied that one skater would get a negative momentum while the other would have a positive value and a further two students demonstrated by their answers that momentum was conserved when they stated that the two skaters would move in opposite direction at the same speed, which showed that they had pre-supposed that both skaters had identical masses.

A group of seven students demonstrated by their answers that they did not think that the law of momentum was obeyed when the two skaters pushed each other apart. One of this group implied that one skater would have more momentum than the other without giving any reason for thinking this while two others decided that one of the skaters would get more momentum than the other. The other four members of the group said that the total momentum would increase. Although they did not state it, it is likely that they perceived the motion after the skaters pushed each other apart as indicating that momentum had been produced and did not appreciate that the opposing directions of movement meant that the momentums had equal and opposite values, thus cancelling one another out. A total of thirteen students gave very vague answers about the momentum of each skater which suggested that they did not really understand conservation of momentum in this scenario. Six of this group said only that both skaters would gain momentum as they moved apart and another seven students merely stated that they would move in opposite directions without commenting on the momentum directly. There were many other students who had incorrect views of the way that momentum would be distributed between the two skaters. Several of these misconceptions were related to the wrong perception of the importance of the relative masses of the two skaters. Two students said that if one skater had a greater mass than the other, the one with the larger mass would get more momentum, while another six students stated that both skaters would only get the same amount of momentum if they both had the same mass. One student thought that only the skater with the greatest mass would move, but gave no reason for thinking that this was the case. Another set of common misconceptions were linked to a lack of understanding of Newton's Third law. Five students decided that neither skater would move because the effects of each would cancel out if they both pushed with the same force. Another two students said that the skaters would move apart only if they exerted different forces on each other. One student thought that only the skater that exerted the greatest force would move, while another student thought the opposite as she stated that only the skater who was pushed the hardest would move.

In situation 3b, where the single skater pushed against the wall, it was clear that many of the students thought that the skater would gain momentum but the wall would gain little or no momentum. This finding is consistent with the findings of Olenick (1997) that many students perceive large objects as being 'immoveable'. This was the reason for developing and examining students' thinking in the 'immoveable wall' analogical sequence. Although only one student overtly stated that she thought momentum was not conserved, nineteen students said that just the skater would move and gain momentum. Twenty eight students thought that the skater would move but that the wall would not end up with any (or very little) momentum, while one student thought that the skater would gain more momentum than the wall.

There were only eight students who described outcomes that suggested that they considered momentum to be conserved when the skater pushed against the wall. Four of this group directly stated that momentum was conserved while one stated that the momentum of the wall and the skater would be equal and opposite. The other three students thought that both the skater and the wall would move / gain momentum although they were not specific about relative values or directions. Two thought the skater would lose momentum into the wall.

When the students stated their perceptions about similarities or differences between the two scenarios, more misconceptions came to light. Only a very small group of three students thought that the single skater would get the same momentum as two skaters, although only one of these students qualified her answer by saying that she was assuming that the single skater pushed with the same force that the two skaters had pushed with. A total of twenty five students incorrectly thought that the single skater would gain more momentum and / or kinetic energy than the two skaters because the wall would not move, while another student justified this same answer by saying that it was a consequence of the skater pushing against a hard surface. One student thought the single skater would move less than the two skaters but did not say why he thought this. One student thought that the wall would get less momentum than the skater. An obvious misunderstanding of Newton's Third law was evident in the answers of some of the students as two of them said that the force on the wall was greater than the force on the skater and another student thought that the force on the skater was greater than the force exerted on the wall. Another two students thought that the skater would not move since the wall had a greater mass than the skater and one student stated that the wall merely acted as a barrier and would exert a force on the skater, but he did not mention the equivalent force acting on the wall.

These results show that less than half of the respondents considered conservation of momentum to be true in either situation. Only thirty one students out of seventy eight gave some indication that they thought momentum was conserved in the situation with the two skaters, and only eight of the students were of the same opinion regarding the skater pushing against the wall. The results also show that for many of the students their misconceptions regarding conservation of momentum were connected to an underlying misunderstanding, or wrong application, of Newton's third law.

In terms of the kinetic energy in this pair of scenarios, there were several theories about the source of the final kinetic energy of the skaters, which are graphically summarised in figure 4.8 below.

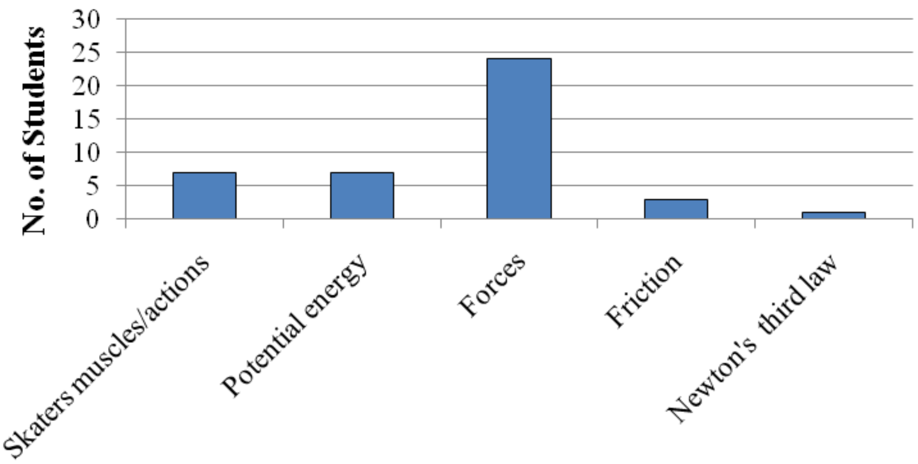


Figure 4.8: Number of students who stated various ideas about the source of the skaters' kinetic energy in situations 3a and 3b.

Several students credited the production of the skaters' kinetic energy to energy conversion processes in the skaters' bodies. Three students stated that the kinetic energy in this situation came from the skaters' muscles, two gave a similar answer when they stated that the kinetic energy was produced as a consequence of work having been done and another two students simply said that it was a result of energy from the skaters' bodies. Seven students said that it was converted from potential energy to kinetic energy, without indicating whether or not they were referring to chemical potential energy or some other form of potential energy. A total of twenty four students linked the kinetic energy with the forces exerted by the skaters and/or the wall. This suggests that they may have been linking the concepts of force and work done, although none of them specifically stated this connection in their answers. Fifteen of this group said that the kinetic energy of the skaters was a consequence of the force acting on them. One student stated that the energy in this situation came from the wall opposing the skaters' muscles, while another two only stated that the wall pushed back. Three students credited friction with the production of kinetic energy but did not say how they thought this worked. One student simply stated that the kinetic energy was produced as a consequence of Newton's Third law without giving any indication as to her reasoning, while another three students had once again misunderstood this law when they said that the forces were unbalanced so one skater moves more than the other.

4.2.4 Situation 4

In this situation the students were asked to think about two similar situations. In the first, a car collided with a large building at 50mph, while in the second, two identical cars, both travelling at 50mph, collided head on.

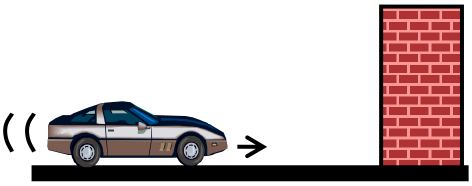


Figure 4.9a: Car hitting building at 50mph.

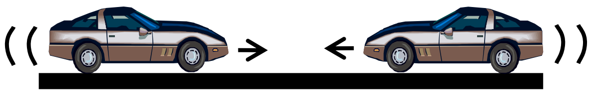


Figure 4.9b: Cars travelling at 50mph hitting head on.

This pair of situations was designed to examine what the students thought would happen, in terms of momentum and energy. It is a common misconception that the head-on collision is worse than the single car hitting the brick wall, because of the higher relative speed. The first of the two scenarios was identical to the target scenario in the 'immoveable object' sequence. A total of eighty eight students answered this question while only one commented that the question was too vague.

Figure 4.10 below summarises the response of students regarding momentum when the car struck the building (figure 4.10a), and the situation where the two cars collided head-on (figure 4.10b).

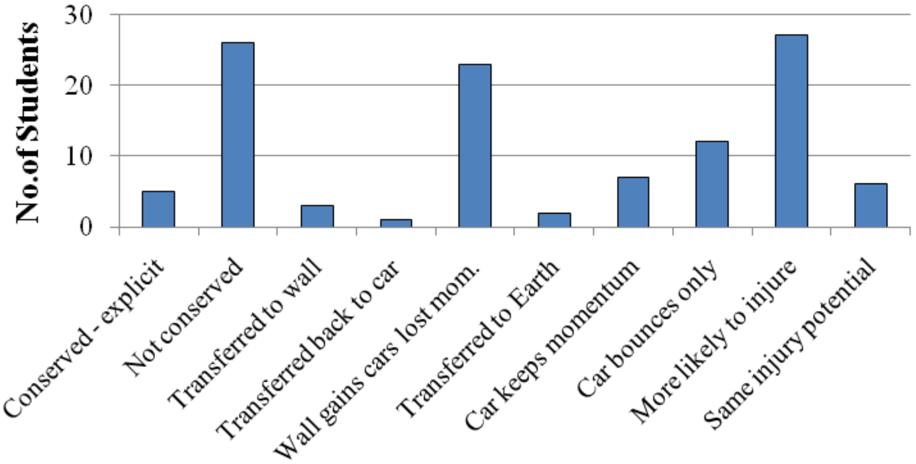


Figure 4.10a: Number of students who stated various ideas about momentum for situation 4a.

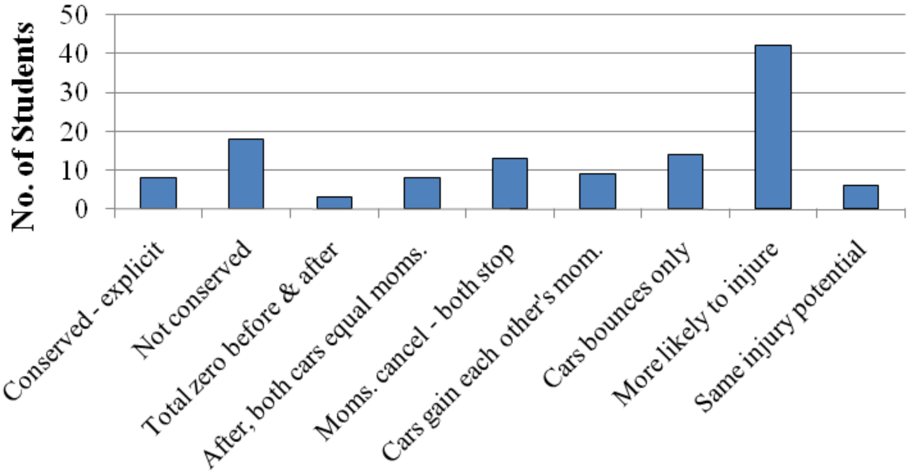


Figure 4.10b: Number of students who stated various ideas about momentum for situation 4b.

Several answers about momentum in the first scenario were vague, showing that many students did not really understand what was happening to the car's momentum. Eight students merely stated that the car would rebound off the wall. Three students said that the car transferred momentum into wall, while another four said that the car would rebound based on the fact that the wall had a bigger mass. One student said that the car's momentum would have been transferred from the back of the car to the front of the car which would get crushed, while one other student only said that the wall would break. Two students thought that the car would go through the wall and another four only said that the car would stop. Although only five students explicitly stated that momentum would be conserved when the car struck the building, there were a reasonably significant number of students who had a fairly good understanding of what happened to the momentum of the car when it struck the wall. Twenty three students stated that they thought the wall would gain the momentum that the car lost. Despite saying this, one of this group said that he thought that the wall would not move. Two students had grasped the concept that the momentum of the car would ultimately be transferred to the Earth when they stated that the earth would get the momentum that the wall gained from the car. However, one of these students was unclear about what happened to some of the car's original momentum when he said that the earth would gain most of the momentum lost by the car and the wall would get a little transferred to it. Twenty six of the students did not think that momentum was conserved when the car stuck the building. Eleven of them tried to justify their reasoning by stating that the building would not move and so the car would lose all of its momentum, while another six said that the wall would not move and car would bounce back from the wall. Seven of the twenty six students also decided that the car would bounce back from the wall but did not consider the resulting change in direction to indicate that there had been a change in momentum as they said that the car would 'keep' most or all of its momentum. One of the group said that she thought there would have been more momentum after collision than before because of the greater mass and the last member of the group just said that he thought that the car would have more momentum than the wall without giving any reason for his thinking.

In the situation where the two cars collided head-on, a greater total of eight students said that momentum was conserved but only three of them specified that the total momentum before and after the collision were equal to zero. Other students had a reasonable grasp of the situation as: eight simply stated that the colliding cars would have equal momentums; another eight thought the cars would stop as one car's momentum would have cancelled out the other; one student mentioned that the forces exerted by the two cars cancelled out; five said that as both cars have equal momentum before the total momentum after would be zero; and one student said that the total momentum before and after would have been the same as both cars were identical. Like the answers to the situation where the car struck the wall, many answers were rather vague. Fourteen students said only that the cars would bounce apart, although two of them specified that this would be because they gained some of each other's momentum; nine students thought that both cars would gain the others' momentum; four students said that the cars would have bounced back with the same momentum; and another two said that the momentum was shared between the cars after the collision and one student thought that some momentum was 'regained' by each car; one student said that momentum would have been transferred from the back of the cars to the front of the cars which would therefore have been crushed. Several students had incorrect ideas about the momentum in this situation, as shown by the following answers. A total of twelve students said that momentum was not conserved in this collision without justifying why they considered this to be the case; another three students said that the momentum after the collision would be greater than the momentum before it; one student said that both cars would bounce back with less momentum; another said that if one car had less mass it would have ended up with more momentum; and finally one student evidently did not understand the distinction between momentum and heat as she stated that the momentum was changed to heat.

In comparison with their answers about momentum, there was less variety in the students' answers about what they thought happened to the original kinetic energy of the cars in each situation. These answers are summarised graphically in figure 4.11 below.

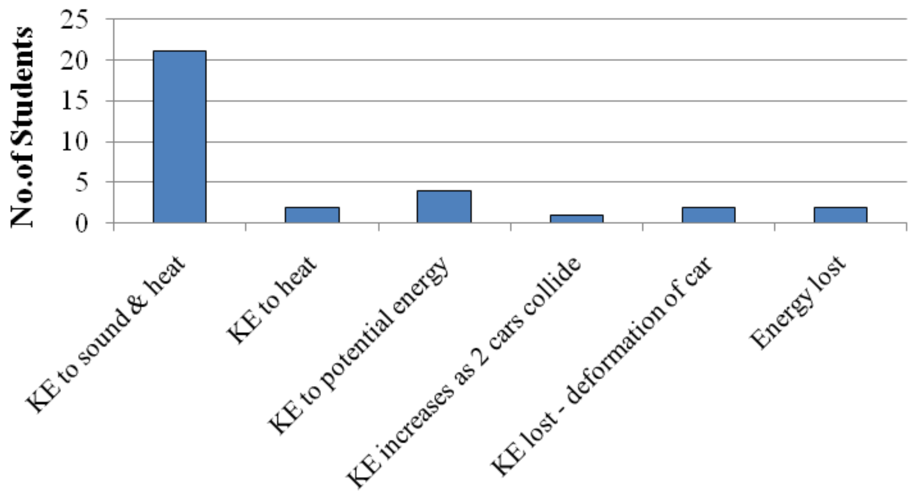


Figure 4.11: Number of students who stated various ideas about kinetic energy for situations 4a and 4b.

Twenty one students thought that the kinetic energy would be changed into sound and heat, while two students only mentioned heat energy. Two students thought that the kinetic energy was lost as a consequence of the deformation of the cars' shapes. One said kinetic energy would increase in a two car collision. Four students thought that the kinetic energy was converted into potential energy and another two clearly didn't think that the total amount of energy was conserved as they just said that the energy was 'lost'.

The answers to the question about which driver (if any) would be more badly injured as a result of the collision highlighted several misunderstandings. Only six students correctly identified that the likelihood of injury was equal for all three drivers, but only one justified this by saying that the changes in momentum in both scenarios were the same for all of the drivers. A total of forty two students thought that the drivers in the cars that hit each other would be more likely to be badly injured. They justified their reasoning in a number of ways, including the following. Six thought that the injuries would be worse because there was more energy involved in this collision; eight thought that injury was more likely because both cars were moving, while another two gave similar reasoning when they said that this collision was equivalent to hitting the wall at 100mph; seven students argued that there was more momentum before the collision in this scenario compared with the other; another two argued that there was double the amount of force when the two cars collided and another five said that both the energy and the momentum would be double in this scenario; finally one student justified her answer by saying that in this scenario the momentum would 'run through' each of the cars. A total of twenty seven students had the opposite view, that the driver who hit the wall would be more badly injured. Again, they tried to justify their answers in a number of ways, including the following. Two students said that there was less distance in which to transfer the energy and momentum; one said that the car hitting the wall would have absorbed all of the momentum since the wall would not move; four students clearly misunderstood the impulse equation as three justified their answer by saying that there would less likelihood of injury as there would be a shorter contact time since the car would stop straight away, while the other student decided that there would be a greater impulse in this scenario. Another two students were misguided about the impulse equation as they thought that the contact time would be longer, which they deduced would make the force on the driver larger as well. Another six students justified their answer by saying that the single car had collided with a solid stationary surface and another two said that this collision was worse because the wall had a larger mass and less give than another car. Finally, one student thought that there was a larger amount of momentum and kinetic energy in this scenario.

4.2.5 Situation 5

This situation required students to consider a bullet being fired at and *lodging* in a wooden block and another identical bullet being fired at a rubber block and *rebounding*.

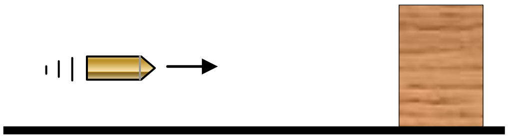


Figure 4.12a: Bullet lodging in wooden block.

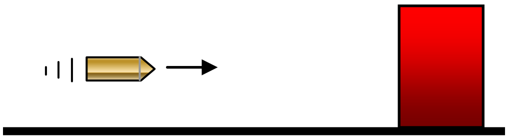


Figure 4.12b: Bullet bouncing off rubber block.

This pair of situations was similar to those in situation 2. The intention of asking about these two situations was to ascertain whether or not the students could deduce and argue the significance of the change in direction of the bullet which hit the rubber, particularly in relation to the greater resulting change of momentum. A total of sixty six students answered this set of questions, although some only answered a few parts of it. Two of the students said that it was difficult to answer the questions without being given the relevant masses and velocities. Figure 4.13 below, summarises the responses of the students regarding momentum when the bullet lodged in the wood.

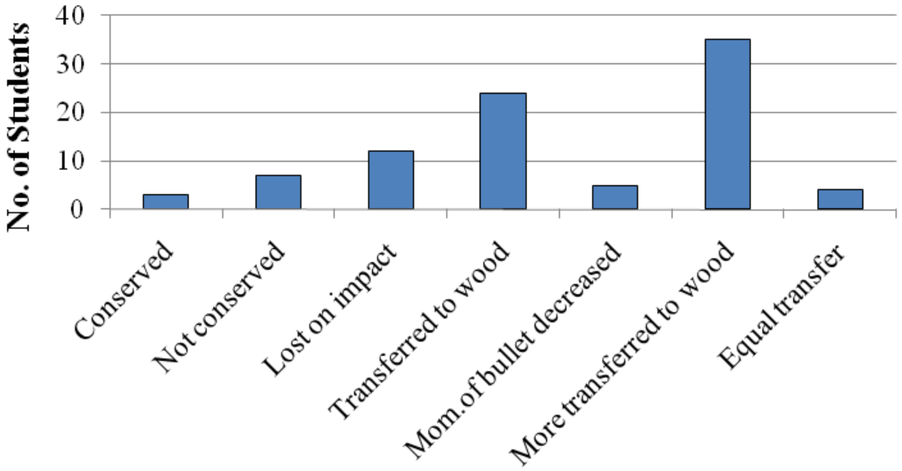


Figure 4.13: Number of students who stated various ideas about momentum for situation 5a.

In the situation where the bullet became embedded in the wood, only three students stated that the total momentum was conserved. Another twenty four students stated that the bullet's momentum would have been transferred to the wood but did not specifically state whether or not they considered the momentum to have been conserved. Five students stated that the total momentum after the collision was less without justifying their reasoning, while two students thought that the momentum after was greater than before because there was a greater mass after the collision. Twelve students said that the momentum was all lost after the collision but it was possible that they were thinking only about the bullet as they did not give any further details. Six students were a little more specific when they stated that the bullet's momentum decreased but they did not indicate what they thought happened to the momentum that the bullet lost.

Many of the students correctly identified what happened to the kinetic energy of the bullet when it embedded itself in the wood. The students' answers are summarised in figure 4.14 below.

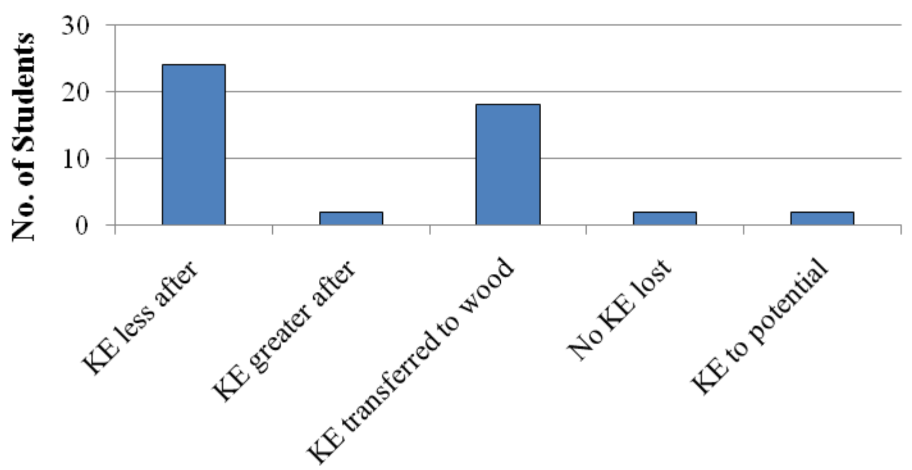


Figure 4.14: Number of students who stated various ideas about kinetic energy for situations 5a.

Twenty four students said that there was less kinetic energy after the collision with twelve of them stating that the lost kinetic energy was converted into heat and sound, while one had the impression that the energy was converted into vibrations. A total of eighteen students thought that all of the bullet's kinetic energy was transferred to the block. Only six students gave answers that showed a lack of real understanding of what happened. Two students thought that the amount of kinetic energy after the collision was greater than it had been before, which one tried to explain by saying that this happened as there was a greater mass after the collision than before, while the other student thought that this was true because the bullet lodged in the wood. Another two students thought that no kinetic energy was lost in the collision. The last two students concluded that the kinetic energy was converted to potential energy but did not elaborate on why they thought this, nor did they state which type of potential energy they thought was being produced.

There was a large variety of answers regarding the question of what happened to the momentum in the situation where the bullet rebounded from the rubber. These answers are summarised in figure 4.15.

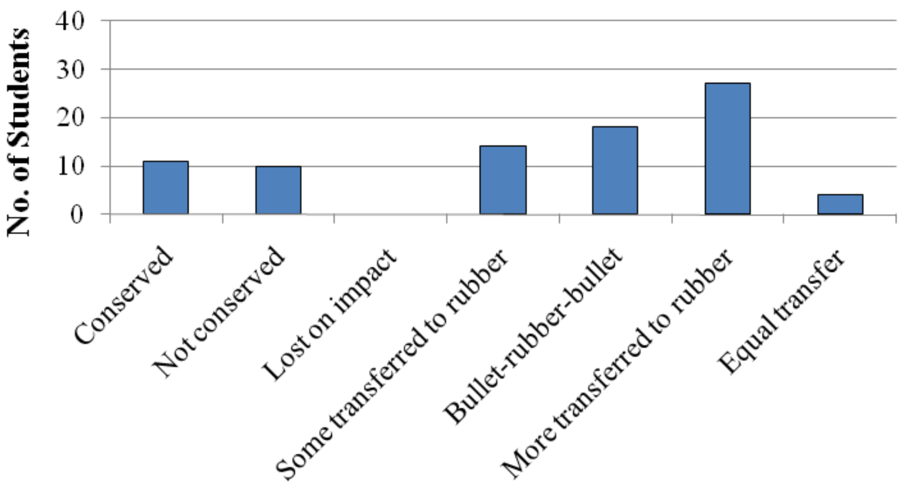


Figure 4.15: Number of students who stated various ideas about momentum for situation 5b.

Six students correctly identified that the total momentum was conserved while another four used a similar phrase when they said that momentum was 'preserved on impact'. Another student appeared to be thinking along similar lines when he said that the momentum of the bullet in the opposite direction was 'cancelled' by the motion of the rubber block. The majority of the students did not indicate whether or not they thought that momentum was conserved in this scenario. Fourteen students were less sure of what happened although they were aware that some momentum was transferred to the rubber block and stated that the momentum of the bullet would decrease as a consequence. However, it was evident that several did not think that momentum was conserved in this collision. Three students thought that the momentum after was greater than before. One of these students tried to justify this by saying that this was a consequence of the force of the impact, but he did not say why he thought that this was a relevant consideration. Another student said that momentum was gained in this collision because he thought that the rubber block 'gave its momentum to the bullet' when it rebounded. Seven students gave the opposite answer as they thought that the momentum was less after collision for several different reasons: two students thought that this conclusion was justified by the fact that the bullet rebounded; one thought that the momentum would decrease because there was a loss of kinetic energy. Two students justified their decision that the momentum decreased by comparing what happened when the bullet hit the rubber block with what they thought happened when it embedded itself in the wood. One said that the total momentum would decrease as the rubber block exerted a higher force on the bullet than the wood, while the other student thought that the momentum would decrease because the reduction in the momentum of the bullet was not as quick as it had been for the wood because the rubber had a longer impact time. Many of the students did not understand the vectorial nature of momentum as fourteen thought that momentum was transferred to the rubber and then back to bullet, while another four had similar ideas when they said that the bullet got some of its original momentum back. These answers show that these students were unaware that the change in direction necessitated a large change in momentum from a positive value to a negative one, or vice-versa.

In a similar manner to the scenario where the bullet embedded in the wood, many of the students appeared to have a reasonable understanding about what happened to the kinetic energy when the bullet hit the rubber. Their answers are summarised graphically in figure 4.16 below.

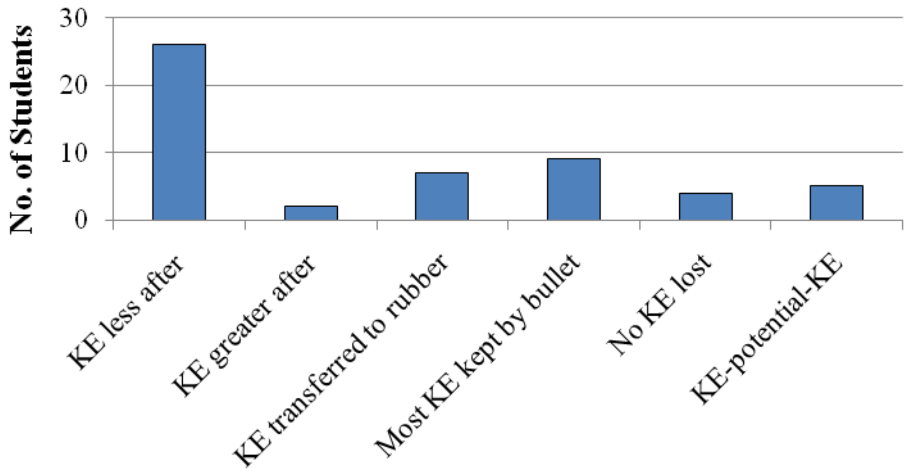


Figure 4.16: Number of students who stated various ideas about kinetic energy for situations 5b.

Twenty six of the students said that they thought that there would be less kinetic energy after the collision, but only ten of these students attributed the loss to the production of heat and sound energy, while another two simply said that kinetic energy was lost as a consequence of the bullet bouncing off the rubber. Seven students stated that kinetic energy was transferred to the block, while nine of the students thought that the bullet kept most of its kinetic energy, based on the fact that it bounced. Five students described the initial kinetic energy of the bullet being changed into potential energy and then transformed back into kinetic energy again when it rebounded. Four students said that they thought that there would be the same amount of kinetic energy before and after the collision, possibly based on the same logic as the five previous students, although they did not justify their answers. Two students clearly misunderstood the concept of conservation of energy as they thought that there would be more kinetic energy after the collision than there had been before, without being able to give a reason for this.

The students were asked which situation they thought would result in the greater transfer of momentum to the block. Nineteen students correctly identified that the momentum transfer was greater to the rubber but only one student clearly identified the proper reason that the momentum that was transferred to the rubber block is larger as it cancels out the amount of momentum that the bullet gains in the opposite direction, to give the same total before and after. Other reasoning that was given included three students who simply said that it was because the bullet bounced off the rubber without detailing why this mattered; one said that it was because the bullet bounced and the rubber moved; and two said that it was because the rubber was more flexible and lighter than the wood. Several of the attempts at justification did not demonstrate a proper grasp of the relevant Physics on the part of the students. Two students stated that the rubber took the bullet's momentum and then fired it back; one thought that it was because the rubber had a higher mass than the wood while another thought the opposite; one student justified her answer by stating that the bullet needed to exert a higher force to penetrate the rubber and another gave a similar reason when he stated that the rubber would not break as easily and would therefore slow the bullet down more.

A total of thirty five students thought that more momentum would be transferred to the wood. This shows that these students failed to take into account the significance of the change in direction of the bullet when it hit the rubber which would result in its momentum changing from a positive value to a negative value. The fact that the bullet embedded itself in the wood was a common justification for thinking that the bullet would transfer more momentum to the wood as seven students argued this while another two said that the wood absorbed the energy and another nine justified their answer by saying that the wood had all of the bullet's momentum transferred to it. Seven students said that more momentum was transferred to the wood because the bullet came to a halt and one argued that this meant that there was a greater impulse. One student thought that there would have been greater movement for the wooden block. Three students argued that the longer contact time between the bullet and the wooden block would result in a greater transfer of momentum, and another three described the rubber block providing the bullet with momentum, or said that the bullet still had momentum after impact. One of the students had very inconsistent reasoning as he stated that since the momentum before had to equal the total after when the bullet hit the wood (but not in the case of the bullet hitting the rubber) it must have received more, despite the fact that he also said that the momentum afterwards was zero, although it is possible that he was only referring to the bullet in that case.

Four of the students thought that neither situation resulted in a greater transfer of momentum. One attempted to justify this by saying that both blocks gained the same momentum while another three students said that both bullets transferred the same amount of momentum to each block because they had the same momentum on impact.

4.3 Overview of students' understandings and difficulties

Although some students had a clear understanding of momentum, the findings reported above show that there were a number of common misconceptions about the concept. The data make it very clear that many students either misunderstood the law of conservation of momentum, or actually disbelieved it in real-life situations. There were several important misunderstandings about momentum evident in the data, which include the following.

1. The vast majority of the students were unclear about the definition of momentum as well as the definition of kinetic energy and were unable to articulate any clear differences between the two ideas, other than the fact that their equations were different. Furthermore, many of the students' ideas about momentum overlapped significantly with their understanding of the concepts of force and inertia.

2. Many students engaged in 'single-object thinking' whereby they considered only one of the objects in a collision, rather then including both objects in their reasoning. This led them to conclude that momentum is lost when the object that they are focused on slows down or stops.

3. Many students had a very 'velocity-centric' view of momentum. This led them to incorrectly conclude that objects (such as the large wall that the single car struck in situation 4) that did not appear to move had no momentum.

4. Many of the students either ignored, or did not understand, the significance of a change of direction in terms of a change in sign of the momentum; they did not treat momentum as a vector quantity. This misconception led students to wrongly conclude that a rebounding object either kept all or most of its momentum, and they consequently concluded that it transferred very little momentum to the object with which it collided.

5. Several students misunderstood the link between the force on an object, the contact time, and the momentum that it had gained or lost, given in the impulse equation ($F \times t = \Delta p$). It was common for students to wrongly over-emphasise the

importance of the contact time in their reasoning rather than understanding that the change in momentum experienced by a decelerating or accelerating object was also linked to the magnitude of the force which was exerted on it.

6. Despite their difficulty in succinctly defining the concept of kinetic energy and in distinguishing it from the concept of momentum, the students generally had a better appreciation of what happened to kinetic energy in collisions. Most realised that at least some of it was usually converted to other forms of energy as a result of a collision.

7. However, quite a number of the students had an incorrect understanding of the terms 'elastic' and 'inelastic' collisions, as they thought that an 'elastic' collision occurred when the two objects bounced apart. It was not at all evident from the answers given by the students that any of them had considered why kinetic energy was not conserved in inelastic collisions. Most of the students were content to simply state that it was converted into other forms such as heat and sound, without attempting to indicate any mechanism by which they thought this would happen. One of the two bridging analogy sequences, which were newly developed for the purposes of this study, examined inelastic collisions in some detail. This sequence was utilised in an attempt to address this lack of explanation (and possibly understanding). The findings from students' interactions with this analogy sequence during think-aloud interviews are reported in chapter 7.

Chapter 5

Findings 2: The initial phase of the interviews

This chapter examines and discusses what was discovered regarding students' thinking about momentum and kinetic energy in the initial phase of the sixty interviews that were conducted. The manner in which the two sets of thirty students interacted with each of the bridging analogy sequences is scrutinised in detail in the following two chapters. In particular, a scrutiny of the ways in which conceptual change was found to have occurred, and was seen to have been triggered, is undertaken in those chapters. In chapter 8, the views of students regarding the use of bridging analogies as a teaching and learning tool are examined. Thereafter, in chapter 9, the ways in which conceptual change has been shown to occur throughout chapters 6 and 7 is discussed in relation to the various theoretical stances outlined in the literature review chapter. The different theories are compared to the theoretical arguments that have been put forward throughout chapters 6 and 7 in relation to both of the bridging analogy sequences.

The initial phase of each interview allowed the level of knowledge of each student regarding some of the basic ideas about momentum and kinetic energy to be ascertained. The thoughts of each student regarding the definitions of the two concepts, and in particular how they differ, was also assessed. Their views on the extent to which they believed that the law of conservation of momentum held true in their everyday experience were also assessed near the beginning of each interview.

5.1 Basic recall of ideas about momentum and kinetic energy

Almost all of the students knew the equations for momentum and kinetic energy although several could not immediately recall the equation for momentum and required more than one attempt to get it correct or in some cases, they were reminded of it before moving into the substantive content of the interview. Of those who could not remember it, they knew that momentum involved the mass and either the speed or the velocity of the moving object. A common error was stating that the equation involved the speed rather than the velocity of an object, but most students who made this mistake readily corrected themselves when they were asked for clarification about whether they intended to say speed or velocity.

5.2 The students' initial views on the law of conservation of momentum

The majority of the students were initially happy to state that they thought that momentum was always conserved. Despite its appearance in the learning outcomes for the Higher Physics course, only 4 of the students (S34, S44, S61 and S63) mentioned the caveat that momentum would be conserved in the absence of external forces acting on an object and student 61 specifically mentioned friction in relation to this.

There were several students who did not believe the law when they were asked about it in the initial phase of their interview. One student (S10) initially indicated that he did not think that momentum was conserved but changed his answer once he had looked at the elastic and inelastic collisions prior to beginning the bridging analogy sequence. Students 17 and 50 specifically mentioned that they were not sure if momentum was conserved in a situation where an object hits a much larger object and stops. Two of the students (S4 and S8) were clearly unsure what was meant by conservation of momentum. Student 30 demonstrated by his statement, shown below, that he felt that it was impossible for momentum to be perfectly conserved.

S30: Something must be lost somewhere it couldn't be perfect.
I: So, you think in the real world momentum might be getting lost?
S30: Yeah.
I: How would you explain that?
S30: Heat loss.

It is evident from this discussion that some students perceived the loss of heat energy from a situation to be an indication that momentum was being lost. This may indicate that they were confusing the concepts of momentum and energy as they were unsure about the difference between them. Students 6, 7 and 19 also indicated in their initial answers that they considered momentum not always to be conserved because it was often transformed into 'other forms of energy' in many everyday situations. This view, and evident confusion between momentum and energy, was found to be a common problem among the students, and is therefore discussed in some detail below. Four of the students (S17, S21, S23 and S28) were not adept at considering all of the objects in a situation and tended to disbelieve the law of conservation as a result of ‘single object’ thinking. They showed that they considered momentum to be lost because the single object that they were focusing on had slowed down or stopped. This was also found to be a common problem at several points during a considerable number of the interviews and is therefore discussed in detail throughout the next two chapters.

Of those that did think that the conservation law was always true, the level of self-determined belief-rating in the law varied between a level two (very low) and the top level of six. Many of the students stated that they believed it primarily because that is what they have been told and so they felt that they had no reason to doubt it. However, some subsequently demonstrated that they were not very sure in the target situation which they were presented with. Student 13 had an interesting reason for his belief in the law, when he stated that he could do the calculations well and that this therefore convinced him of the veracity of the law.

S13: The total momentum of something before a collision it is involved in is equal to the total momentum after, so it’s conserved.

I: OK. And how much, I am going to ask you several times to rate things that you tell me on a scale of one to six where one means you don’t believe it really at all, to six means you totally agree with it. So how much would you rate that as a belief for you?

S13: About four probably.

I: Why is that? Why do you believe it so much?

S13: I know how to do questions, no problem at all.

I: So, you can do the questions?

S13: Yeah.

I: So, that means that you believe it because you can work them out?

S13: Pretty much, yeah.

I: Do you think it is true in real life as well, other than just the physics questions?

S13: Yeah, like the car crashing and the energy being transferred and stuff, that makes sense to me.

I: Now, what would you say momentum actually is?

S13: A measure of the energy and the direction of it. It’s a vector.

As with student 30, discussed above, the last statement in this excerpt casts doubt on whether or not he was actually thinking of conservation of momentum in his assertions. It would appear that they could have been thinking of energy instead, although their justification for their level of belief still holds true.

In contrast with these views, students 9, 21 and 41 seemed unconvinced by the calculations that they carried out in class as they considered that the calculations were significantly simplified in order to make them appear to work. Students 55, 56 and 59 also mentioned that they considered there to be lots of factors that would affect whether or not momentum was conserved in the 'real world' which would not be reflected in the calculations that they did as they would become too difficult or complex for them to be able to do.

5.3 The students' understanding of momentum and other related concepts

The early phase of the interviews clearly demonstrated that the concept of momentum is confused and intertwined with other physical quantities in the minds of many of the students, particularly the concepts of force, inertia and energy. When asked to explain what they thought the momentum of an object told us about it, many students gave explanations which showed a high degree of overlap in their minds between the different physical quantities.

5.3.1 Momentum and force

The following excerpts demonstrate that a large number of students have a mental map in which the concepts of momentum and force significantly overlap with one another. Despite these initial comments, each of the students were able to discuss the idea of momentum in a contextually correct manner during the rest of the interview which suggests that they could use the terminology correctly but that they are not very clear on the distinctions between force and momentum. The following comments were made by students when they were initially asked to explain what they understood by the term 'momentum' as it had been used in their Physics lessons.

I: What is it a measure of, do you think?
S14: A measure of mass times velocity.
I: OK.
S14: When two cars hit each other, the momentum is the hitting force.
I: So, you think it is linked to the force that they hit with?
S14: No. Without my sheets I can't remember what the actual definition of momentum is.
I: Well, you've given me the definition, but what do you think it measures about a moving object?
S14: The impact of its collision.

Students 15 and 41 gave similar responses when they discussed their views of momentum in the following ways.

S15: The amount of push it has got, if you know what I mean.

Student 41 was more explicit in stating that he felt that momentum was the same as force.

S41: Em, it's the, … It's the force of a moving object.

This statement was then followed up shortly afterwards when he said the following.

S41: Just like momentum's kind of the, it's like eh, it's the, …, kind of the power the object has. Like I don't mean power as in the physics sense, but just like, ...

I: So, did you mean force as in the physics sense, or not?

S41: Well, just kind of like the strength of the object, really. Like, how much impact it could create.

Student 45 demonstrated by her initial remarks that for her, the concepts of momentum and force are strongly linked to the point whereby she struggled to separate them from one another.

I: Em, now. You said there it's 'a force' and 'an energy'. Do you think that momentum is the same as a force, or different from a force, or what do you think?

S45: I believe it's the same.

I: You think a force and a momentum are the same thing?

S45: I kind of see it as a, …, I don't know, a bit like "pressure". I don't know really [laughs].

I: So, it's all a wee bit mixed up?

S45: Yeah. I see it as some sort of thing, but I don't know how to describe it that well.

In a similar manner, student 59 was clearly struggling to separate out the two ideas.

S59: Just kind of forces acting that we can't see.

I: So, do you think momentum is the same as force?

S59: I wouldn't say it's the same as force, …, I would say that it's eh, …, a different sort of force, but how to explain it, it's a different sort of, …, quantity it's acting on.

I: But you think there is a link to force somehow?

S59: Yeah.

Students 22, 62 and 65 also initially stated that they thought of momentum and force in the same ways. However when they were asked to clarify this, it became evident that they perceived differences between the two concepts but were unclear about what the distinctions actually were.

I: What can you tell me about momentum? Anything at all?

S22: It's a force.

I: It's a force? Is it the same as force, or is it different from force?

S22: Different.

Student 62 also appeared to be struggling to separate the concepts.

S62: When an object is moving it has momentum.

I: OK. And what do we mean by momentum though? What would you say it was? What is it a measure of?

S62: A force.

I: Is it the same as the force?

S62: It's different to the force, but similar.

In the case of student 65 his working definition of momentum came to light when he was discussing his perception of energy.

S65: I see energy as a thing that is around you and is transferable into another type of energy but with momentum it is almost like a force.

I: You said momentum is like a force or is momentum a force?

S65: I think it is a force.

I: So, is momentum the same thing as force?

S65: Yes.

I: How come it's not measured in Newtons then? I mean momentum isn't measured in Newtons.

S65: Perhaps it is similar to a force, but not quite.

The initial answer given by student 10 showed that he viewed momentum as a type of 'impetus' force, whereby moving objects are perceived to carry a force with them. This is a widely reported misconception about force which many people use to explain why they think that objects keep moving until they 'run out' of force (see

Driver et al., 1985 and Driver et al., 1994) in which several pieces of research that discuss this phenomenon are highlighted).

I: First question in this, what can you tell me about momentum? What do you know about momentum?

S10: Basically the force that an object carries when it is moving.

This view was then emphasised again in another statements given a few seconds later.

I: So what do you think it is measuring? You have hinted at what you think it is measuring already. If I measure the momentum of something, what am I measuring about it, would you say?

S10: I kinda know what it is but I don't know how to explain it.

I: Have a go. See what you think.

S10: The force it has got, what it would do to something when it hits it, how much force it exerts on it.

Given that momentum and force are often discussed at the same time in relation to moving objects, it is perhaps not surprising that the concepts become somewhat merged together in the minds of many students. In particular, when the quantity impulse is introduced as being both the product of force and time as well the change in the momentum of an object, students seem to easily overlook that the force relates to the *change* in an individual object's momentum, rather than to the value of it at any given time. This issue was highlighted during the initial phase of the elastic/inelastic collision interviews, where the majority of the students struggled when they were asked to use the impulse equation ($F \times t = \Delta p$) to explain or reason out why momentum was conserved in a collision. There were several reasons for these difficulties.

The most common problem was a failure to understand Newton's Third Law, whereby both vehicles involved in the collision exert equal and opposite forces on one another for equal amounts of time. When this problem was compounded by a lack of clarity regarding the difference between force and momentum, the student had great difficulty in enunciating the reasons for the conservation of momentum as given by the impulse equation. Student 59 gave a clear example of this difficulty as he failed to grasp the idea that the two vehicles in the elastic collision would have equal and opposite forces acting on them. Instead, he viewed the change in the momentum of each vehicle as being the result of a transfer of force which caused an equivalent transfer of momentum. His difficulties were therefore made more complex as a result of him seeing the transfer of momentum between the vehicles as being equivalent to the transfer of a force.

S59: The change in momentum is going from that cart into that cart which then, …, transfers the force that way.

I: So, tell me what happens to the momentum of the blue car, of the red car, whatever one starts, it doesn't matter really?

S59: Initial momentum to zero, and then that is transferred to that one, which goes from zero, to presumably whatever that blue car's initial momentum was.

I: So, the blue cart loses momentum and the red cart gains?

S59: Yes.

I: How much compared to how much that loses? How much is it: more, less, or the same?

S59: About the same but not fully.

I: Ok, so why, what has that got to do with the force? And the time? Any idea?

S59: Eh no, …, the force is just transferred from there to there.

I: So, you are saying that force is transferred in a similar way to the way that momentum is transferred, is that what you are saying?

S59: Yes, …, but I wouldn't know how to put time into that sort of, …

The following excerpt from student 49 shows another example of a person who struggled to understand Newton's Third law. Consequently, he had problems in explaining the relative changes in the momentum of each vehicle. This, in turn, meant that he found it difficult to explain why momentum is conserved in the inelastic collision, despite having already managed to do so (with the assistance of some guided questioning) for the preceding example of the elastic collision.

I: So, you're saying that the red car's momentum changes?

S49: Yeah. So, you find the change in the red car's momentum, then the time of the collision, then you can figure out the force, that the blue car applies on the red car. And then, em, …, figure out the change in momentum of the blue car, and you'd just have the same time of collision, and then you can find out the force of the red car and the blue car.

I: And how would its force compare with the blue and the red?

S49: Eh [long pause]. Would it be less? Well, I'm not sure 'cause, …

I: Why are you thinking it would be less, what makes you think that?

S49: ...'Cause the blue car keeps going in the original direction, and the, ... , so you'd think that it had more force going this way than that way.

For others, the difficulty in justifying the conservation of momentum lay in realising that the increase in the momentum of one vehicle was matched by the decrease in momentum of the other. This problem was often caused by an initial lack of appreciation for the subtleties of Newton's Third Law as the students failed to appreciate that the changes in momentum were precipitated by the forces acting on the vehicles. The problem was resolved for many students by careful questioning, which enabled them to think through the relative changes in the motion of the two vehicles (by being encouraged to re-examine the relative speeds before and after, particularly in the case of the first, elastic collision).

For a few students, their difficulty was related to a simple failure to acknowledge or recognise that there were two vehicles involved in the collision, rather than just the one which had captured their initial attention. This resulted in them tending to discuss the change in momentum of one vehicle in terms of the force acting on it, while failing to recognise the role of the other vehicle in maintaining the total amount of momentum during the interaction, meaning that they were somewhat perplexed by the feeling that momentum was being either generated or was disappearing according to their line of reasoning. These students required to have their reasoning guided through careful questioning in order to assist them to resolve the resultant cognitive conflict between what they had been taught about momentum always being conserved, and what they perceived to have happened during the collision that they had witnessed.

5.3.2 Momentum and inertia

Momentum was also understood as being similar to inertia, as demonstrated by student 4 who apparently felt that the momentum of an object was linked to the continuation of an object's motion. This is perhaps the most understandable view as everyday usage of the word often implies that momentum is connected with something that continues to move or is hard to stop once it gets underway. In fact, Fullick (1994) gives a similar working definition of momentum as being a measure of a moving object's 'unstoppability'.

S4: Momentum for me, usually I don't think of it as formulas, when I write it down I usually put the formulas, but I don't usually remember the formulas so, momentum I think is, eh, the energy which is, used after the kinetic energy, eh like when kinetic energy finishes, but it's the momentum that takes an object further.

I: It keeps it going?

S4: Yeah, it keeps it going. For example, in a car, when a car stops, and it puts the brakes on after going high rates of speed, the momentum, will just take it a bit further, even though the brakes are applied.

I: So, how do you see the difference between momentum and kinetic energy? Because you have mentioned both there.

S4: Yeah, well that's the little bit I have to explain a bit more I think, kinetic energy is just like, from potential, when a force is applied and it is moving, and the forces are being applied, so kinetic energy for me, is that, when the force is being applied.

I: So, only while the force is there?

S4: Yeah, the force is there and yeah, the force is there and an object is moving, that's kinetic energy for me.

I: And momentum?

S4: And the momentum starts when the force is finished, and the momentum carries the object a bit further.

Student 6 held a similar view as he described momentum as being linked to situations in which objects collide with one another. In addition, he linked the momentum of the colliding object with its energy and weight.

I: We are talking about momentum. First question is just to set the scene. What can you tell me about momentum from what you have studied in physics?

S6: I don't really know how to explain it. It's like when something crashes into something that is stationary, because of the speed that the other object is moving at it will move that forwards.

I: So, it has got something to do with crashing objects?

S6: Yeah.

I: OK. If I was to ask you for a definition of momentum what would you say it was?

S6: When you are running and you try and suddenly stop, you will fall forwards.

I: So, what is making you fall forwards do you think?

S6: Energy?

I: So, there is something to do with the energy when you are moving, yeah?

S6: Yeah.

I: So, how does that link to your momentum when you are moving? What is the momentum when you're moving?

S6: Is it your body weight, when you try and stop but you're running, it's your weight?

5.3.3 Momentum and velocity

Throughout many of the interviews, it became apparent that the velocity of an object was felt to be a greater indicator of an object's momentum rather than it being viewed as a joint combination of its mass and velocity. In effect, the momentum of an object was often judged purely in terms of its velocity. Indeed one student's initial definition of momentum stated this explicitly when he said the following.

S28: It is how fast something is going.

5.3.4 Distinctions between momentum and kinetic energy

All of the students had real difficulty trying to describe and explain the difference between momentum and kinetic energy. It was commonly acknowledged that both are properties of a moving object but the equations for each are different from one another in that the kinetic energy depends on the square of the velocity while the momentum does not. Most knew that momentum was a vector while kinetic energy is a scalar, by virtue of it being a form of energy. A very common response given was that the two quantities were not the same but were closely linked to one another and so the students were struggling to explain what the fundamental difference was between them. The following extracts from interviews demonstrate some of the struggles that were experienced by the students in trying to separate the two ideas in their thinking.

One of the most commonly encountered misconceptions involved momentum being changed into energy, or vice versa, as a consequence of a collision or other kind of interaction between two objects. This difficulty is demonstrated in the following quotations from students 7, 54 and 58.

I: What is happening to that momentum? Where is it going once the ball has not got it?

S7: Into other energies.

I: So, do you think momentum and energy are the same or different from each other?

S7: I'd say they were different, but similar.

Students 54 and 58 also had the two concepts rather merged together, although for them, an object had momentum as a consequence of it having kinetic energy.

S54: Em, …, I think the energy is what is allowing it to move, like, because if it didn't have the energy it wouldn't move, but the momentum is kind of the result of it having energy.

Student 58 appeared to go further and demonstrated a belief that an object with energy in some way creates momentum.

I: Ok, first question. What can you tell me about momentum, what can you remember from what you have been taught?

S58: Eh, …, not really that much to be honest, …. Eh, it's kind of, …, what I think of momentum is kind of amount of energy that something has got for a period of time.

I: Ok, so are momentum and energy, in your opinion then, the same or are they different in some way?

S58: I'd say that they are sort of the same but you have the energy creates the momentum, so when something is moving it has kinetic energy so, even though the energy has changed from say potential energy it is still an energy form.

I: So are you saying that you think momentum comes from kinetic energy or,…, what’s your thoughts on that?

S58: I'm not particularly sure.

I: Or are they different?

S58: I think they are different in the way they affect different things but the way I have always pictured it, energy and momentum kind of, …, to me they are the same.

Student 35 appeared to be suggesting that he considers that momentum is a form of directed energy and shows he considers these properties of a moving object to seem very similar to one another.

S35: Because energy you can see the effects of, ... Momentum is just basically part of speed.

I: So, if I asked you what the difference was between kinetic energy (which is moving energy) and momentum, what would you say?

S35: There is not a lot of difference except momentum tells us basically what that object will do, where all the energy that the object has will go to.

I: How does it do that?

S35: It basically tells us what happens to the energy.

Student 49 has a similar view of momentum and the way in which it relates to the kinetic energy of an object.

S49: Em, ... Kinetic energy’s the, …, total energy it has, and momentum’s the directed energy, ’cause it’s a vector.

Student 8 had the momentum and potential energy of an object intertwined in his thinking, although the reasons for that particular combination were not evident from his comments.

S8: I think momentum is the energy, the potential energy of momentum, the potential energy is momentum of something that is moving.

I: Explain what you mean by that. Are you saying momentum is the same thing as potential energy or are they different?

S8: Yeah, I think they are the same.

Several students had managed to separate the two ideas out to some extent in their thinking and made some interesting observations in an attempt to explain what they perceived the difference to be. Some of these statements show a degree of thoughtful insight while others, such as the comment by student 16, show that although they have a sense that the two ideas differ, they have the concept of momentum confused with the idea of velocity (as discussed for other students above).

> S11: Momentum is measuring the impact, it is measuring the damage of the impact but the kinetic energy is how much energy the object has going into.
>
> ....
>
> S16: The momentum will measure how far it is travelling per unit of time where the kinetic energy will be, how much energy it has in it. So they are different from each other. Energy is measuring how much energy is in it.
>
> ....
>
> S29: I'm just trying to think how to put it into words. It is like kinetic energy is actually the movement, but momentum is the movement during and after a collision. Is that right?
>
> ....
>
> S63: Kinetic energy is a measure of the energy something has whereas momentum is the measure of moving.

As discussed in the introduction and the literature review, the difference between the two quantities only becomes apparent when the motion of an object is changed, although the values of both are different during steady motion, by virtue of their different equations. It was found that very few students spontaneously discussed the change in momentum of an object being linked to the time that a force acts ($F \times t = \Delta p$). None of the students discussed the idea that the change in the kinetic energy of an object was linked to the displacement through which a force is applied ($E_W = F \times s$). These distinctions between momentum and kinetic energy did not seem to be apparent to them, either because they did not remember these equations, or possibly because these ideas had never been pointed out to them by their teachers in relation to these equations. These initial findings therefore suggest that much needs to be done to assist students in understanding the ways in which the concepts of kinetic energy and momentum differ from one another. Perhaps the proposed lesson outline given in appendix 7 would help to achieve this. Further research will be required to ascertain this.

Chapter 6

Findings 3: The 'immoveable' object sequence

As discussed in the methodology, each of the bridging analogy sequences was worked through by 30 students. It was found that the students engaged well with the analogies and consequently quite a few of the interviews were longer than had been initially envisaged from the pilot study. Every interview resulted in detailed thought processes or ideas being elicited from the students which warranted further exploration or clarification. Consequently, many supplementary questions were asked in addition to the set of core questions which formed the basis of both the semi-structured interview protocols. This shows that the interviews and the analogical sequences in particular, were highly effective in encouraging the students to think carefully and to do so aloud. As a consequence, the students' thought processes therefore became readily accessible for analysis, which had been one of the primary intentions in choosing the methodology that was employed. As will be seen in chapter 8, a high percentage of the students specifically acknowledged and commented very favourably on the way in which the interviews and the analogies in particular encouraged them to think for themselves. This was a marked feature of many of the responses during the review phase of each interview when the students were asked to describe what they thought of the use of the sequence as a learning strategy.

An analysis of the students' thinking as they engaged with one of the two sequences enabled changes in many to be demonstrated and the reasons for the changes, or the hindrances which caused problems or difficulties to be analysed in detail. The effectiveness of both sequences in causing conceptual changes will be discussed in detail. The immoveable object sequence will be analysed here in chapter 6, and the inelastic collision sequence will be examined in the chapter 7. A more theoretical analysis of the ways in which conceptual change was found to occur, as a result of students' interactions with both sequences, is discussed in chapter 9.

In both sequences, several of the students struggled to relate one or more of the analogies in the sequence to the target situation. Spiro, Feltovich, Coulson and Anderson (1989) argue that single analogies often exert a 'reductive force', whereby an incomplete analogical representation of some target situation often becomes the *only* representation that is remembered by the learner. They suggest that the main draw-back of using a single analogy is that it can often result in the formation of misconceptions for one (or more) of several reasons. Students can directly (or indirectly) focus on misleading properties of an analogy or they can be misled by missing properties of the analogy in relation to the target situation. A tendency to inappropriately map properties of the analogy to the target, or to focus on surface, descriptive aspects of the analogy, can result in a misunderstanding of underlying causation in the target domain. An important aspect of the target is often missed because an analogy is insufficiently detailed. Finally, they argue that incorrect properties of the target, or inaccurate associations between the analogy and the target, can be generated from the use of inappropriate or incorrect common language meanings of technical terms, or the use of non-technical descriptive language.

Spiro et al. (1989) also give a number of reasons why students often accept deficient or even irrelevant analogies. They argue that analogies are often reinforced in the mind of students as being valid and useful because of a number of perceived similarities between the analogy and the target. In particular, similarities in the names, physical appearance, or relationships between objects can cause misconceptions to develop. Perceived connections in the mind of a learner between the way that the analogy and the target work or correspond to each other, can also be problematic, especially when those connections are wrong or inaccurate. Overly simple, or convenient, but incorrect explanations can reinforce the inappropriate use of an analogy. Likewise, when a student incorrectly identifies multiple supporting or interconnecting factors between an analogy and a target, the inappropriate use of the analogy becomes more likely.

Spiro et al. (1989) go on to argue that the use of a series of carefully chosen, linked analogies can reduce the undesirable side-effects that a single analogy can cause. It will be seen in the following analysis of students' interactions with both sets of bridging analogies in this study that this suggestion is borne out by the interview data. The negative effects of single analogies within both sequences are also clearly displayed in the data, and these are discussed and analysed in relation to the set of potential hazards which Spiro et al. enunciated. However, the corrective influence of subsequent analogies is also often clearly evident in the data, and incidences of this are also examined.

6.1 Overview of 'immoveable' object sequence results

Before working through the set of analogies of the 'immoveable' object sequence, each of the students was introduced to the target situation picture of a car colliding at speed with a large and apparently immoveable building. They were asked to state whether or not they considered momentum to be conserved in this situation and how much they believed that they were correct on a scale of 1 (not at all) up to 6 (totally sure). Where the student had indicated that they thought momentum was conserved, they were asked to explain how their thinking could explain the conservation. They were also asked to give a believability rating for their theory based on the same six point scale. The reasoning given by the students were grouped into nine main categories which are shown in the interview analysis sheet in appendix 5. The theoretical stance of each student was tracked after they had examined each analogy and their final theory and belief ratings were examined after they had completed the series.

The student-driven nature of the interviews, in terms of the direction in which each section progressed, resulted in a need to explore the thinking of students in some depth using extended questions. This made progress through the sequence slower than initially anticipated. The main benefit of this was that more detailed and potentially useful data was obtained. However, due to time constraints outwith the control of the researcher and the participants in some of the interviews, not all of the students were able to work through all five of the analogies. A few of the interviews therefore only got as far as dealing with analogy 4 before having to jump to the review phase. Any interviews that did not get as far completing analogy 4 were deemed to be only partially complete and were therefore discounted for analysis purposes. This was the case for interviews 3, 33 and 53.

Table 6.1 below, shows the initial and final theories given by each of the participants along with their self-assessed belief rating in their theory. It can be seen from the entries that many of the students had changed their ideas markedly by the end of the sequence and that they had therefore encountered a degree of conceptual change as a result of working with the bridging analogy sequence. For some of the students, their personal theory had not changed much but their belief rating had increased, showing that their thinking had been changed to some extent. As might be expected however, not all of the students' made progress towards the accepted theory regarding the explanation for considering momentum to be conserved when an object collides with an apparently immoveable object.

The entries in the theory columns of the table briefly summarise the views stated by each student, both prior to, and immediately after, working through the analogical sequence. In cases where a student decided that momentum was lost, this was indicated by entering "lost" along with any mechanism that was stated by the student given in brackets. So, in the situation where a student stated that momentum was lost as a result of heat and sound energy being given out, the entry made was "lost (heat & sound)". Students 20, 47, 57 and 62 gave two opposing initial theories, both of which are entered in the table. In these cases, the initial belief-rating is given alongside their main theory, although student 47 gave a rating for both of her theories. Only student 21 initially stated that she thought that the momentum stayed in the car, which she felt could be explained by virtue of its recoil from the building after the collision. This was entered as "stays in car".

Many of the students initially stated that they thought momentum was transferred to the building. The means by which each student considered this to have occurred (where this was mentioned) is given in brackets. In several cases, students felt that at least some momentum was transferred into the building but could not identify a mechanism for its transfer. In such cases, the entry in the table was "transfer (unclear)". Many students initially stated that, in their opinion, momentum was transferred through the building but were only a little more specific when they indicated that it was transferred to the bricks or the wall as a whole in some indeterminate way. Other students were more specific and indicated that damage to the building, bending or denting of the surface was the result, and an indication of the transfer of momentum to the wall. Some students indicated that they thought there would be vibrations, shaking or a shockwave. In each of these cases the students' suggested mechanism was recorded in brackets after the word "transfer". Students 2, 35 and 46 indicated that their ideas were a guess, and so this was signified by placing a question mark after their idea. Students 44, 46 and 47 initially stated that they felt that the entire building would move in some way and so this was indicated by the word “movement” in their entries. In one case (student 5) the initial theory stated was that momentum got transferred into the building via vibrations and by the force of the car hitting the wall. This was entered as “transfer (vibrations & force). Student 40 gave a similar reason when he said that he thought that momentum was transferred to the building but then became a force. This was therefore entered as “transfer (becomes force on building)”. Students 35, 46 and 63 suggested in their initial ideas that they thought that the momentum would eventually be transferred via the wall, bricks or movement of the entire building, to the ground and thus ultimately to planet earth. This was signified by recording the word “earth” as part of their entry. For example, student 35 had “transfer (bricks-earth?)” recorded for his initial theory, which indicated that he was guessing that the momentum was transferred to the bricks and then to the ground in some unspecific way. In a few cases, students also stated that the building (or parts of it) would have a very small velocity, since it had a very large overall mass. If they hinted at this, without stating it clearly, then this was recorded by entering “big m, small v – vague” in the table. If instead, they made direct and clear reference to this, then the corresponding comment entered was “big m, small v – clear”.

After the analogies had been worked through, all of the students indicated that they considered at least some of the momentum had been transferred to the building and in most cases they were giving a more detailed mechanism by which they thought this had occurred. Where the mechanism was not clear, the same nomenclature of “transfer (unclear)” was used. As can be seen in the table 6.1, the majority of students gave a more detailed, and theoretically more accurate, mechanism for the transfer of momentum to the building after they had worked through the analogical sequence. Where this occurred, it was indicated pictorially in the final theory column of the table by appending the symbol [↑] after their final theory. Where a student had not changed his or her theory, the symbol [↔] was placed beside their final theory. The final theory given by student 4, for example, was not markedly different from his initial idea, although it did include the idea that momentum may be transferred to the building which he had not mentioned initially [↔]. By the end of the sequence, student 6 had decided that momentum was not conserved when the car struck the wall, despite having said initially that it was. The symbol [↓] was used to indicate this change to an incorrect response. The final theory given by student 35 had become less detailed, and so the same symbol [↓] was used to indicate this decrease in theoretical accuracy. Similar symbols have been included in the final column of table 6.1 along with the final belief ratings of each student. This was done in order to give a quick and clear indication of whether a particular student's belief-rating had increased, decreased or remained the same by the end of the sequence, in comparison with their rating of their initial theory.

After working through the analogical sequence, all of the students had decided that momentum was being transferred to the wall. Several students were unsure how the momentum had been transferred, in which case the entry "transfer (unclear)" was recorded for the final theory given by that student. In many cases however, a specific method of transfer was given by a student. In these cases, the final theory entries do not include the term "transfer", in order to save space; only the stated method is given. The entry "brick-brick" signifies where a student had stated that they thought momentum was transferred from one brick to the next through the building. Student 51 specifically indicated that she thought that the transfer of momentum from one brick to the next was by means of vibrations. This is therefore reflected by the final theory entry for her in the table. Student 35 discussed the transfer of momentum from one atom to the next in succession across the width of the building, and this was therefore recorded as "atom-atom". Several students indicated that they thought that the momentum was passed through the bricks of the building and ultimately got transferred to the ground. The entry "brick-brick-earth" was made in their row of the table. A few of the students had more than one final theory, in which case, both ideas were noted and the belief–rating for their main theory was recorded. As was the case for the initial theories, an entry was also made to indicate when a student discussed the significance of the building's large mass in relation to the velocity of any movement, and whether or not this indication was vaguely or clearly stated.

No.	Higher Grade	Initial Theory	Belief Rating	Final Theory	Belief Rating
1	B	Shared & Transfer (unclear)	4	Brick – brick **[↑]**	5 **[↑]**
2	B	Transfer (vibrations?) Wall – earth	4	Brick – brick – earth **[↑]** (Big m, small v - vague)	4 **[↔]**
4	Fail	Lost (heat & sound)	2/3	Transfer (unclear) then lost (sound) **[↔]** (Big m, small v - vague)	3/4 **[↑]**
5	B	Transfer (vibration & force)	3	Brick – brick **[↑]** (Big m, small v - vague)	5 **[↑]**
6	B	Enters wall then back into car	1	Enters wall then back into car Momentum lost **[↓]**	4 **[↑]**
7	C	Lost (heat & sound)	2	Transfer (unclear) **[↑]**	2 **[↔]**
8	Fail	Lost (heat & sound)	3	Some transfer (shaking) **[↑]** & some lost	5 **[↑]**
19	Fail	Transfer (unclear)	2	Transfer (unclear) (Big m, small v - clear) **[↑]**	2 **[↔]**
20	B	Lost Maybe some transfer?	3	Transfer (unclear) **[↔]** (Big m, small v - vague)	4 **[↑]**
21	A	Remains in car	2/3	Brick – brick **[↑]** (Big m, small v - clear)	5 **[↑]**
22	B	Lost (heat & sound)	2	Transfer (unclear) **[↑]** (Big m, small v - vague)	5 **[↑]**
25	F (WD)	Lost	3	Brick – brick – earth **[↑]** (Big m, small v - clear)	4/5 **[↑]**
28	F (WD)	Transfer to bricks	5	Brick – brick – earth **[↑]** (Big m, small v - clear)	6 **[↑]**
29	F	Transfer (bending wall)	1	Brick – brick **[↑]** (Big m, small v - clear)	5 **[↑]**
34	B	Transfer (shockwave)	5	Brick – brick – earth **[↑]** (shockwave) (Big m, small v - clear)	6 **[↑]**
35	C	Transfer (atom–atom-earth) (Big m, small v - clear)	6	Atom – atom **[↓]** (Big m, small v - clear)	5 **[↓]**
40	C	Transfer (becomes force) (Big m, small v, vague)	5	Through wall – earth **[↑]** (Big m, small v - clear)	5 **[↔]**
41	B	Transfer (unclear)	3	Brick – brick – earth **[↑]** (Big m, small v - clear)	5 **[↑]**
43	C	Transfer (shockwave) (Big m, small v - clear)	5	Brick – brick – earth **[↑]** (Big m, small v - clear)	5 **[↔]**

44	A	Transfer (movement) (Big m, small v - clear)	2	Brick – brick [↑] (Big m, small v - clear)	4/5 [↑]
46	B	Transfer (movement–earth?) (Big m, small v - clear)	3/4	Brick – brick – earth [↑] (Big m, small v - clear)	4 [↑]
47	B	Lost (heat) Transfer (movement)	4 3	Brick – brick – earth [↑] (Big m, small v - clear)	5 [↑]
48	A	Lost (becomes energy)	1	Brick – brick – earth [↑] (Big m, small v - clear)	5 [↑]
51	B	Transfer (dent)	4	Brick – brick, vibration [↑]	5 [↑]
52	B	Lost	1/2	Transfer (unclear) [↑]	4 [↑]
57	F	Lost May transfer (damage)	3	Brick – brick [↑] (Big m, small v - clear)	4 [↑]
58	F (WD)	Transfer (unclear)	4	Transfer (unclear) – earth [↑]	4 [↔]
62	F (WD)	Lost May transfer(unclear)	 2	Wall-earth [↑] (Big m, small v - vague)	5 [↑]
63	A	Transfer (wall - earth) (Big m, small v - vague)	5	Wall - earth (Big m, small v - clear) [↑]	5 [↔]
64	F (WD)	Transfer (unclear)	2	Brick – brick – earth [↑] (Big m, small v - clear)	3/4 [↑]

Table 6.1: Initial and final immoveable wall theories and belief ratings for each student

6.2 Analogy one

As discussed in the methodology chapter, the first analogy in the immoveable object sequence involved running one ball-bearing into another identical one. This was deliberately intended to be a distant analogy of the car colliding with the building since, unlike the building, the second ball-bearing was clearly observed to move after being struck by the first. It is therefore not surprising that this analogy was only specifically mentioned by two of the students as having been instrumental in coming up with their final theories during the review of the sequence.

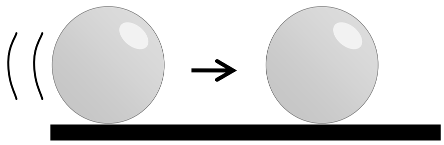


Figure 6.1: Analogy 1 - Ball running into identical ball.

Analogy one gave the students an opportunity to think about a collision in which it was relatively obvious to the majority that momentum was being conserved. As has been discussed above however, the links between the analogy and the target situation of a car colliding with an apparently 'immoveable' building were not particularly obvious. Consequently, most of the students only identified similarities that could be classed as being at a 'surface' level, but were able to identify differences, including the key one that the second ball-bearing clearly moved after the collision, in contrast to any perceivable motion in the case of the building. As a result of their perceptions of the similarities and differences between the analogy and the target, many students did not demonstrate any change in their conceptual theory as a result of this analogy, other than an increase or decrease in their belief rating about conservation of momentum when a car hits a wall. Of those students who thought that momentum was conserved in the target situation, five decreased their belief rating, three increased their rating, while several either stayed the same, or they did not give a belief rating after the analogy to enable an assessment to be made. Two students were found to have been negatively affected as they changed from considering that momentum was conserved when the car crashed into the building, to considering it to have been lost. However, for three students, the analogy resulted in a positive conceptual change, as it assisted them to change their theoretical stance to one which was closer to the accepted scientific idea.

Figure 6.2 below, contains two charts which summarise the number of students who stated each of the ‘immoveable’ wall theories that were identified in the transcripts. These were the students’ ideas about what happened to the car’s momentum when it struck the building in the target scenario. Each theory was allocated a code (see table 6.2) in order to make the charts easier to read. Figure 6.2a shows the number of students who stated each theory prior to working through any of the analogies from the bridging sequence; and figure 6.2b shows how many students were enunciating each theory at the end of working with analogy 1. The differences between the two charts indicate the overall level of conceptual change that resulted from the thirty students’ interactions with the first analogy. It should be noted that several students had more than one theory at several stages throughout the sequence and so the total number of students indicated does not add up to thirty in each chart. For example it was common for students to state that momentum was both lost and transferred to the building.

‘Immoveable’ wall theory	Theory Code
Momentum lost	A
Momentum stays in car	B
Momentum shared between wall and car, unclear method	C
Momentum transferred to wall, unclear method	D
Momentum transferred to wall, vague mention of large mass, small velocity	E
Momentum transferred to wall, clear mention of large mass, small velocity	F
Momentum transferred to wall, brick to brick	G
Momentum transferred to wall, brick to brick, clear statement of large mass, small velocity	H
Momentum transferred to wall and then transferred to earth	I
Other	J

Table 6.2: Codes for the ‘immoveable’ theories expressed by students which are in the charts showing the numbers of students who enunciated each theory at the end of each analogy in the sequence.

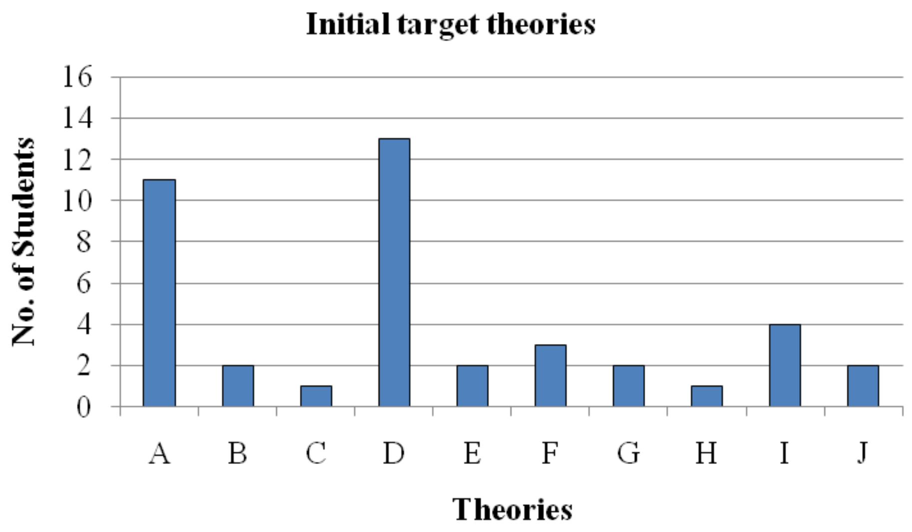


Figure 6.2a: Number of students stating each ‘immoveable’ wall theory prior to working with the analogies.

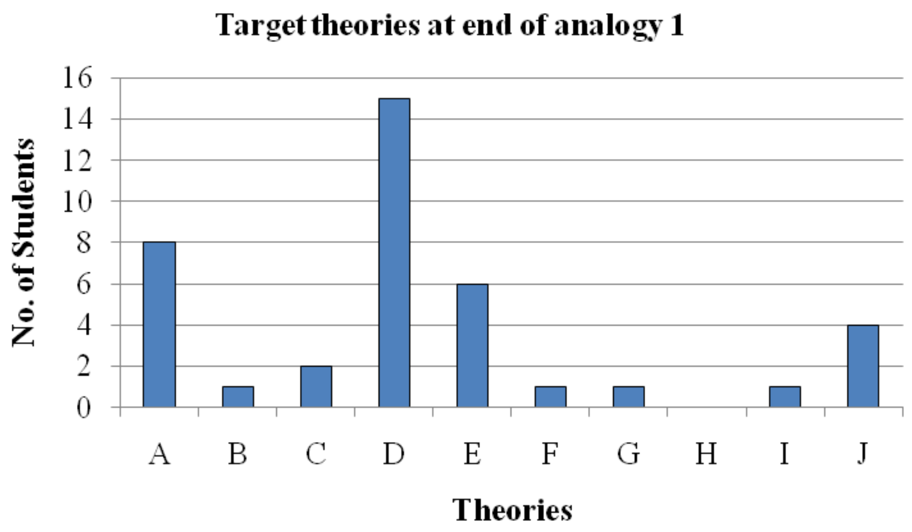


Figure 6.2b: Number of students stating each ‘immoveable’ wall theory at the end of analogy one.

Conservation of momentum was clear to the majority of students in the first analogy. Apart from students 4 and 8 (both of whom showed little or no sign of conceptual change throughout the sequence), all of the students (including those whose initial idea was that momentum was being lost when the car struck the wall) stated that they felt that momentum was conserved when the ball bearings collided. This had been the intention of including this analogy as it made the concept of conservation of momentum more accessible and visible, since the second ball clearly moved off with almost the same velocity as the first had beforehand and the first ball moved very slowly after the collision.

Students 4 and 8 were the only ones who stated that momentum was not being conserved when the two ball-bearings collided. Student 8 said that this was because some of the momentum was transferred to the second ball, but he thought that some was lost because energy was being lost.

I: Now, in terms of the total momentum before that crash happened, compared with after when both balls were then moving, how do those totals compare? So both balls are involved after, only one before. How does the total before and after compare, do you think?

S8: There would be slightly less momentum.

I: When?

S8: After.

I: Why?

S8: Because there is energy lost.

I: So, you are saying momentum becomes energy? Is that what you're saying? Or momentum is energy?

S8: Becomes.

I: Now, what would you say was happening in that collision to the momentum? You're saying some of it becomes energy, what about the bit that doesn't?

S8: It gradually loses the rest.

I: Of the momentum? I'm talking about just after the collision has happened.

S8: It keeps momentum and keeps moving. It transfers, some of the first ball's momentum transfers to the second ball.

I: How sure are you of that idea on a scale of one to six?

S8: Five.

I: Fairly sure. Why are you so sure?

S8: Because the first ball is moving and then slows down when it hits the second ball and the second ball starts moving, so I think it would be transferred.

I: Now, in terms of this idea of not all the momentum being there after the collision, immediately after compared with immediately before, how much are you rating that?

S8: Three.

His difficulty centred on a struggle to differentiate between momentum and energy. In his mind, the two ideas were so strongly inter-connected, and therefore overlapped so much, that he could not separate them. As a consequence, he found it very difficult to consider momentum conservation as being possible when it was clear to him that energy was being lost as sound. Student 4 demonstrated, by his comments, that he harboured the same misconception, which resulted in him exhibiting a very similar, incorrect reasoning process. After discussing his thoughts about the car hitting the wall, he conceded that he was using the concepts of momentum and kinetic energy interchangeably. He realised that this was not a valid thing to do, but he was unsure how he could describe what was happening in terms of momentum.

I: Ok. How would you use that situation to try and explain this to someone? Could you?

S4: Hmm, …, if, …, if this ball was held, maybe, with a hand, then that was rolled.

I: Into it?

S4: Into it, then I would think I would be able to explain it, but I think, …

I: So, what would you say?

S4: Em, I would say then this would, eh, the second object has a greater mass, or has a greater weight, in terms of the first one, so the first one when collides, eh, doesn't cause much damage to the second object because it has a greater mass and eh, …, its the same as eh, an example, a car colliding, a car coming with a greater speed can collide with a bus but the car would have more damage, because the bus has a greater mass.

I: Is momentum conserved if you did that?

S4: Momentum is lost, it's not conserved, I think.

I: It's not conserved if you crashed a car into a bus?

S4: … Em, it's not conserved because it's lost due to, again, sound and heat.

I: So, that would still be how you would be explaining this to somebody. How convinced are you that the explanation is right?

S4: I'm not as convinced – a three or a two.

I: So it's gone down a bit?

S4: Yeah, because I think, what I'm trying to explain is the momentum, is eh, …, instead of momentum, I'm trying to explain the eh, …, energies, and I'm using the energy laws to explain momentum, …, eh, that's why I'm going down the scale.

I: So, are you not sure that that's the right way to do it or what?

S4: I, …, I'm kind of convinced what I'm using, is of the energies, the laws of the energies, it's not the momentum I'm using.

I: So, can you think of a way to use the momentum logic, as you have said?

S4: Momentum, …, eh, I don't think that eh, …, velocity, …, I don't think I could explain momentum right now.

6.2.1 Conceptual difficulties encountered by students in relation to analogy one

Several students, who decided that momentum was being conserved in the analogy, were initially confused by the change of speed in the first ball, as the following excerpt from the interview with student 58 demonstrates. When asked to say how the total momentum prior to the collision compared with the total afterwards, she gave the following answer.

S58: Eh, the momentum of the first one immediately before is a lot, greater than immediately after.

I: But if you take both balls into consideration before and after?

S58: Eh, ..., I would say there is less because the second ball isn't going as fast as the first one did.

I: But is the first ball still moving after it hits?

S58: Yeah, …, oh sorry, yeah I suppose they are equal.

I: How sure are you that they are equal or do you still think they are a bit less?

S58: About a four, that they are equal?

Her difficulty, along with the several other students, was centred around her concentration on just the first ball. This gave the impression that she felt that momentum was being lost as a result of her 'single object' thinking. Once she was guided to consider both of the balls as part of an inter-connected system, her view changed and she decided that conservation of momentum was in fact occurring. In order to check that she was now thinking in terms of the system of both balls, rather than just one, and to make sure that she had not just changed what she had been saying to accommodate the interviewer's views, she was then immediately asked to explain what she thought was happening to the momentum of the first ball as a result of the collision.

I: So, tell me what is happening to the momentum from the first ball as a result of the collision?

S58: It's becoming less; there is less momentum in that.

I: In the first ball?

S58: It's kind of transferred the momentum to the second one.

I: How sure are you that that is true?

S58: About a four.

From this statement, it was clear that she had grasped the concept that momentum was conserved when the 'system view' of both objects was taken into consideration. This was further confirmed by her self-assessed belief-rating of a four.

Student 29 demonstrated inconsistent thinking during the analogy. He changed from initially saying that momentum was lost, to briefly thinking that the total momentum was greater after the collision than it had been before. The main reason for his struggle was that he found it difficult to visually compare the speed of the first ball before and after the collision, until he was encouraged to roll the first ball reasonably quickly, which made its change in velocity much more obvious. At times he appeared to be mainly guessing in order to come up with answers and did not appear to be good at applying logic to the situation. However, as can be seen in the excerpt below, he eventually concluded that momentum was conserved, but he only managed to resolve this fully when he described what he thought was happening in terms of numbers, which helped him to think it through and explain what he was thinking.

I: What happens to the momentum of the first ball when it comes in? Tell me from the beginning. It's got momentum and it makes contact with the second ball. What happens?

S29: The momentum would be a lot less in the first ball.

I: So it loses momentum?

S29: Yeah.

I: And where does that momentum go?

S29: Into the second ball.

I: Now, what you're saying therefore is that momentum of the first ball comes in, it loses some and the second ball gets some. How much does it get, compared with what that loses?

S29: It would be, well the first ball hits the second one, if it loses some, the rest of the momentum will be carried on to the second ball.

I: So you're saying whatever this one loses, that one gets it? Is that what you're saying?

S29: No. The total momentum of the first ball, and whatever it loses will be taken away from the total, and then whatever the rest is, will get carried on into the second ball. Does that make any sense?

I: Explain it a wee bit more. So, let's say it comes in with ten units. It hits the second ball. Tell me in terms of numbers what you think is going on.

S29: Say the momentum after the collision of the first ball is at two.

I: So, it has dropped from ten to two.

S29: And then the other eight is carried on into the second.

I: So, it gets the eight that that has lost?

S29: Yeah.

I: So, what is the total before, compared with the total after?

S29: The total before will be more. The total before will be ten and that will be eight because that will be stationary.

I: But you said that that still had two didn't it?

S29: Yeah.

I: So, what do you think?

S29: It would be the same.

I: How sure are you because you have come at it from a twisted route there? Give me a confidence rating.

S29: Five.

I: That's quite strong, considering a minute ago you were saying more and then less.

S29: I know.

I: So why are you now so sure it is the same?

S29: When we were doing the calculations.

I: So, because I have used numbers; that has helped you to see it?

S29: Yeah.

I: Even though they're just imaginary numbers?

S29: Yeah.

The similarities identified between this analogy and the target situation can predominantly be deemed to be at the 'surface' level. Students tended to concentrate on the idea that the first ball collided with the second as did the car with the building. Only nine of the nineteen students who had already stated that they considered momentum to be conserved in the target situation mentioned the 'deep' (theory level) similarity of momentum conservation in both the analogy and the target. In terms of the reasons given by Spiro et al. (1989) for the potential reasons for the failure of an analogy to assist a learner, this relatively poor result would be an example of the tendency to focus on surface, descriptive aspects of the analogy, which results in a failure to identify the same underlying causation in both the analogical and target domains.

Two differences between the analogy and the target were commonly identified. The first difference was that the car would rebound from the building, but the first ball continued to move in the original direction. The second commonly identified difference was that in the analogue, the second ball clearly moved afterwards, while in the target, the building was either considered not to move at all, or to only move by an imperceptibly small amount. Student 46 discussed the 'deep' similarities and both of these differences. He qualified his reasoning about the similarity of the conservation of momentum by drawing attention to the degree of movement in the wall being markedly different to the movement of the second ball.

S46: Em, …, There's not many similarities, I think, because the ball doesn't go backwards, like the first ball which I pushed in to it doesn't go backwards, and the second ball actually moves as well.

I: Mmm, hmm.

S46: And, …, momentum's conserved.

I: So is that a similarity - that momentum's conserved?

S46: Uh, huh.

I: Is there any similarity in how they act, or do you think that they're just totally different? … The first ball represents what?

S46: The car.

I: And what does the second ball represent?

S46: The building.

I: Do you think there's any similarity in those or do you think they just represent them but not very well.

S46: No, they are similar, but that's, … It's not like in proportion. That should be a really heavy ball, compared to that one. And, that should be like rooted to the ground.

I: To be more like the building?

S46: Uh, huh.

In a similar manner, student 43 implied the 'deep' similarity of some momentum being transferred to the building by the car. She also correctly pointed out differences between the analogy and the target, but her answer showed that she could use these differences as part of her explanation about what happened to the building. As a result of acknowledging and working with these differences, she found the analogy to be 'fruitful', as suggested by Posner et al. (1982), as she could use it to help explain what she considered to be happening when the car struck the building.

S43: Em,…, well the fact that you know the car would probably bounce back means that it keeps some of the momentum, so that's a similarity. The difference is that the building isn't going to slide across the tarmac, whereas the ball did.

I: OK. Could you use this to explain what's going on here to somebody in any way?

S43: I could try. Em, …

I: To someone that didn't understand what was going on, what would you be saying to them?

S43: I'd probably be saying that, you know, here's your car coming along, there's your building, ..., no, ..., I don't know. Hang on, I'll think about it, ... It's the fact that, that moves that, kind of. I'd probably say 'The reason that moves, whereas the building wouldn't, is because of the fact that it's not stuck, the ball's not stuck down, it's in a shape that it's supposed to be able to move, whereas the building is made not to move, and since it's a lot bigger and what's being transferred to it isn't enough to make much difference, whereas the ball's the same size as the ball that went in to it.'

6.2.2 Negative conceptual changes resulting from interaction with analogy one

While discussing the target scenario, prior to engaging with any of the analogies, student 35 had stated that momentum would ultimately be transferred to the world.

S35: The momentum will have to go somewhere so the car will possibly wheel backwards and part of the momentum will go into the wall. It might be a bit hard to believe at first.

I: How would you explain the momentum going into a big building or a big wall?

S35: It makes the world move a tiny bit. It is pretty unnoticeable but it does happen.

I: Where did you get that idea from?

S35: From my teacher.

I: How much do you believe that, on a scale of one to six, the idea that momentum is going into the wall and makes something happen to the world on that scale of one to six?

S35: Six.

I: Why do you think that?

S35: Because we have been told that energy is a constant, by Newton and of course it hits the wall, we would have to say that energy has to go somewhere.

I: Remember it's momentum we are particularly interested in so tell me about momentum. How does the momentum get into the wall in your opinion? How is it being transferred?

S35: By the collision.

I: How is that happening? How would you explain that to somebody?

S35: When the car hits the wall, the energy will be transferred through the car to the wall and that will either make the wall move or make it fall apart.

I: Now when you say the wall moves, or the building moves, do you think the building moves?

S35: In a global scale, in a universal scale, by a tiny amount so it is pretty unnoticeable.

I: But you think it does do it?

S35: It does do it.

I: And do you think that is the same idea with the momentum?

S35: Yeah.

His justification for this position was primarily based on the premise that his teacher had told him this and therefore he believed it. While talking about the first analogical situation, he continued to describe a universal view of the transfer of momentum in the following way.

I: OK. Now you are saying that the momentum of this ball does what when it hits the other ball? What happens to its momentum?

S35: It gets transferred.

I: From where to where?

S35: From that ball to that ball.

I: OK. And how sure are you of that?

S35: Pretty sure. Four.

I: So why are you less sure of that?

S35: I'm just not really certain.

I: What is worrying you about that, as opposed to the total amount of momentum being the same? You seemed very sure about that.

S35: Because there is more to the experiment here. This wooden bit here so it could be transferred to an unlimited amount of places, there is the air…

I: Are you sure that there is momentum being transferred from this ball to other things?

S35: Yes.

I: How sure are you?

S35: Very. Six.

I: So, you think some is going into that ball and some is going, maybe where else?

S35: Into the wood, into the air, into the drag produced by the air.

This was a very confident start, but it then became apparent that he was confusing energy and momentum with one another as shown in this subsequent extract.

S35: Energy is like the unit that exists, momentum is just the way we describe it.

I: Describe what?

S35: The motion.

I: So what is the difference between that and kinetic energy because you could say kinetic energy describes motion as well, measures it in some way as well.

S35: Kinetic energy is what we would use instead of momentum to say 'well that car is moving that way'.

I: Can you not use momentum to do that?

S35: Momentum, …

I: What is interesting is you keep switching between the two.

S35: It's confusing me.

Despite his initial certainty and confidence, it became very apparent during analogy one (and several other stages of the interview) that this conceptual overlap caused him a great deal of difficulty which initially became apparent at the point when he was asked to describe how the first analogy compared with the target scenario. The preceding discussion had moved him away from merely repeating what he had been told by his teacher to having to justify his own thinking. It also transpired at this stage that he was not really thinking in terms of a universal scale of transfer as he stated that the wall would not move.

I: What similarities or differences do you see between this and the car crashing into the wall?

S35: The similarity here is they both collide, the energy still goes somewhere. The only difference is, if this was the wall, that wouldn't move.

I: At all?

S35: It might move a little bit, but the energy being produced would go up my finger.

While trying to explain his thinking about the comparisons between the analogy and the target he also started to discuss elastic and inelastic collisions.

I: OK. Now we were talking about similarities and differences between this and the car hitting the wall. You mentioned that this ball moves and the wall doesn't move. Doesn't move at all or just less?

S35: If I put that [the ball-bearing], if that was the car, there is chance that the car might, …, I don't know if that is elastic or not but this is inelastic. It won't keep moving.

I: Do you think the car hitting the wall would be an elastic, or an inelastic collision? What is the difference?

S35: I would say it's probably elastic.

I: That [shows student the picture of the car rebounding from the wall] is what you have described after where it bounces back. So that is pretty much what you are talking about. What is an elastic collision?

S35: Where it would bounce back.

I: Is that the definition of an elastic collision?

S35: No.

I: What is the definition?

S35: The momentum will be different after. It won't all have went [sic] away. The energy won't have settled either.

I: So what's the difference between an elastic, and an inelastic collision? Definition-wise?

S35: The momentum is, …

I: You should have been given a definition.

S35: The momentum in an inelastic collision is conserved.

I: What about in an elastic one?

S35: The momentum wouldn't be conserved.

I: So why did you say earlier then that you thought that momentum is always conserved?

S35: Because I'm really confused right now. I don't know.

It became clear from this interaction that he was actually rather unclear about conservation of momentum as he changed his mind about it several times during this analogy. He had a tendency to mention many different things that he had heard in lessons (including an out-of-context reference to quantum mechanics during the initial stages of the interview). The analogy was useful in the sense that it had unsettled his thinking, arguably because he knew what to say but did not really understand it or believe it. This caused him to rebuild his thinking as will be seen in his interaction with the subsequent analogies.

Three of the students clearly found the first analogy counter-productive as they changed their views about the target situation from considering momentum to have been conserved, to saying, after the analogy, that they thought that it was not being conserved. Of these three, student 62 had initially given mixed messages, regarding whether or not she thought momentum was conserved in the target scenario. When asked to state what her overall feeling was, she said that she thought that momentum was conserved and rated her belief in this at level 3. However, after tackling analogy one, she then stated that momentum was not being conserved when the car hit the wall, despite rating herself at level 5 for momentum being conserved in the analogy. Her reasoning for this belief was based on logic and the intelligibility of the analogical situation, as the following quote shows.

I: Why are you so convinced about this one?

S62: Because it just seems logical that if both of them are moving after the impact but the first one slows down then it seems logical that momentum is conserved.

In contrast with this, her main difficulty in using the analogy was that she could not see any connections between the analogy and the target, other than both involved collisions between two objects. Her main source of cognitive conflict was in terms of the suggestion from the analogy that there would have been some movement for the wall.

I: How does that compare with the original situation of the car hitting the brick wall? I want you to tell me any similarities or differences you think there are.

S62: The wall doesn't move in the one with the car but the ball bearings both move, so momentum is conserved. Because the wall is stationary, momentum isn't conserved but because both the balls have the ability to move then they are conserved.

I: So you see them as quite different do you?

S62: Yeah.

I: Do you think there are any similarities?

S62: In that there is an impact.

I: But that is about it?

S62: Yeah.

The idea of the wall gaining momentum was not intelligible enough for her and so lack of sufficient similarity between the target and the analogy put her off the idea. She did not perceive the analogy as sufficiently similar to the target in terms of its finer detail and therefore it caused her to deduce that her original, rather tentative, hypothesis must have been incorrect.

Student 58 experienced the same struggle in trying to come to terms with the wall moving, despite being happy to state that the momentum that the car lost was transferred to the building, prior to encountering the first analogy

I: Ok, so, going back to this then, what are the similarities or differences that you think there are between the balls hitting together and the car hitting the building?

S58: Eh, probably the momentum of the car, when it hits the brick wall is the same as when the two balls hit because it goes from having, …, like a lot of momentum to having basically no momentum, …, but the difference of the brick wall is that you can't see where momentum has gone that you have lost.

I: So, in terms of the car hitting the brick wall, what are you saying about the total momentum before and after, what is your current thoughts on that?

S58: Eh, I would say that before there is a lot more momentum than there is afterwards.

I: In total?

S58: Yeah.

I: So, there is some getting lost?

S58: Yeah.

I: Even when you take the wall into consideration before and after as well?

S58: Yeah, because if it took all the momentum of the car, it would be enough to shatter the wall, …, it would try and keep moving, …, but, because it is rooted it would just fall apart.

I: So, you are saying that because it is not obviously moving, it's not got enough momentum to account for what that has lost. Is that what you are saying?

S58: I think so. I think because you can't see what's happened.

I: So you have changed from saying the total momentum before and after is the same, to going back to saying, as you did at the beginning, that you think some is getting lost. Is that what you are saying?

S58: I think so. I'm just not at all sure, at all. It's all really confusing.

In essence, the two ideas were too far removed from one another to allow a strong enough connection to be made between them. S58's thinking regarding the analogy itself was inconsistent (as discussed above) in that she changed her mind about whether or not momentum was being conserved, as she switched between a 'single object' and a 'system' view of the collision. Ultimately, she struggled because the result of the collision in the analogy did not connect with her experience of objects hitting large objects, which she expressed in terms of not being able to 'see' the same thing happening when the car hit the building. This meant that she felt that there were features of the analogy that did not correspond with the target situation, which resulted in cognitive conflict that she could not resolve at that stage.

Likewise, student 20 struggled at the end of the first analogy, to decide whether or not he thought that momentum was conserved when the car hit the wall, despite having been content that momentum was conserved when the two ball-bearings collided. As with other two students, he decided that momentum must have been transferred to the wall, but he also felt that some momentum was being lost as he could not envisage the wall moving in any way.

I: So what is your story then for this one [the target situation] about momentum at the moment? Is it conserved or isn't it, in your opinion?

S20: I don't think it is conserved.

I: Give me a rating.

S20: A three. I'm really not sure.

I: What is happening to the momentum of the car?

S20: It's decreasing, …, that's the thing that's getting me. To me, the momentum in the car is decreasing, …

I: When it hits this?

S20: Yeah, so it must be giving momentum to the wall.

I: So, you think the wall is getting momentum? How sure are you?

S20: Three again.

I: Why are you struggling to take that on board?

S20: Just because it's not moving.

In a similar manner to student 58, he struggled to connect the principle behind the analogy with the target situation as there were features of the analogy that did not correspond sufficiently closely with the target situation. This resulted in cognitive conflict that he could not resolve at that stage.

6.2.3 Non - changes resulting from interaction with analogy one

Four of the students had been happy to state that they felt that momentum was conserved in the analogy, but had not changed their minds regarding the target situation, where they still considered their initial view, that momentum was being lost, to be correct. Conservation of momentum had been intelligible for them in the case of the analogy itself, but they could not transfer this concept to the target. For students 21, 25 and 47, the stumbling block to transfer was that they could not imagine the building moving at all. The following excerpt shows how this problem resulted in student 21 not being able to change her views regarding the non-conservation of momentum in the target scenario.

I: Do you see any links between that and this situation? You can mention similarities or differences.

S21: Well, there is not that many similarities because they [the two ball-bearings] can both move and the wall couldn't move so I don't know…I find that [the analogy] easier to understand because I can actually picture it happening whereas something going into a wall I don't picture that happening so much because I have never really seen it.

I: So what does the first ball represent?

S21: If it was compared to that situation?

I: Yeah.

S21: It would be the car and that would be the wall.

I: But you don't see that second ball as being like the wall?

S21: No, unless I was holding that still and I did that. I don't know if that would help.

I: Tell me what you think, if you did that.

S21: [Tries experiment while holding the second ball].

I don't know. For a start, that rebounded a wee bit or stayed the same, and this felt as though, because of the power of the collision, felt as though it was going to move but because I held it in place like the building would be in place, the mass was too big for it actually to move.

I: Did it move at all?

S21: Yeah, a teensy bit.

I: Is that like this at all do you think?

S21: I don't know if it is really possible for the building to move or not, or a wall.

Her difficulty could be viewed, in terms of the problems listed by Spiro et al. (1989), as being caused by having an important aspect of the target missing because the second ball-bearing was free to move. However, even after identifying this issue for herself, and trying out her own suggested modification, she was still unable to envisage the wall gaining any momentum. Consequently, she experienced cognitive conflict when she tried to make connections between what she could see, and believed was happening in the analogy, and what she thought would happen in the real-life situation. The concept of movement in the wall was too far-fetched for her to make that connection with the analogy.

In a similar way, student 52 still clearly had difficulty in imagining the wall gaining momentum as shown by the following statement that he made when he was comparing the first analogy with the target situation. In addition however, the concepts of momentum and energy significantly overlapped in his mind, which resulted in a further difficulty in using the analogy to make progress.

I: Now, tell me then what your thoughts are with this collision at the moment the car hitting the building. Is momentum being conserved or not, in your opinion?

S52: Not.

I: How sure are you?

S52: Four.

I: Has that gone up?

S52: Yeah.

I: Why?

S52: Because I have seen this collision, and I have seen the end. Because I saw the second ball move off at the same velocity, therefore possibly the same momentum, if you eh, …, maybe momentum is conserved? So if you look at the impact of the car and the wall, eh, …, the wall does not have momentum, so it can't be conserved.

He had actually become slightly more convinced that momentum was not being conserved when the car hit the building, after working through the first analogy.

Both before and after tackling the first analogy, student 47 had suggested that some of the momentum from the car would be transferred to the wall, but she thought that not all of the momentum that the car lost would have gone into the wall. The extract below shows that she also felt that the wall would not move, unlike the second ball-bearing in the analogy. Initially she had stated that the missing momentum would have been lost as heat energy but, after analogy one, she felt it would have been lost, since kinetic energy was being lost in the collision.

S47: I still think it wouldn't be completely conserved.

I: Ok.

S47: Due to the fact that the brick wall didn't move.

I: Ok. In terms of a belief rating for that, what would you give it?

S47: Three/four.

I: So fairly sure it's not. Ok. What are you saying in terms of the momentum, are you saying, what happens to the momentum of the car in other words, is what I'm getting at?

S47: The momentum of the car would be less once it's hit the wall.

I: And what happens to the bit that becomes less, that comes out of the car, presumably?

S47: It somehow gets to the wall.

I: All of it, or some of it?

S47: Some of it.

I: And why do you think just some of it, and not all of it?

S47: Some of it might have something to do with the kinetic energy, and that could be lost through the collision.

The conceptual connection between momentum and energy in her mind was evidently quite strong and the analogy was not sufficiently convincing to make her break that connection and form a new, more accurate one, whereby momentum was thought to be different from energy and could be conserved as a result of transfer to the wall.

6.2.4 Positive conceptual changes resulting from interaction with analogy one

Three students, who had initially stated that they considered momentum to be lost in the situation where the car crashed into the wall, had changed their minds after tackling the first analogy, and had decided that they thought that momentum was conserved in the target situation. There were several triggers for this positive change of view. Student 57 initially said that he thought that although momentum was transferred from the car to the wall, some would also be lost and rated himself at a belief-rating of three for this theory. Once he had considered the first analogy, he felt that there was enough similarity between the analogy and the target, in terms of how they worked, to make him change his mind about conservation of momentum.

I: If I was to ask you what you would be more inclined toward, what would it be? As in terms of momentum being lost or not being lost?

S57: Probably conserved because, …, I just, …, they are quite similar, those two situations.

I: Go on?

S57: As one is stationary and one is moving, …, but I just can't see why, that, …, I mean, that it is all to do with the mass of the stationary objects, that is affecting it.

I: Affecting how it's working in some sort of way?

S57: Yeah.

I: So you are saying that you are inclined towards saying that momentum in this crash situation is conserved? How convinced are you that that's true, on the scale of one to six?

S57: Well, I think that the momentum will be, …, won't affect the wall, it will just affect the car but it'll be probably be acting in another direction.

I: So, what is the car going to do?

S57: Like, hit the wall, …, and like, …, it sort of, …, momentum will keep going.

I: Keep going? How?

S57: Like, until the car is crushed.

I: So what happens to the momentum when the car has hit the wall?

S57: Eh, I would say it's, it is still in the car, like.

I: Even when it stops? Because you said earlier though that the car would stop, did you not?

S57: Yeah.

I: So, how are you explaining that?

S57: About the mass of the car because of velocity, because of, …, would be decreasing, but I'm not sure where the momentum goes, and what would happen.

I: So, you're not sure about that?

S57: Yeah.

I: So, how convinced are you that momentum is being conserved here, which is what you are guessing at, I would say, that you are hedging towards, but you are not sure about: give me a rating?

S57: About three.

I: So reasonably unsure?

S57: Yeah.

It is clear from the extract that he did not consider the similarity to be very strong, but he seems to think that they are sufficiently similar to make him change his mind.

Prior to starting on the analogical sequence, student 48 had stated that she thought that momentum would be lost when the car struck the building because some of it would have been changed into energy. However, she only rated her initial theory at a believability level of one. After working though the first analogy, she had changed her theory to momentum being conserved and rated herself at level four for this. Her thinking was that some of the car's initial momentum was being transferred into the wall. There appeared to be three triggers for her changed thinking: she had remembered what she had been taught about conservation of momentum always being true; she used visual cues from the analogy to reason out her transfer idea; and her experience with the analogy resulted in her change of mind.

I: What would your current thoughts be in this situation? Do you think momentum is or isn't being conserved when the car hits the wall?

S48: That it is.

I: And why do you think that?

S48: Because, just because I got told that, I don't understand it. I just got told that it was.

I: So, it must be true because someone told you? How much do you believe that this is true here? At the moment?

S48: Four.

I: Why has it gone up, because I don't think you said a 4 before?

S48: Because I'm just going to claim that's what I got told, so, …

I: That it's based on what you have been told, ok. What would your reason be, if you were to say to somebody, if somebody asked why it's been conserved here, what story would you give them? How is that happening? So the car comes in with a certain amount of momentum, what do you think is happening when it hits the wall?

S48: It transfers it to the wall.

I: Why do you think that?

S48: Because it hits it.

I: And where have you got that idea from?

S48: Because the same thing happens with the two balls.

I: So, is it because you can see a transfer of momentum there that you think there is something similar happening here?

S48: Eh, yeah.

I: How sure are you of that?

S48: A three.

When she was asked to explain how she thought the momentum was being transferred to the wall, she was unable to articulate any kind of detailed mechanism.

However, the extract above clearly shows that she has experienced a degree of conceptual change as a result of her interaction with the first analogy, in conjunction with her associated thought processes.

Student 22 admitted during his thinking about analogy one that he had been primarily guessing when he said, in the initial phase of the interview that dealt with the target situation, that he thought that momentum would be converted to energy.

I: And in terms of the total before, where the first ball was the only thing moving, compared to after, when both balls are moving, how do you think the totals, before and after compare?

S22: They would be equal.

I: How sure are you of that on that scale of one to six?

S22: Four.

I: Why are you so sure of it here?

S22: Because you see this ball moving whereas in the diagram you don’t.

I: So, because this ball moves after that one hits it, you think that the chances are, momentum is being conserved?

S22: Yeah.

I: OK. So you don’t think there is any momentum being converted into heat or anything like that here?

S22: No.

I: So, what’s happening in terms of energy in this collision, would you say?

S22: Energy is being lost.

I: As?

S22: Heat and sound.

I: But that has not come from the momentum?

S22: No.

I: So, why did you say here that you thought the energy was coming from the momentum? What is your thinking here, versus there?

S22: It was just a shot in the dark.

I: Just a guess?

S22: Yeah.

He was then asked to compare the analogy with the target situation and gave a very detailed answer, as follows, which showed that his change of answer was triggered partly by what he had seen and experienced in the analogy; and partly as a result of his prior learning being actuated.

I: What similarities do you see between this situation and the original of the car hitting the wall or the building?

S22: Similarities?

I: Or differences?

S22: The difference is you can see it in real life.

I: You can see what?

S22: You can actually see what is happening whereas the diagram you have got to think and remember what is going to happen.

I: Do you see any similarities between what happened here and what you think would happen there?

S22: Both collide.

I: So, what represents what?

S22: What do you mean?

I: What in this situation represents things in that situation?

S22: The first ball represents the car. The second ball represents the wall.

I: And do you think there are any similarities between the second ball and the wall or do you think they are very different?

S22: Different, because the wall is bigger than the car and it won't move as much.

I: That's an interesting comment - 'won't move as much'. Tell me what you're thinking.

S22: The wall will crumple and it will be pushed back on a microscopic scale.

I: What has made you think that?

S22: I just remember something.

I: Is it memory, or is it something to do with this?

S22: More memory, I think.

I: Is it just this or have you thought about it?

S22: I have thought about it.

I: Has anything triggered that thought, would you say?

S22: I'm just thinking about the car and wall colliding, really.

I: So it is just having thought it through a bit more?

S22: Yeah.

He described the cause of his conceptual change as “thinking it through”, which seems to have caused him to make connections with prior thinking and learning, which resulted in conceptual change.

6.3 Analogy two

This analogy consisted of the student running one of the ball-bearings used in the first analogy into the palm of their hand, which they had laid across the wooden track that the ball was running along. As discussed above, the first analogy was primarily intended to assist students to comprehend and believe in the idea of conservation of energy when two objects collide. This analogy sought to help them to envisage the idea that momentum could be transferred from a small object (a ball-bearing) to a much more massive object (their hand), by way of them being able to directly feel the effect on their hand. In short, it provided them with a direct, experiential link to one of the more difficult sub-concepts in the target scenario. Some students found this analogy highly beneficial in explaining the target situation, while others did not. During the review of the sequence, a total of eight students identified this as one of the analogies that they found to be particularly helpful because it provided physical experience which helped them to identify that momentum was being transferred to their hand, despite the lack of visible movement that this caused.

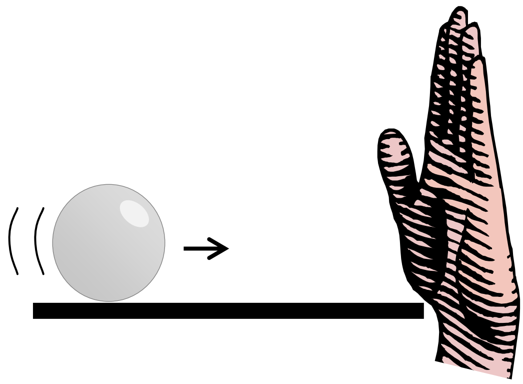


Figure 6.3: Analogy 2 - Ball running into hand and stopping.

The second analogy resulted in many of the students experiencing conceptual change in terms of their belief in: conservation of momentum in the target situation; their ideas about how a large and apparently 'immoveable' building could be thought to have gained momentum; or, in some cases, both of these aspects of their thinking were altered. As acknowledged by many of the students in several of the excerpts below, the analogy triggered conceptual change primarily as a consequence of the physical sensation of momentum being transferred to part of their body that did not move with a perceptible overall velocity as a result of the collision. This resulted in many of them successfully connecting this experience with the target situation and consequently caused them to change their mental model/theory, and/or increase the intelligibility and believability of their personal construction of the situation.

As a result of interacting with analogy two, there were several changes to students' 'immoveable' building theories. Two students had down-graded their immoveable theory to a less accurate version, while another two had decreased their belief rating in their existing theory. Two students added the idea of momentum being transferred to the building to their existing idea that momentum was being lost. Seven students experienced significant conceptual change when they altered their theory from stating that momentum was not conserved in the target situation, to stating that they thought that it was conserved after thinking about this analogy. Eight students revised their 'immoveable wall theory to include more detail than they had done previously, while six students increased their belief rating in their prior theory. Figure 6.4 below, summarises the number of students who were stating each of the identified theories at the end of analogy one (figure 6.4a) and by the end of the second analogy (figure 6.4b). Figure 6.4a contains the same information as figure 6.2b, given earlier. It is reproduced here as this allows the overall numbers of students who held each theoretical stance at the end of the successive analogies to be compared easily.

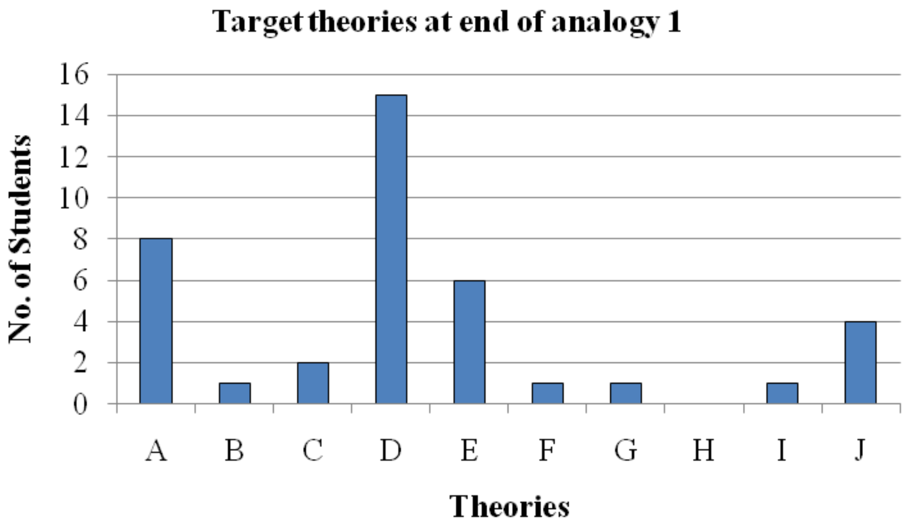


Figure 6.4a: Number of students stating each 'immoveable' wall theory at the end of analogy one.

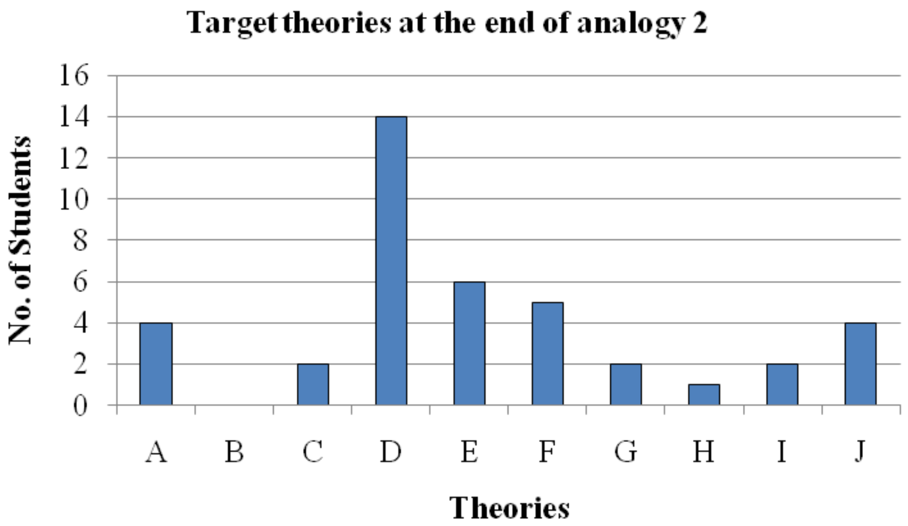


Figure 6.4b: Number of students stating each 'immoveable' wall theory at the end of analogy two.

The analogy was also effective in highlighting a problem in many students' reasoning which is often evident in the numerical calculations carried out by students when they are solving problems. Very few students took cognisance of the idea that a change in direction involves a change of sign in the momentum. In turn, this means that when an object changes direction, it has a larger change in momentum than occurs when an object with the same mass and initial velocity stops. The majority of the students failed to recognise this, but instead referred to the ball-bearing or the car 'getting back' most of its momentum when it rebounded with a lower magnitude of velocity than it had prior to the collision. This demonstrated that many students harbour a misunderstanding of the vector nature of both velocity, and consequently momentum, which is consistent with the findings of Williams (1976), Grimellini-Tomassini et al. (1993), Graham and Berry, (1996) and Pride et al. (1998). Students from the full ability range (judged in terms of their final Physics grade) harboured this misconception, which suggests that Williams (1976) was justified in placing this sub-concept of momentum at the highest level of his cognitive scale. For a small number of students, this failure to appreciate the significance of the change of direction in relation to the momentum of the car and the building was not simply ignored, but proved to be a significant stumbling block. It caused them to deduce that momentum was not being conserved, and/or that it was not being transferred to the building.

6.3.1 Negative conceptual changes resulting from interaction with analogy two

By the end of this analogy, only students 4, 6, 8 and 20 were of the opinion that momentum was not being conserved when the car struck the building. In the case of students 6 and 20, this was a change from their previous two answers, which suggests that elements of this analogy were counter-productive for them. An assessment of thinking processes exhibited by student 6 during this section of the interview showed that his difficulties were caused by a combination of confusion, cognitive conflict and twin-tracking. Thinking which was judged to show 'twin-tracking' involved a situation in which a student demonstrated by their out-loud thinking that they were wrestling between two different ideas and trying to decide between them which one was correct or at least more intelligible to them. The following excerpt shows how he began to become confused by his experience of the analogy.

I: Now, in that situation that you have just done, do you think momentum is, or isn't conserved?

S6: (Long pause). I don't think it is.

I: Why not?

S6: I think that when it moves my hand a wee bit it will lose some momentum.

I: What is losing some of it?

S6: The ball loses momentum moving my hand and the rest is transferred back.

I: Now in terms of afterwards, you have got the ball and your hand, whereas before it was just the ball. How would those two totals compare?

S6: I think they would be different.

I: Which would be the bigger of the two in your opinion? Before or after?

S6: Before.

I: So, where is the bit that is disappearing or missing? Where is it afterwards?

S6: It's lost in moving my hand slightly.

I: So, does your hand have any momentum?

S6: I think it has a wee bit in the way it moves.

I: So, is that the missing bit or isn't it?

S6: I think it is part of it but I think there is more where is loses some but I don't know where that would happen.

I: So you think your hand has got some of the momentum but you think there is a wee bit getting lost somewhere but you don't know how?

S6: Yeah.

I: How sure are you that you are right?

S6: About two again I think.

I: Is that for the total before being bigger than the total after? How sure are you of that?

S6: A five.

When comparing the analogy with the target situation, S6 exhibited a twin-tracking thought processes as he struggled to decide between two different ideas about whether momentum is lost or transferred to the building.

I: OK. So, tell me what your up-to-date thinking is with this then. Are you saying that momentum is or is not conserved in this situation at the moment, in your opinion?

S6: It is not conserved.

I: Now, a minute or two ago you were saying it was conserved, so why have you changed?

S6: I just think it would lose some somewhere.

I: How is that loss happening do you think?

S6: (Long pause).

I: In other words what I want you to do is tell me what happens to the momentum of the car when it comes in after it has hit the wall. Tell me the story of what you think is happening to the momentum.

S6: It will go in and it will crash, then it will roll back a wee bit but not as fast or as far as it first came in.

I: So why is it doing that in terms of momentum?

S6: I think some momentum is lost, into making a wee indent in the building, slightly.

I: Now, is that losing the momentum or is that giving the momentum to the building?

S6: Giving the momentum to the building.

I: So do you think there is, or isn't, momentum (using your word) transferred to the building?

S6: I think it is a wee bit but then I don't know how it will get transferred back. I just think it does for some reason.

I: Give me a rating of how much. If I was to say to you that before you were saying that momentum is conserved here. Give that a rating for me now. Has your rating gone down or up? Are you more or less sure of that original plan?

S6: About a two.

I: Is that down or up? Are you less sure of that, or more sure of that? In other words are you saying you think it isn't conserved now?

S6: Yeah, I don't think it is conserved.

I: And how sure are you that it isn't?

S6: A four or a five.

S6's cognitive conflict about why the car ended up moving backwards, more slowly than it had hit the wall, resulted in him deciding that momentum was being lost as he could not justify how the transfer of momentum to the building could explain this phenomenon. Arguably, the underlying reason for his difficulty was an over-concentration on the motion of the ball-bearing and the car, which resulted in him not being able to fully appreciate what would happen to the building as a result of the collision. He had realised that momentum was being transferred to his hand by the ball in the analogy, and he was making a connection between that result and the target situation. However, he was evidently confused by his perception that both the ball, and therefore by association, the car, were "getting back" some (but not all) of their original momentum. His assertion that momentum was lost as a result of the car making "a wee indent in the building slightly", shows that he was trying to find a compromise which merged the two conflicting ideas in his mind, but ultimately the idea that momentum was being lost won over the other option.

Student 20 found this analogy hard to comprehend and this altered his thoughts about the target situation. The analogy was successful in improving his belief that momentum was being transferred from one object to another. This occurred because he could feel the effect of the ball-bearing on his hand. However, he was also troubled by the change in direction of the ball-bearing after it had struck his hand.

I: What do you think is going on in terms of momentum there?

S20: It's passing on momentum to my hand.

I: How do you know?

S20: Because it is denting my hand and making it push back.

I: Would you say that the total amount of momentum before and after were the same or different in that case?

S20: Different. A rating of three. I'm not too sure, but I think it's different.

I: Why do you think it is different?

S20: Because the ball bounces back and it doesn't move forwards because it is hitting my hand.

I: Does your hand gain any momentum?

S20: I think it does.

I: And does it gain what the ball has lost? Or do you think there is something going on elsewhere as well as that?

S20: I think there is something going on elsewhere.

I: And what do you think that something else is?

S20: I'm not too sure. I think something else is going on. It could be the same. I'm not too sure.

I: Why are you saying it could be the same?

S20: Because the momentum is passed on to my hand.

I: So how convinced are you, that there is momentum being given to your hand?

S20: Probably four now.

I: You're fairly sure it has got momentum?

S20: Yeah.

I: How much of what the ball loses, do you think your hand gets? Because you are fairly sure that the ball has lost momentum. So, how much of what the ball loses, does your hand get? Does it get all of it, or just some of it?

S20: Just some of it.

I: How sure are you of that?

S20: Four or five. I'm pretty sure.

I: So what happens to the bit that disappears, for want of a better word?

S20: I'm really not sure.

I: But you've just got a gut instinct that something is disappearing?

S20: Yeah.

In essence, he was basing his theory about the loss of momentum on a feeling, which he admitted he was rather unsure about, rather than basing it on the (albeit) circumstantial evidence before him, or on any physics principles that he had been taught. This demonstrates the powerful effects of pre-conceptions and existing mental schema on thinking patterns, and emphasises how difficult it can be to alter these pre-existing ideas. In this case the existing ideas were counter-productive as they resulted in him deciding that momentum was not conserved in both the analogy and the target, whereas prior to this, he had stated that it was conserved. In contrast to this backward step, he made progress in relation to the transfer of momentum to the wall because of his experience with the ball-bearing on his hand. This came about as he began to make connections in his mind between his experience and the previous analogy.

I: Now why do you think the ball moves a lot and your hand moves a little?

S20: Because of the force pushing back from my hand of the weight of my hand, not allowing my hand to push it.

I: So, it has got something to do with the size of your hand, does it?

S20: Yeah. See that ball was quite light so it can be pushed easily whereas my hand is quite firmly positioned so I don't think that ball could push my hand.

I: But you still think it is getting some momentum?

S20: Yeah.

I: Because of what?

S20: It is denting my hand and it pushes it back a wee bit.

I: What was your definition of momentum again, your equation?

S20: m times v.

I: So you are saying that the mass of your hand is being moved at a speed?

S20: Yeah, but it’s not much because, …

I: What I am wondering is why do you think your hand moves less than the ball?

S20: Because of its mass.

I: So, its mass is bigger, …

S20: So, it is not going to, …, yeah, its mass is bigger, so it is not going to move as much.

I: As fast do you mean or as far?

S20: As far and as fast.

I: But you still think there is momentum getting transferred to your hand?

S20: Yeah.

When the student was asked to discuss any similarities or differences that he thought there were between this analogy and the target situation, it became apparent that his experience with the analogy had caused conceptual change as his belief-rating in the idea that momentum was transferred from the car to the wall increased from level 3 to a level 4.

I: Now how does the ball in your hand compare with the situation with the car hitting the wall? Similarities and differences?

S20: It is quite similar I think.

I: Go on.

S20: My hand could be like the wall and the car is like the ball so the car would dent the wall just like when the ball dents my hand so I think they are quite similar.

I: Any other similarities in terms of this movement you are talking about of your hand?

S20: The wall is a lot more stationary like my hand than the car so that is why I am getting confused if momentum is getting passed on because it is not actually moving.

I: Did your hand move much?

S20: Not much, but a wee bit.

I: Do you think the wall moves?

S20: I think it probably does now.

I: Give me a rating.

S20: Four.

I: So you think there is something about the wall shifting?

S20: Yeah.

I: And you have become a bit surer of that I detect, is that right?

S20: Yeah.

The analogy appears to have triggered conceptual change regarding the transfer of momentum, partly as a result of the visual and experiential cues that it provided, but also as a result of the student making connections between what he had experienced and what he had previously been thinking, or perhaps some prior learning. By making these connections, it made the idea of momentum transfer to the wall more intelligible and therefore more believable to him. However, when he was then asked to explain his thoughts on the conservation of momentum, it was evident that he had not really changed his views on it.

I: What about conservation of momentum here? Is the total that the car had the same as the car and the wall have between them after? Or has a bit gone missing do you think?

S20: I'm really not sure.

I: What is your feeling on it?

S20: I can't make my mind up, whether or not it is losing a bit of momentum or it is just the same?

I: What is your gut feeling?

S20: That it is losing momentum somehow.

I: And how is that happening, do you think?

S20: Because the car has stopped moving after it has collided with the wall.

I: Did it stop dead here?

S20: No it moved back slightly so it would have a wee bit of momentum but I think it has lost some.

I: The car has or the whole system?

S20: The whole system, …, no the car has.

I: What about the whole system because at that stage something is happening to the wall.

S20: I think the wall is taking on momentum.

I: Is it taking on what the car has lost?

S20: Yes.

I: All of it?

S20: Most of it, I think.

I: Give me a rating for how much you believe that.

S20: Four.

I: So, are you now saying that there is a wee bit of momentum lost, but you are not sure how?

S20: Yes.

I: How sure are you that some is being lost?

S20: About three.

This interaction emphasises again the way in which students can have two ideas in their minds which they work on in parallel in an attempt to decide between them. At this stage he was still unsure about the concept of momentum conservation and was therefore still basing his thinking primarily on a feeling. As will be seen in the analysis of the third analogy, a break-through occurred for him in this regard as a result of that example.

In contrast, students 22 and 46 were continuing to state, by the end of analogy two, that they considered momentum to be conserved in the target situation. However, they had decreased their belief ratings about conservation of momentum by one point. Student 22 stated that he had no particular reason for reducing his belief rating. It is therefore reasonable to assume that it may simply have been a result of a cautiousness that was observed in the belief ratings of many of the students at various points in both analogical sequences. In the case of student 46, this uncertainty was demonstrated clearly when he was asked to state why his belief rating had dropped slightly.

I: Ok. So what are you saying then about momentum? About the total before and after in the collision? The real one with the building and the car.

S46: It'd be conserved I think.

I: How sure are you?

S46: Five.

I: About a five?

S46: Yeah.

I: Ok, it's gone down a wee bit.

S46: Yeah.

I: Why?

S46: Just, …, just, the more I think about it, I think there's like gaps in my knowledge, so I might be missing something.

This statement shows an interesting level of self-awareness and critical analysis in this student. He acknowledged that, while thinking through the situation, he had become aware of gaps in his knowledge, which consequently made him wary of claiming that he was very sure that he was correct. It could therefore be argued that he was trying to make connections between what he was doing in the interview and what he already knew or had been taught. He had become less secure in his thinking and reasoning as a consequence of the lack of clear links between the relevant pieces of knowledge in his mind. This uncertainty appeared to have been triggered by the dawning of an awareness of gaps in his knowledge.

6.3.2 Mixed conceptual changes resulting from interaction with analogy two

Students 4 and 8 both ultimately maintained their position that momentum was lost in the analogy and in the target situation. More positively, both decided that the building would have momentum transferred to it, which student 8 thought would happen because the building would "shake".

As a result of working through the second analogy, student 4 concluded that a small amount of momentum had been transferred to his hand. This subsequently resulted in him suggesting a new 'immoveable wall theory' in relation to the target situation.

I: So what about the momentum of your hand? Is there anything going on there, when the ball hits it?

S4: Em, I don't think there is much going on in the hand at all.

I: Does your hand get any momentum in that collision?

S4: Well, I think a little tiny bit, maybe.

I: How do you think that works?

S4: That works?

I: How is it getting momentum?

S4: The mass of the ball, when it collides; well, when the ball collided with the hand, em, …, the momentum was transferred into the palm of, ..., into the hand.

I: So how did you come to that idea, because that is a change of idea really, so where did that idea come from?

S4: That's come from like, where the momentum is lost, the momentum is lost due to the collision and it's transferred into that, …

I: So, when you say it's lost you mean from the ball?

S4: The momentum is lost from the ball.

I: And where is it going are you saying?

S4: It's lost in the collision.

It is evident from this excerpt that he was having difficulty in reconciling his ideas regarding momentum being lost from the ball-bearing and it being transferred to his hand. He then exhibited a twin-tracking process as he went back to a previous idea about the possible effect of the difference in relative mass of the two colliding objects that he had mentioned, briefly, during analogy one.

I: So where is it going, if it's lost it's presumably going somewhere? So where do you think it's going?

S4: Well, if my hand was a larger object it would give, eh, the momentum to the other object and that move, perhaps, …

I: Now, does the fact that your hand is heavy, I mean, are you saying that it can't get momentum?

S4: It would get momentum, but it wouldn't move because, it has much greater mass, and velocity came from, and couldn't move my hand.

I: So you think your hand is getting some momentum, is it?

S4: I think, of course I think the hand gets some momentum.

At this stage he seemed to have moved towards becoming more convinced that momentum had been transferred rather than lost. He then became confused by the combination of the ball-bearing's changing velocity and the relative masses of the ball-bearing and his hand.

I: Now, in terms of the total momentum before, when it was just the ball moving, and after when the ball is moving and something had happened to your hand, and so you have ball on its own before, and ball and hand after? How does those totals before and total momentums added together after compare?

S4: Well if, …, in theory I think, what I would, questions I did was, if the momentum before equals the momentum after, it was something like that, …

I: So is that true here?

S4: I think, eh, …, momentum before equals momentum after, but in this one, if you pause it, for example, pausing the ball colliding with the hand, do you mean that?

I: Well, yeah, do you mean like a freeze frame?

S4: Yeah, a freeze frame.

I: Ok, tell me about that?

S4: Well, over there, the velocity would be a zero, because the ball stops for a split second before going back, the direction it came from, …, em, …

I: So, at that stage the hand is involved as well, so what is happening to it?

S4: The hand, …, well, the hand, …, is just, …, is just rebounding the ball because, …

I: So is it getting any of the momentum we mentioned earlier?

S4: It's, …, I think it's taken in the momentum, eh, …, half or a bit more because when the ball travels back, it doesn't go as far.

I: So are you saying that you think the hand is getting some momentum into it?

S4: Yes.

I: So the total before, when it was just the ball, compared to when the ball and the hand got involved after, how do those two totals compare?

S4: I think the velocity would be different of the ball, …, the momentum, …, of the ball before colliding.

I: Remember it's the total momentum, not just the ball. So try and think about the total, that's what I'm trying to get you to tell me, whether you think the total is the same or different, from the total after? Not just of the ball.

S4: … I'm not so sure in that one.

I: So if you take the hand and the ball, both of those, you have said that there is some momentum in the hand, and you are saying that there is still some momentum in the ball after, and you add them together, how does that total compare with the ball on its own before hand?

S4: Then it would be, I guess, momentum after would be more than the momentum before

I: Why?

S4: Because, before it was, …, it had less, mass I think, …, for example, it had less weight.

After discussing the analogy and the similarities and/or differences that he thought there were between the first two analogies, he was asked to explain how he felt the second analogy compared with the target.

S4: I think they are quite similar, …, because my hand was, eh, can compare with the building in the picture.

I: So, tell me about the building after the collision? What's happened, when the car hits it?

S4: The momentum, it takes, …, well some of the momentum is lost in the collision.

I: Due to, …?

S4: Due to heat and sound production in the collision. But the brick wall, well the building doesn't move because em, …, well it's cemented but it doesn't move because it,…, the impact, of the eh, …, was not great enough to move a whole building, because it has a much, much, much bigger, eh mass.

I: So are you saying the building gets no momentum then?

S4: I'm sure it does get a bit of momentum as, eh, …, a bit of the building would like, break down, just, …

Following this there was a brief discussion about whether or not damage was a necessary condition for momentum to have been transferred. He concluded that momentum would be transferred even if no damage had resulted, but that some would be lost as heat and sound energy. When he was then asked to rate his belief in what he was suggesting, he showed that he was twin-tracking in his thinking about loss and transfer as can be seen in his first statement in the following excerpt. His difficulty was predominantly caused by a failure to understand the technical language that he was using and by an inability to correctly distinguish between the concepts. This relates to Spiro et al.'s suggestion that analogies can fail to help because of an inappropriate or incorrect use of technical terms.

I: So, in terms of momentum being lost, which is what you are currently saying. How sure are you that you are right in that scale of one to six?

S4: I'm thinking momentum being lost and being transferred is the same thing.

I: Oh, tell me about that then?

S4: Because momentum being lost, the momentum of the car is being lost, some of the momentum, or that same amount of momentum, is being transferred onto the other object.

I: The building?

S4: Yes.

I: Ok, so does that mean you are going off your sound and heat thing or what?

S4: No, I'm not going off the sound and heat thing but, just, …, but it just comes from there, that momentum is lost.

I: From the car?

S4: Yes, in producing sound and heat.

I: So where is it going?

S4: Then it won't be transferred as I said before it would, but I think it will be transferred to the building as, it would be used up in producing heat and sound.

I: Ok, so how sure are you of your idea there?

S4: Well, …

I: On the scale of one to six?

S4: Well I'm quite sure in producing heat and sound, some of the energy would be lost but not momentum, …, but I'm not so sure about momentum.

I: So give me a scale, roughly?

S4: Two, …, three.

In the end, he tried to merge the two ideas that he was comparing in his mind but his overall impression was that momentum was being lost as heat and sound, although by this stage he had become aware that the car was transferring momentum to the building, although he was unable to clearly identify how this was happening.

Student 8 also ran into difficulties regarding the difference between momentum and energy, which ultimately resulted in him deciding that momentum was not conserved in analogy 2. He also maintained his previous position that it was also not conserved in the target situation. When he was asked to explain his reasons for stating that momentum was lost when the ball-bearing collided with his hand, he stated the following.

S8: If it [kinetic energy] is mass times velocity squared and then is energy, and momentum is velocity times mass then one is the square of the other so you can convert them between each other.

After talking through the analogy, student 8 also demonstrates twin–tracking when he was asked to explain his thinking regarding the target situation. He has clearly taken on board the concept of momentum being transferred but he is also maintaining that momentum is lost as sound.

I: Now, what would you say about momentum before and momentum after in the car situation now? What is your thinking?

S8: The car bounces back and it loses momentum when it hits the wall but it has still got some and it bounces back.

I: So where does the lost momentum go?

S8: Into the wall.

I: All of it?

S8: No. All the lost?

I: Yeah. Some of it goes from the car into the wall and some of it goes back into the car. So is the total that you've got at the end of all that the same as the total you had at the beginning?

S8: No. Some is lost to sound as well.

I: Now in terms of how you think some is getting lost to sound, give me a rating on that from one to six.

S8: Five.

I: In terms of some of the momentum getting transferred to the building, what would you rate that theory as?

S8: Five.

I: Fairly sure. Why are you so sure?

S8: Because it has to go somewhere and that is where that car is hitting.

I: So, how would you explain it ending up in the building? Because you said earlier that the building doesn't move so how is it getting into the building? What is happening to the building in other words?

S8: It's shaking.

I: You think it shakes a bit?

S8: Yeah.

The analogy had clearly triggered a degree of conceptual change for him. However, his pre-existing idea was still in his mind and had not been replaced. He rated both of his competing concepts as equally believable. This suggests that he was trying to compare the two ideas in order to decide between them.

6.3.3 Positive conceptual changes resulting from interaction with analogy two

For many students, the second analogy triggered noticeable levels of conceptual change towards the accepted explanation regarding conservation of momentum in the target situation. Seven students had experienced significant conceptual change as they had completely reversed their previous views by deciding that they believed that momentum was conserved in the target situation. One student had increased her belief rating in conservation of momentum in the target situation from level three to a level six. Eight students had revised their 'immoveable wall' theory which they were using to explain how they thought the wall could be considered to have gained momentum after the collision, while five students had become more convinced about their existing 'immoveable wall' theory.

Students 1, 19, 29, 34, 40, 51, 57 and 63 had all adapted their 'immoveable wall' theory as a result of working with the second analogy. Student 51 decided that the building would shake when the car struck it and considered this to be an indication that momentum was being transferred to it.

I: Do think there is any movement in the wall?

S51: It might sort of, …, it might get a dent in it, or it might shake a bit

I: So, where did you get the shake thing from, because you didn't mention that before? Why do you think that?

S51: Because my hand did.

I: Tell me what you think your hand was doing?

S51: Kind of, …, experiencing the force.

I: Which made some sort of movement happen? And what do you think is happening with the wall then?

S51: It's experiencing a force from the car, …, because of the momentum.

I: And what is the consequence of that force?

S51: It gets some momentum.

I: And how do you imagine this momentum being in this wall, how would you explain a wall, or a building having momentum?

S51: … Eh shaking or, …

I: How sure are you that you are right with that idea, on that one 1 to 6 scale?

S51: A four.

I: So, has that gone up from your thoughts about the building having some sort of movement before?

S51: Yeah.

I: So, why are you more inclined to believe that now?

S51: It just sounds more likely.

It is clear that she had made a connection between the experience of the ball-bearing hitting her hand and the car hitting the building. Her idea that the building might shake appeared to have been generated spontaneously. However it is possible that she was relating this to previous learning or a prior experience as it did not appear to have been thought up entirely randomly, given that she justified her increased belief-rating in terms of this idea seeming more intelligible to her.

As a result of considering the collision between the ball-bearing and their much larger hand, students 1, 19, 29, 34, 40 and 63 realised for the first time, with varying degrees of certainty and clarity that, when the building was struck by the car, the resulting movement would be very small as a consequence of its very large mass since momentum is the product of mass and velocity. The realisation was significant as, prior to this, each of these students had only grasped the idea that momentum was transferred to the building, but had struggled to justify how the wall could be considered to have gained the momentum that the car had lost. Student 63 went further than the others at this stage when he stated that he thought the momentum of the car would ultimately be transferred to the ground, which he had only very vaguely hinted at before embarking on the analogical sequence. The following excerpt from the interview with student 40 demonstrates the change in thinking which this group of students all experienced regarding the relationship between the mass of the building and its movement.

I: Now how does this analogy, the ball in to your hand, compare with the original of the car going in to the building?

S40: Well your hand and the wall both have very, very large mass compared to the ball or the car. Em, both the ball and the car move in one direction, then collide, then go the other way.

I: Ok. And in terms of conservation of momentum and the reasoning behind it, is there anything, similarity or different?

S40: Well, they're the same.

I: In what way?

S40: The wall must move very slightly.

I: Now you're saying 'must move', give me your belief rating at the moment.

S40: 'Cause the momentum must be conserved, so, …, if that moves with a certain momentum that way, …

I: Are we talking about the car?

S40: The car, the ball.

I: Are you saying they're much the same idea?

S40: Mmm. Right. The wall, because it's got a big mass, it can afford to move with a very small velocity to compensate for the change in momentum.

I: So you're saying it's got a change in momentum, but you can't see a movement because what?

S40: It's got a really big mass, so, …

I: How sure are you that you're right?

S40: Five.

I: Ok, it's gone up. Why's it gone up? Because a wee while ago it was a three. Any particular reason it's gone up?

S40: I did it myself and my hand moved.

I: So, is it because you're seeing some kind of link between the hand and the wall that it's making you more confident, is that what it is?

S40: Definitely.

His statements demonstrate that the primary trigger for conceptual change was the links that he made between the analogy and the target situations. This enabled him to identify 'deep' similarities between the two situations which caused him to revise his specific theory about the building. It may be that he had reviewed his general theory about the way that all things operate in relation to the law of conservation of energy but it is not possible to ascertain this from his statements. His conceptual change was coded as being of several types, in common with many other examples which were exhibited by most of the students at various stages during both analogical sequences. He was judged to have shown evidence of the following types of conceptual change from the various theoretical standpoints: a change in an acquired idea and the associated cognitive structure; complex system building; target enrichment with new features being added; modification of his mental model; revision of his specific theory; and connections being made between his new thinking and (i) the analogy, (ii) his existing mental model and (iii) prior learning and knowledge in Physics.

Student 57 had already vaguely suggested, from his comments at the end of the first analogy that he thought that the building would not perceptibly move as a result of its very large mass. By the end of the second analogy he had extended his theory by stating that he felt that that the momentum would be transferred through the wall from one brick to the next.

Five students did not adapt their existing 'immoveable wall' theory, but they had become more convinced about their theory as a result of working with analogy two. In the case of student 64, he had become slightly more convinced of the idea that momentum was transferred to the wall and then to the earth. Students 2 and 43 grew in confidence regarding their theory that momentum was transferred to the building as a consequence of vibrations which travelled through the building and a vague mention that there was no noticeable movement as a consequence of the large mass of the building.

Both student 46 and student 48 became more confident in their much vaguer idea that momentum was being transferred in some way to the building. Although student 43's belief rating grew, she stated (in a similar way to student 29 during the first analogy, discussed above) that she was uncomfortable about making judgements regarding conservation of momentum (or otherwise) without the back-up of numerical values to justify her thinking.

I: How convinced are you that it's conserved?
S43: Still quite convinced, like five.
I: About a four or a five, is that what you're saying? So you're still not, you're still sitting about the middle-ish kind of range, or are you more convinced now than you were?
S43: I'd say I'm just about, I'm pretty much convinced. I mean, I'd like numbers to back it up.
I: I'm deliberately not giving you numbers here though.
S43: I'd love some numbers. Numbers would give me something conclusive rather than just my observations.
I: Why are you so keen on numbers?
S43: Because then I could check how well the numbers tally up.

I: Has it got anything to do with the fact that you're used to using numbers?

S43: I like numbers because, I don't know, they're just observations, I don't know.

I: So you find this harder?

S43: It's more difficult because of the fact that I could say 'Well it looks like it's going slower', but I don't have any kind of equipment apart from my eyes to tell me that.

As mentioned in the methodology chapter, a deliberate decision was taken in the design of the sequences to avoid using measurements as it was hoped that this would encourage the students' reasoning to become more evident. It was also intended to divert them from merely performing the calculations that they would have been familiar with, in order to make them think through what was going on at a deeper conceptual level. From the progress made by student 43, despite her concerns about the lack of numerical values, it would appear that this strategy was successful.

Student 48 had also become more convinced about her transfer theory and gave the following reason for doing so.

I: Do you think, you said earlier about momentum getting transferred from the car to the wall, is that what you are still thinking?

S48: Yeah.

I: How sure are you that that's true at the moment?

S48: Four maybe.

I: It's gone up a wee bit, has it?

S48: Yeah.

I: Why?

S48: Because I can like compare my hand to the wall and my hand did move slightly

I: So, you think, does that make you think that it's more likely that there is some sort of transfer going on there?

S48: Yeah.

It is obvious from her statement that her increasing confidence was a direct result of her being able to make comparisons between the analogy and the target situation, which in turn meant that her theory became more intelligible and believable.

The most significant conceptual changes were exhibited by seven students. By the end of the second analogy, students 5, 21, 25, 47, 52, 58 and 62 had all changed their minds and were stating that, in their opinion, momentum was being conserved in the target situation, having previously stated, to varying degrees of certainty, that they thought this was not the case. At the end of the first analogy, students 5 and 21 had been unclear about whether or not they considered that momentum was being conserved in the target situation. Consequently, they were judged to believe that it was not being conserved. In comparison, students 25, 47, 52 and 58 had all explicitly stated their opinion that momentum was not conserved when the car collided with the wall after they had worked through analogy one. Of the four students who completely reversed their decision, three had stated this opinion both prior to encountering the sequence and after the first analogy, while student 58 had changed her mind about the target situation after working through the initial analogy (as discussed previously), but reversed her decision after considering the second analogy.

Prior to encountering the analogical sequence, student 5 had stated her belief (at level 4) that momentum was transferred from the car to the wall, in the target situation, in the form of vibrations that she thought would travel through the building. However, after working through analogy one, student 5 then stated that she thought that the car's momentum decreased to zero when it hit the wall, but was not at all sure where it went thereafter, as demonstrated by the following extract taken from the end of her deliberations about the first analogy.

I: Are there any similarities in the way these two things work, do you think?

S5: Well one is the car hitting the wall. The momentum will decrease so that is similar to that one.

I: Why does it decrease here?

S5: Because once it hits the wall the speed will eventually come to zero.

I: So what do you think is happening to that momentum?

S5: It is decreasing.

I: To what? Is it going anywhere or is it disappearing?

S5: I don't know.

As discussed previously, several students (including student 58, whose thinking during analogy one was analysed above) had a 'single object' perspective. It can be seen in the above extract, that student 5 was only considering the car, and not perceiving the wall as being part of a system of objects, between which momentum could be transferred. Consequently, she was unable to understand that momentum was being conserved in the collision between the car and the wall. She struggled to see any links between the first analogy and the target scenario, other than at a surface level, which appeared to result in her losing faith in her initial hypothesis. However, her interaction with the second analogy altered her thinking as it enabled her to make experiential links, at what was deemed to be a 'deep' (theoretical) level, between what happened to her hand when the ball-bearing collided with it, and what she thought would happen to the wall when the car struck it. The development in her thinking, which resulted from her experience of the ball hitting her hand, can be seen clearly in the following extract, which occurred immediately after the one above

I: OK. Let's move on to our second analogy. I'm going to get you to run this ball into your hand so put your hands flat like that and run the ball into your hand and tell me what you notice happening.

S5: It bounces back off my hand.

I: Anything happen to your hand?

S5: A force. Momentum went into it to push it back.

I: You've just said there momentum went into your hand. Why do you think that?

S5: Because once the ball hit my hand, my hand wanted to go that way a wee bit, my hand wasn't going to move because it wasn't that great a force but it still wanted to move. I could still feel it trying to move.

I: In terms of the momentum, beforehand we had the ball was the only thing moving, it then hit your hand, how does the momentum before the ball hit your hand, when it was just in the ball, compare with the total of the ball and the hand after in your opinion?

S5: Do you mean the momentum of the ball once it hit and then once it came back?

I: Not necessarily just the ball, because there is the ball and your hand at that stage.

S5: I reckon probably about the same.

I: So how would you explain them being the same to someone that didn't understand?

S5: (Long pause).

I: So the ball is moving, then it hits your hand. What happens to the momentum when it has hit your hand?

S5: The momentum is shared out between my hand and the ball so the momentum of the ball will decrease but the momentum of my hand increased. The ratio to each other would be equal.

I: You just said that some of the momentum was shared with your hand. How do you know there was momentum in your hand?

S5: Because my hand wanted to go and it slightly jerked that way a bit.

I: Now you've said that you think the total momentum before is the same and the total after, how sure are you that that is right on that scale of one to six?

S5: Four or five.

I: In terms of the momentum being somehow shared with your hand, in your words, how sure are you of that idea?

S5: Five.

I: Quite sure?

S5: Yeah.

I: Because you could feel it presumably?

S5: Yeah.

Having experienced the ball trying to push her hand back, she had reverted back to thinking in terms of momentum being transferred from one object to another. She was considering the system of both objects, as opposed to only thinking in terms of the object that was initially moving. When she was then asked to describe how she felt the analogy compared with the target situation it became clear that she was connecting her experience with the target situation at a 'deep' level, as shown below.

I: Let's go back to our original of the car hitting the wall, what similarities and differences do you see between the ball bearing and your hand and this?

S5: Maybe the momentum from the first object didn't affect the second object greatly - as the ball did with my hand, it didn't move. The wall wouldn't probably move at all. I don't know. The first object decreases once it hits the wall.

I: And where does it go?

S5: It rebounds back on the car.

I: So the car gets some back you're saying?

S5: Yeah.

I: Does it get it all back or is some of it going somewhere else?

S5: Some of it will go into the wall.

I: So how would you explain that if you can't see the wall moving?

S5: See, when it hits the wall, the bricks will break and stuff like that?

I: I'm trying not to tell you any answers.

S5: When it hits the wall, I would imagine bricks would get pushed in and break and that sort of thing.

I: Would it still be true if it didn't break bricks?

S5: I don't think so. I'm not sure. No.

I: So you think there needs to be bricks broken?

S5: There has to be bricks moving and broken.

I: In terms of how sure you are of momentum being conserved here (with the car and the brick wall, or the building) give it a rating of one to six.

S5: Four and a half.

I: In terms of your idea of some of the momentum going from the car into the building, what are you giving that?

S5: Four.

Her statements suggest that she recognised that her hand had a larger mass than the ball-bearing. This realisation, along with the physical experience of having the ball-bearing strike her hand, triggered the idea that the much larger wall could have momentum transferred to it by the car. Her deliberations, however, demonstrate that she was harbouring a couple of misconceptions. Firstly, she had difficulty in perceiving the wall getting momentum unless there was some form of damage caused to it, but her belief rating of four, suggested that she was quite convinced that momentum was being transferred to the wall. The second misconception is a more fundamental issue that betrays a misunderstanding of the vector nature of momentum. In common with many other students, she described the car as getting some of its original momentum 'back' when it rebounded from the wall. This shows that she had failed to realise that the change in direction demonstrated that the car had a significant change in momentum from a positive, to a negative value (or vice-versa). This misunderstanding meant that she was likely to have perceived the wall as having only a small amount of momentum transferred to it. Consequently, this would have intensified her struggle to justify the transfer of momentum to the wall as a consequence of her first misconception, whereby she felt that the transfer of momentum required there to have been noticeable damage to the wall.

As discussed above, in the analysis of the first analogy, student 21 had been convinced that momentum was conserved in the analogy (giving herself a belief rating of five and a half) but was not convinced that momentum was being transferred to the wall by the car as she could not imagine that the wall could move in any way. However, the second analogy resulted in a significant amount of conceptual change occurring in her thinking.

When she initially ran the ball-bearing into her hand, she experienced a degree of uncertainty and cognitive conflict when trying to explain the movement of her hand, as demonstrated by her last comment in the extract below. Her comments also show that she was still trying to work out how to justify conservation of momentum.

> I: OK. Let's move on. Second analogy. I'm going to take that ball away and I want you to put your hand there so the first ball runs into the palm of your hand and run it reasonably fast into the palm of your hand. Now what do you notice in that collision?
>
> S21: It rebounds quite a bit.
>
> I: Although you could catch it with your hand if you wanted.
>
> S21: Yeah. My hand moves a tinsy bit.
>
> I: Now why is it moving?
>
> S21: Because momentum is conserved and, …, I don't know.

The conceptual change that S21 experienced was initiated by her spontaneously starting to make connections between her experience in the analogy, when the ball-bearing collided with her hand, and what she began to imagine would happen to the wall. The fundamental trigger was the realisation that her hand had only moved a little as a consequence of its much greater mass, in comparison with the mass of the ball-bearing.

> I: So you're saying your hand moves a teensy bit and you think it has got something to do with conservation of momentum?
>
> S21: Yeah, well if I believed completely in conservation of momentum, then I would say that it is because it moved a little bit, because it would. If it had to be the same before and after, if that [the ball-bearing] was coming in with a high velocity and a little bit of mass and then this [her hand] had more mass. If it was a building, then it would have to move a little, little bit for it to equal the same.

I: So, the mass is big and what is small?

S21: The velocity.

I: That's interesting. You're basically saying that you think that is moving a wee bit because it has a big mass but a small velocity. Is that what you're saying about your hand?

S21: Yeah.

In order to assess the extent to which genuine conceptual change had occurred, as opposed to an isolated or fleeting idea, she was then asked to enunciate any similarities or differences that she thought there were between the analogy and the target.

I: Now, inevitable question then. What do you think the links are, if any, between what you have just done and the car?

S21: So, if that was the same situation then the car would rebound and again if there was anything to do with the conservation of momentum then the wall would have to move because otherwise the velocity would be zero so the momentum would be zero so there would be no momentum at the wall.

I: How convinced are you in the analogy (with the ball into your hand), how convinced are you that momentum is being conserved there?

S21: About four or five.

I: Fairly sure there?

S21: Yeah.

I: In terms of this idea of some of the ball's momentum being transferred to your hand, how convinced are you of that idea?

S21: Five.

I: Why?

S21: I don't know.

I: What is convincing you here that momentum is conserved and some of it is ending up in your hand?

S21: Because this with a mass and quite fast velocity, when it comes into my hand, I can, …

I: Why are you so sure that your hand ends up with momentum?

S21: Because my hand has a mass and it feels as though it is moving a wee bit when it hits it, it is like it hits and it goes like that a bit.

I: So the skin bends a bit, is that what you're saying?

S21: Yeah.

I: Now, here you said something about it being similar. What are you saying about conservation of momentum here?

S21: Momentum is pretty much conserved.
I: Give me a rating of how much you believe that.
S21: Five-ish.

It is clear from her statements that she had become much more convinced that momentum was being conserved in the target situation. In addition, she was more certain of her idea that momentum was being transferred to the building as a result of the collision between it and the car. The reasons for this change in her confidence were then explored.

I: What has made you think that it is more likely now, here [in the target situation]?
S21: I think because before I thought that the wall wasn't getting any momentum but, …
I: Why do you think it might be now? I mean, you're not saying a six, but why are you saying you are a bit surer that it might be now?
S21: Because I thought it was impossible for the wall to have velocity but now I can see it having velocity, even if it is a really small velocity.
I: So how would you explain it moving? Are you saying that the whole thing shifts?
S21: No. I don't know. I suppose it depends on the building.
I: But you think there is some kind of movement there?
S21: Yeah.
I: How convinced are you that there is some kind of movement, some kind of transfer of momentum, to the building?
S21: Well I can't really think of anything else that could explain it so maybe a four or five.

It appears that the experience of the ball-bearing moving the skin of her hand very slightly had triggered the development of her theory in relation to the building. Her comment about being able to 'see' the building having velocity shows that it had enabled her to transfer the idea to the building by making a mental connection between the two situations. She has undergone conceptual change as a result of making these connections between her existing mental model and the analogy.

It can be argued that this form of conceptual change shares traits with the theoretical standpoints of Ausubel, Tiberghien, Vosniadou and diSessa, which were examined in the literature review in chapter 2. She had engaged in 'meaningful learning' (as discussed by Ausubel) because she had altered her thinking about what would happen to the wall. As a result of this change of thought process, her perceptions regarding conservation of momentum in the target situation, was altered in the light of her experience with the ball-bearing. This suggests that there had therefore been a change in her cognitive structure. Both Tiberghien's 'modelling' theory and Vosniadou's 'theory restructuring' approach describe conceptual change in terms of the revision of the learners' mental 'model' or 'theory'. When both positions are examined, these terms seem essentially synonymous with one another. Student 21 had clearly altered her theory regarding the conservation of momentum when a car collides with a building. In common with many of the statements made during the interviews by other students, it is not possible to state categorically that she has changed her thinking about conservation of momentum, in *every* circumstance, since she only specifically refers to the analogy and the target situations. However it is clear that she had undergone conceptual change regarding the specific situation in which a car collides with a building. It could therefore be argued that she demonstrated, by her out-loud thinking, that as a result of making connections between the two scenarios, she had altered her 'specific theory', rather than her more fundamental 'framework theory', in Vosniadou's terminology; while according to Tiberghien's theoretical stance, it can be seen that she changed her 'mental model', as opposed to her deeper 'underlying theory'. An alternative view would be that she has engaged in what di Sessa refers to as 'complex system building' as she connected the various ideas and pieces of knowledge that the analogical situation triggered in her mind. She then linked those with the target situation in order to come up with a more complex conceptual understanding of the real-life scenario which was more accurate and robust.

As summarised earlier, students 25, 47, 52, 58 and 62 all experienced an even greater degree of conceptual change as a result of their interaction with the second analogy. Each of them changed their views entirely about the conservation of momentum in the target situation from stating that momentum was not conserved to believing that it was. Furthermore, several of them had refined or changed their personal theories regarding what happened to the momentum when the car struck the building.

The physical experience of running the ball-bearing into their hand, and feeling the resulting impact, was instrumental in causing each of these students to alter their thinking. Student 62 made this very clear when she was asked to explain why she had changed her views about whether or not momentum was conserved in the target situation and the process by which she had devised a new theory regarding how she thought the momentum was transferred to the building.

I: Have you changed your mind? Earlier you were saying that momentum wasn't conserved there.

S62: Yeah.

I: So why have you changed your mind?

S62: Because I could feel the impact on my hand. I didn't think the wall would move but if it is the same you would feel a tiny bit but it wouldn't be very noticeable.

I: How sure are you, on that scale of one to six, that momentum is being conserved?

S62: Four.

I: So it has gone up?

S62: Yeah.

I: What about your idea of some of the momentum being transferred to the wall which is what I think you're saying, are you?

S62: Yeah.

I: How sure are you that you're right?

S62: About a five.

I: Why are you up at a five because I think before you gave it a three. Why has it gone up?

S62: I think it seems more likely.

I: Why?

S62: I don't know. Just the experience of having that hit my hand and thinking it might not move but there would be a tremor probably or the impact would be felt.

Student 25 also revised her thinking and understanding of the transfer of momentum and came up with a theory about a mechanism for its transfer as a result of the experience gained in analogy two. In addition, thinking about this analogy resulted in her significantly altering her views about the conservation of momentum in the target situation. The extract below demonstrates that the experience of running the ball-bearing into her hand made the idea of momentum being transferred from a small object to a much larger and reasonably immoveable object, more intelligible. This realisation caused an improving level of believability in the concept. This process is consistent with the ideas of Posner et al. (1982).

I: What is happening to the momentum that the ball has, as it comes in when it hits your hand?

S25: Nothing.

I: Does your hand end up with any momentum?

S25: It must have a wee bit because it's moving.

I: So how did it get that momentum?

S25: From the ball hitting it.

I: So what did the ball do with the momentum?

S25: Em…

I: What words would you use to describe how it got from the ball (some of it) to your hand?

S25: I don't know. It sort of passed on a wee bit?

I: Passed it on, ok. Now, you're saying that momentum passed on to your hand and the reason you know that is because of what? How do you know that is the case?

S25: Because my hand moved a bit.

I: So how convinced are you on this scale of one to six that some momentum has ended up in your hand?

S25: Five.

When she was asked to discuss her thoughts about any similarities or differences between the wall in the target scenario and her hand in the analogy, she gave a previously unstated mechanism by which she thought the momentum could have been transferred to the building. Her theory about vibrations appears to have been generated spontaneously, but when she was asked to explain the thinking behind her suggestion, her answer suggests that she had made a link to things that she had possibly seen, read or experienced previously.

I: Now tell me what similarities and differences you think there are between your hand and the wall.

S25: I think it would depend on the wall because if it was a building it wouldn't move but if it was a wee wall then it might.

I: The whole wall might move or bits of it?

S25: Bits.

I: Are you saying a building wouldn't move at all?

S25: Doubt it. I don't know.

I: Could bits of a building move?

S25: Yeah.

I: What bits might move if that was the case? What would you think?

S25: I'd reckon if it hit a corner of something it could take bricks out or something.

I: Would there be anything that would happen to the whole building in any way?

S25: I don't know. It could send vibrations or something through.

I: How much do you believe that that might be the case? What would your rating of that be?

S25: Four.

I: Fairly sure. Why do you think there might be vibrations through the building? What is making you think that?

S25: Because if something hits something then it is going to move but because it is so big and steady, it's a strong structure.

I: So you don't think the whole thing is going to go somewhere but you think there might be some kind of vibration going through it and you'd reckon about a level four for that?

S25: Yeah.

I: What's made you think that? Where have you got that idea from?

S25: What idea?

I: This idea of the vibration through the building?

S25: Just because. I don't know. I just think something has to happen and a good building is not exactly going to fall over.

Having subsequently indicated that she believed that a small amount of momentum was transferred from the car to the building (at a belief rating of 4), her thoughts about conservation of momentum in the target situation were then explored. At first, the single object reasoning that she had been using previously was given again. But when she was guided to consider both the car and the building, her answer changed. It became clear that she (along with many other students, as discussed already) had been considering momentum to be lost because the car was moving more slowly after the collision than it had been before. The realisation, during her interaction with this analogy, that it was possible (and believable) for the wall to gain momentum, subsequently helped her to successfully reason that momentum could be considered as being conserved.

I: Now in terms of conservation, if you're saying that the car passes a bit on to the building, what happens to the bit it is not passing on?

S25: When the car rolls back.

I: So what is the car doing? Is it keeping some of the momentum? If you do the total before, just the car, versus the total after, how do you think they compare?

S25: I don't think it would be the same.

I: If you added the two bits together?

S25: Yeah.

I: So what do you think is happening, is there more or less after?

S25: Less.

I: So what has happened to the missing bit? The bit that you are saying is gone somewhere.

S25: The car still has it.

I: But that is still being counted because we are including the car are we not, after? It is still moving so we include it. It is part of the deal because before it is car and building, just the building happens not to be going anywhere or doing anything, after it is still car plus building.

S25: Yeah, so the car has more than the building.

I: Yeah, but if you add the car plus the building after, compared with just the car plus the building which wasn't doing anything before, how would the total before compare with the total after?

S25: It would be the same.

I: How sure are you?

S25: Three.

I: Now you have changed. Why have you changed?

S25: Changed what?

I: You've changed from saying it isn't conserved to now saying it is. What has made the difference?

S25: Because I don't know where else it would go.

Prior to working with analogy two, her opinion was that momentum was not conserved (belief rating 3). Now she was saying that she thought that momentum was conserved (belief rating 3). The statement in which she said "I don't know where else it would go" is particularly significant as it suggests that she had been comparing alternative ideas in an attempt to explain what happened to the momentum as a consequence of the collision. Therefore the conceptual change that had occurred resulted from a decision that momentum being transferred to the building was the best explanatory option, and consequently she reasoned that momentum was being conserved when both the building and the car were considered as being part of an inter-dependent system.

The categories of conceptual change that student 25 was considered to have exhibited were the same as those discussed in relation to student 21 above. Although it is clear that student 25 had decided that momentum could be transferred to a large object, and that momentum was conserved in the system consisting of both the car and the building, it cannot be claimed from the interview data that she demonstrated 'accommodation' according to the criteria of Posner et al. (1982). Similarly, it cannot be shown that she had fulfilled Vosniadou's criteria for 'framework' theory alteration, or Tiberghien's equivalent of changes to her 'underlying' theory. Her comments do not indicate that she had changed her 'central concepts' and so it was not possible to categorically state that she had altered her 'generalised' theory about momentum, although her 'specific' theory, regarding the car and building, was clearly revised.

Student 47 also changed her views about conservation of momentum, deciding that it was conserved after working with analogy two. In addition, she became more convinced (belief level 4) that momentum was being transferred to the wall having previously been rating herself at level three for the same idea. She also began the process of developing a perceived mechanism for the transfer of momentum to the building.

Her justification for stating that momentum was conserved in the analogy showed a good level of logical reasoning, based on the fact that she could feel that her hand moved when the ball-bearing collided with it. When asked to explain her thinking further however, it became evident that she was also relying heavily on what she had been taught for justification.

I: Did you feel anything?

S47: I could feel it slightly.

I: What could you feel?

S47: The ball pressing on to it and then bouncing back.

I: Does that suggest anything happening to your hand?

S47: That it's slightly moving.

I: So there's a slight movement there, is that what you're saying.

S47: Slight movement.

I: Now in terms of momentum what's happening there? Tell me the story of the momentum from the beginning.

S47: When it hits, it travel backwards, but momentum should be less since this one moved, but it has to both (that moving backwards, plus the momentum of the hand) has to equal the momentum before. It's that conservation.

I: Ok, now, interesting phrase there, 'has to' equal. Is that what you believe or are you just going by what you've been told.

S47: What I've been told.

I: How true do you think it is in the situation?

S47: About a four, still.

I: So you're saying here you think momentum probably is being conserved?

S47: Yeah.

A few minutes later, she was asked to state how the analogy compared with the target situation. Her answers make it apparent that she had experienced conceptual change as a result of being able to identify several surface and deep (theory) level similarities between the two situations. These connections were the triggering factor in her making progress as can be seen in the following extract.

I: In terms of what happens to momentum are there any similarities or differences do you think?

S47: I think they're quite similar because then the momentum of the ball, which represents the car, would be less, afterwards - after it's crashed and moving backwards.

I: Mmm, hmm. And the wall?

S47: The wall, since I thought there was a tiny bit of movement, 'cause I could feel it pressing in which is sort of movement, that could be like the wall moving but not enough to actually break it.

I: How convinced are you that that's right, 'cause you didn't mention that before so that seems like a new idea?

S47: Yeah. Still about a four.

I: Fairly sure of that?

S47: Yeah.

I: So where did you get that idea from?

S47: Just the fact that when it hit off I could feel that one bounce back but yet I could feel something happening to my hand. It's like indentation of my hand. It had to press off that to move back.

I: And are you saying there's maybe something similar happening in the wall?

S47: Yeah, that's what I'm thinking.

It then became apparent that she had also changed her views about conservation of momentum in the target situation and had started to think about the possibility of the building moving a little in some way as a direct result of making these connections.

I: Now, tell me what you're thinking is in terms of momentum, in the original? In terms of it being the same before and after or different before and after.

S47: I think it should be the same now.

I: Why have you changed?

S47: Just after that last one I felt it pressing, it makes me think that the wall could in fact move slightly, but it won't maybe move as much to actually break it.

I: Mmm, hmm.

S47: I'm thinking it still moves but it won't be like enough for us to actually see that it's moved 'cause it'll just go back.

I: So are you saying that you're more convinced that the wall's got momentum now, is that what you're saying?

S47: Mmm, hmm.

I: How convinced are you on that scale of one to six that the wall ends up with some momentum?

S47: I think it'll be about maybe four-ish.

I: Is that more confident than before, or less?

S47: More confident than before.

I: What would you have said if I'd asked you earlier how confident you were that the wall ended up with momentum?

S47: [Laughs]. I'd have thought it was a bit stupid, so probably about a three.

I: So it's gone up a wee bit?

S47: Yeah, it's gone up a bit.

I: Ok, now, how sure are you, you seem to have changed from saying it's not conserved, momentum's not conserved here, to saying it is? Am I picking that up correctly, or have I got that wrong?

S47: Yeah. You've got it right.

I: How convinced are you that that's true? You were giving it a three or a four, saying that it wasn't conserved. You're now changing and saying it is conserved, I think?

S47: Mmm, hmm.

I: How sure are you that that's right?

S47: I'd say about a four.

I: So you've flipped completely to the other side but you're as sure?

S47: Yeah.

I: Why such a big change, because that's a fairly big change?

S47: [Laughs] I don't know, it's just after feeling that move, it's made me think that the wall maybe could absorb some of it.

I: Ok. And because you're happier that the wall's got momentum, you're happier to think it's conserved?

S47: Yeah.

In order to check that she had really changed her mind, her previous idea about momentum being lost was explored. It became apparent during this discussion that she had also been trying to reconcile the difference between momentum and kinetic energy during this phase of the interview, and this was causing her to experience a degree of cognitive conflict.

I: Before you were saying something about losing momentum?

S47: Yeah.

I: Have you gone off that idea?

S47: I still think it might lose slightly some, but I'm not that sure if it would be momentum or more kinetic energy.

I: Which do you think's more likely to be lost?

S47: Kinetic energy.

I: Why are you thinking of that?

S47: ’Cause that can be changed to other forms of energy, like heat, whereas I don’t think momentum could really be changed to heat or anything.

I: Why?

S47: Don’t think, ’cause I think momentum’s more to do with the energy of kind of like movement.

I: Mmm, hmm.

S47: Rather than, actual…

I: So is it because you’re not quite sure what the difference is between momentum and kinetic energy that’s causing a bit of confusion, is that what it is?

S47: Yeah.

I: Ok. But you’re thinking momentum can’t easily be changed in to other things, is that what you’re saying, but kinetic energy can?

S47: Yeah, that’s what I’m saying.

She was displaying clear signs of a ‘twin-tracking’ thought process, through which she was attempting to resolve her difficulties. It is apparent from this discussion that the process of conceptual change is far from straight-forward, and that it is non-linear in nature. It seems to involve the learner in undertaking a series of comparative processes, during which various ideas and pieces of knowledge are connected on the basis of whether or not they appear to be linked and the extent to which they make more sense than alternatives. It can also be argued from this data that existing mental links are sometimes weakened, or possibly severed completely, as a result of other more intelligible, believable or connectable ideas taking precedence over them.

This process was also exhibited by student 52 who also experienced conceptual change which resulted in him deciding that momentum was being conserved in the target situation by the end of analogy 2, with a belief rating of four, having previously said the opposite at a the same belief rating of four. The ball-bearing causing a dent in the skin of his hand was instrumental in making him change his mind as he was able to state clearly that it showed that momentum was being transferred to his hand. Despite this progress, he showed that he was experiencing some cognitive conflict in relation to the impulse equation in order to decide whether or not momentum was being conserved when the car struck the building.

I: Tell me what you think is happening when the car hits the building then, about conservation of momentum or not, and what you think is happening? First of all what are your thoughts about the total momentum before versus after, in this collision?

S52: It's, …, (long pause).

I: Tell me what you are thinking?

S52: I'm thinking about the equation of impulse, which is ft = mv – mu. Eh, so because of the mv – mu. I'm thinking there is a difference in momentum.

I: But is that overall, or is that just an individual object?

S52: That's for an individual object.

I: So what about the overall momentum before versus the overall momentum after, in that collision, what do you think? How sure are you?

S52: Four.

Having remembered that the equation did not apply to the overall situation, but only to an individual object, he was able to disconnect this idea from his thinking about the momentum of the system of the car and the building. This resulted in his confidence level in the idea that the total momentum was conserved increasing from a three, which he had stated a minute or so previously, to a four.

When he was asked to explain how this shift in thinking came about, his answer showed that he was also trying to reason out a mechanism that he felt could explain how the momentum was transferred to the wall.

I: Why you are giving it a 4 whereas before you were just a given it a 2 or a 3 or something?

S52: I don't know, I'm just understanding it a bit better

I: Why? What is going on that is making you understand it better?

S52: Eh, just going through the process of, …, ruling out things.

It is very clear from this comment that he was using a twin-tracking process to compare ideas and was using this to decide which made more sense to him as an explanatory tool. He then used a mixture of logic and comparisons with the previous two analogies in order to come up with a satisfactory solution to his dilemma as shown below.

I: So what’s the process? You say you are trying to work out what you are saying. Are you comparing stuff?

S52: Yeah, I'm comparing the two ball-bearings, …, with the car and the wall, and the ball-bearings in the hand.

I: And what is your thinking when you are comparing this?

S52: Where is the momentum going, and how, …?

I: What conclusion have you got? So if we take the car hitting the wall, what happens to the momentum? You’re sort of sure that it’s total after is the same as the total before. So what is happening to that momentum that the car had at the start?

S52: It’s gone back into the car

I: All of it, or some of it?

S52: …I'm not sure, because the velocity afterwards is less.

I: So what does that suggest to you? What does that make you think?

S52: That not all of it is.

I: So where is the bit that is not in the car?

S52: That’s what I’m not sure about,

I: Where do you think it might be?

S52: Em, …..

I: You were saying a minute ago that you were comparing the previous two analogies to that, do they suggest anything to you, as to where it might be?

S52: In the wall.

I: How likely do you feel that is? How much do you believe that?

S52: A three or four.

I: How come? Explain?

S52: Because it has to go somewhere. Em, …, so, …., and it’s not going back into the car and the only other place it could go, is the wall

I: So why is that, em, what is it about that that’s making you wary, because it sounds like you are a bit wary about that idea?

S52: Yeah. I'm not sure whether a wall can have momentum that’s all.

I: Why?

S52: Because it’s a solid object that in this case probably won’t move all.

Student 58 had similar struggles in her reasoning, as she also engaged in ‘twin-tracking’ as she moved from stating that momentum was lost in the target situation, at the end of analogy one, to deciding that it was being conserved by the end of analogy two. In particular, she struggled to decide whether or not momentum was conserved when the ball-bearing ran into her hand. However, the extract below demonstrates that she began to make significant progress when she began to realise that her hand and arm had a much greater mass than the ball-bearing.

S58: Yeah, it's disappearing somewhere, because, …, it might just be because your hand is slightly bigger proportionally than the ball.

I: Go on?

S58: But, I don't know, it just doesn't make sense that, …, I think there is a transfer of the momentum going on, but, ...

I: From ball to hand?

S58: From ball to hand, but I think that there might be a little, there is some form of momentum is lost.

I: Overall lost?

S58: Overall lost.

I: So, it's not in your hand?

S58: Yeah.

I: It's somewhere?

S58: It's somewhere.

I: Why do you think that?

S58: Eh, because, …, the ball loses momentum and it loses quite a lot of it, but your hand only gains only a little bit of it, you can only feel a little bit of it.

I: How do you know that it only gains a little, what are you basing that on?

S58: Eh, …, by what I feel and how much my hand moves.

I: Does the fact that your hand is bigger than the ball - you mentioned that earlier - has that got anything to do with it?

S58: I think so, because it would take a lot more, …, momentum to move that, so maybe the ball is, …, maybe there is no momentum lost. It's just that your hand is bigger, and so it would take more of a bigger momentum to make it move as fast.

I: So which of those two stories are you more inclined to go with?

S58: Eh, …, the second one actually.

I: Why? Why have you changed?

S58: Because the size is completely proportional, when you work it out, the momentum is p = , …, m x v, and the mass of my hand is bigger than the mass of this ball, even though this ball is heavier, it's still bigger, the hand is bigger?

I: Ok, so tell me your story then in terms of momentum there? Before versus after, what's your current thinking?

S58: Before the impact the ball has, …, greater momentum than when it hits the hand but, …, it transfers some momentum to the hand and then it has less momentum, but there is no momentum lost because your hand has taken in the momentum the ball has transferred to it.

I: How convinced are you that that's true?

S58: … A five.

I: A five. So you have one from saying that we have lost momentum, and now you're saying I'm level five out of six, that you think the total momentum before and after are the same?

S58: Eh, yeah.

I: Ok, so why the sudden, fairly big change it has to be said, what has made the difference in your thinking?

S58: I think because the way the mass, of your hand is completely different than the mass of the ball, so when it hits, its momentum is transferred, your hand is still bigger so it would take a lot more momentum for it to move as fast.

Having established the significance of the difference in mass between the ball-bearing and her hand, she then successfully made clear links between the analogy and the target situation which enabled her to encounter and demonstrate that she had undergone clear conceptual change that was coded as being of the same types as students 21 and 25 discussed above.

I: Ok, so how does the one with the ball and the hand compare with the original of the car and the wall?

S58: A lot more than the two balls together, because, …, if you were to make the car go fast and hit the wall, the wall would take, would have some momentum transferred into it, and the car would have very little or none, but it would still be left with the same amount of momentum.

I: Before and after?

S58: Before and after.

I: And how, …, you're saying that the total momentum before and after the collision, in the car and the wall is the same, is that what you're saying?

S58: Yeah.

I: How sure are you that you're right?

S58: A four.

I: About a four. How do you explain the wall getting momentum?

S58: Eh, the momentum from the car, when it collides with the wall is transferred into the wall.

When she was the asked to identify the reasons for her change in thinking, it became evident that (like student 47, discussed above) the main conceptual change trigger for her was experiencing the ball-bearing running into her hand, which is clearly demonstrated by her comments shown below. This resulted in an increase in the intelligibility and believability of momentum conservation, but it also enabled her to give a clear explanation of what she thought would have happened in the target situation; the analogy had enabled her thinking to become more 'fruitful' in the sense that Posner et al. (1982) use the phrase to imply that it was useful in explaining another situation.

I: And how would you explain that to somebody, because earlier you said that 'no way'?

S58: Eh, …, just because you can't see a physical movement doesn't mean it's not happening and to move the wall as fast as the car you would have to have a lot more momentum probably some wheels involved.

I: Now what has convinced you of that? Because you sound reasonably convinced?

S58: I think from actually doing the experiment with the hand and the ball

I: And why did that help?

S58: Because you can feel, you can imagine that that [the hand] is the wall and that [the ball-bearing] is the car and you can feel, …, that even though there is still some left in the ball, you can feel that it is in your hand that you are getting something.

I: And that is making you think that the wall is getting something?

S58: Yeah.

I: How convinced are you of the story about the car giving momentum to the wall is right?

S58: A four and a half.

I: And how convinced are you that the total before and after here, is the same - which is what you seem to be saying?

S58: A four and a half maybe, a four, four and a half.

6.4 Analogy three

The third analogy required the students to run the ball-bearing that they had run into their hand in the previous analogy into a set of three identical ball-bearings. The student observed that the first ball stopped, the first two balls in the group of three did not move, but the third one moved off at the same speed that the original one had prior to its collision with the others. It was hoped that this analogy would encourage the students to consider the momentum that the building received being transferred from brick to brick and ultimately to the earth. In practice, it was found that certain aspects of this analogy caused difficulties for some students, while other students underwent conceptual change towards the accepted reasoning. A total of nineteen students rated this as one of the most useful analogies in the sequence in helping them to develop their 'immoveable wall' theory.

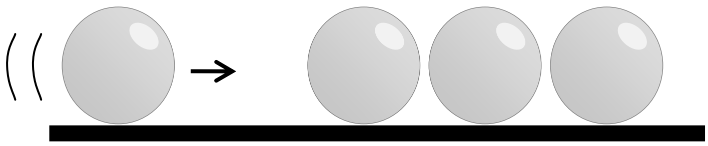


Figure 6.5: Analogy 3 - Ball running into a set of identical balls.

Twelve of the students clearly increased their belief-rating regarding conservation of momentum in the target situation by the end of this analogy, while another twelve had not changed their belief rating, including three students who continued to state their prior opinion that momentum was not being conserved in the target situation. Changes in the belief-ratings of the other six students were unclear, sometimes because they were not asked for a belief-rating as a result of the direction in which the conversation had developed. Sixteen of the students developed their 'immoveable wall' theory by including a new feature. Students 52 and 58 clearly found this analogy confusing as they both changed from saying that momentum was conserved in the target situation, to stating that they thought that it wasn't by the end of this analogy. Figure 6.6 below, summarises the number of students who were stating each of the identified theories at the end of analogy two (figure 6.6a) and by the end of the third analogy (figure 6.6b). Figure 6.6a contains the same information as figure 6.3b, given earlier. This enables comparisons to be made readily between the overall numbers of students who held each theoretical stance at the end of the successive analogies.

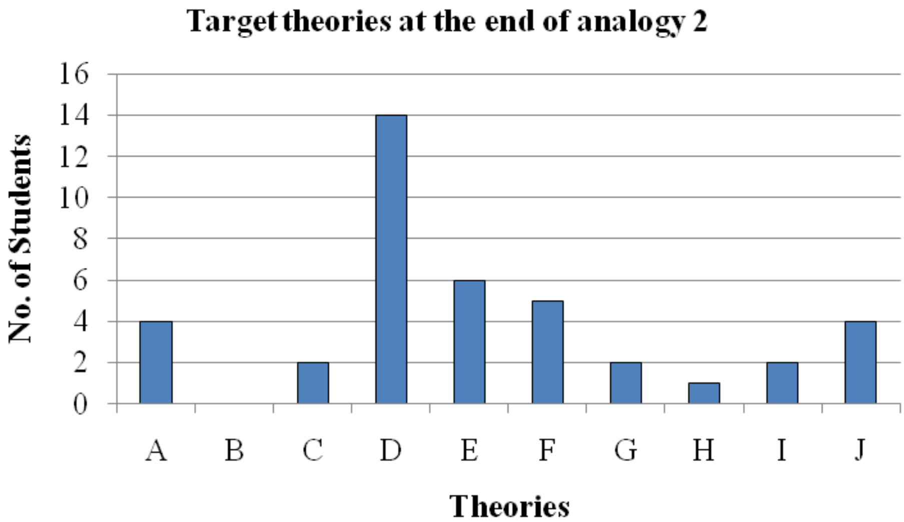


Figure 6.6a: Number of students stating each 'immoveable' wall theory at the end of analogy two.

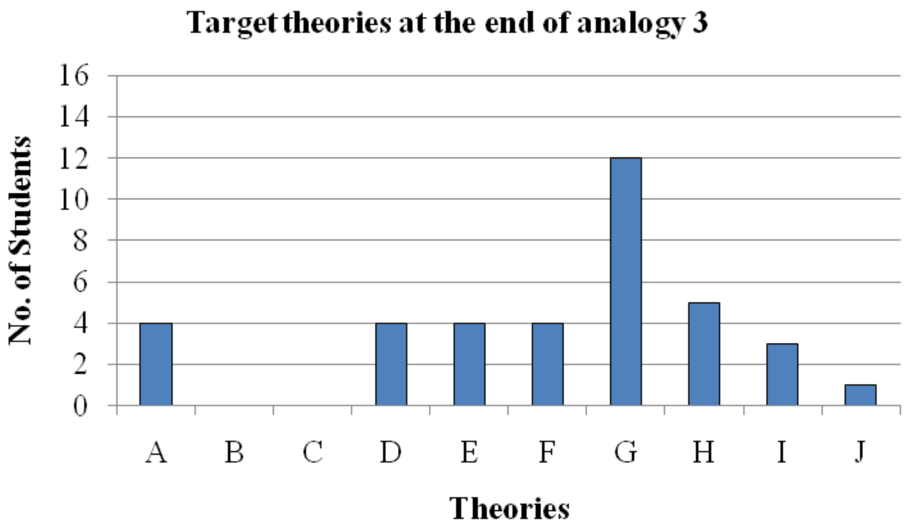


Figure 6.6b: Number of students stating each 'immoveable' wall theory at the end of analogy three.

6.4.1 Conceptual difficulties encountered by students in analogy three

The most common problem encountered by students in working with this analogy was attempting to relate the movement of the last ball-bearing to what happened when the car hit the building. They had noticed that the last ball-bearing in the analogical scenario had moved off at the same speed that the first ball-bearing had collided with the set of three. This perturbed several of the students as the building or wall that the car collided with did not behave in a similar manner because bricks would not be ejected from the far end of the wall or the entire building as a consequence of the collision.

6.4.2 Negative conceptual changes resulting from interaction with analogy three

This problem resulted in one student changing their prior answer, and concluding at the end of this analogy that momentum was not being conserved in the target situation. The following extract from the interview with student 58 demonstrates how this came about. She started off being sure that momentum was conserved (belief-rating of five) based on her observations linked with logical reasoning and the intelligibility of the idea, as she was able to give a well-reasoned argument for her conclusion, which was as follows.

> S58: The momentum, from the first ball, …, is being, …, transferred through the first two and then the third, which gives that, the momentum obviously to move.
>
> I: Now, total momentum before the collision, versus total after, how do you think they are comparing there?
>
> S58: Eh, …, it's a bit strange that the balls don't move, the other two, …, but I think, eh, the total momentum after and the total momentum before are the same.
>
> I: How sure are you that that is right?
>
> S58: Eh, quite sure, because obviously you can't tell without a speedometer, and a light gate, but eh, ..., they do look like they are going roughly the same speed as before.

She subsequently displayed clear signs of cognitive conflict and twin-tracking when she was asked how she thought the three ball-bearings compared with the wall. Her difficulty centred on the behaviour of the last ball-bearing when it was ejected from the group of three. She had incorporated the concept of the momentum being transferred from brick to brick for the first time, but the lack of movement of bricks at the far edge of the building caused her great difficulty, which she openly acknowledged.

S58: I think it's similar, in the way that the momentum was transferred through all the different bits, so to speak.

I: Through the different bricks? Is that what you are saying?

S58: Yeah. So, depending on how thick the wall was, maybe by the time you got to the very last brick on the edge of the wall, the transfer would be so much that it's lost, that it's just not, ...

I: When you say lost, what do you mean?

S58: I don't know, it's just, …, I can't describe it, without completely contradicting myself.

I: Does momentum get lost as it goes from brick to brick to brick, is that what you are saying? Or is there something different happening?

S58: I think it's, …, it's more losing energy than it is losing momentum, I don't know, I can't describe it.

I: So, how would you justify, you are saying that this wall is getting momentum, what is your thinking, to justify that?

S58: Eh, because, you can see, …, that when you click the two balls, when you hit them together, the last one moves away because it has gained this momentum, eh, from the other two. But in the brick wall, …, there is a lot more of the transfer going on.

I: Brick, to brick, to brick?

S58: Brick to brick, which is confusing me, because if it was brick to brick to brick, then a brick would fall out somewhere, that is just how I would see it. If it hits here, then a brick over here would eventually fall out.

I: So, why do think, ..., well bricks generally don't, is what you are suggesting? So, why do you think that is?

S58: Eh?

I: Why don't they fly out the other side? Because you are saying that's what is happening here. But you seem to be worrying about the fact that that doesn't happen in the wall, any idea why?

S58: Maybe there isn't actually conservation of energy, perhaps, there is momentum lost.

I: In the brick one?

S58: In the bricks.

At this point, she had come to the conclusion that momentum was not being conserved and acknowledged that she had changed her mind again. Her reasoning for reverting back to saying that momentum was not being conserved was then explored and found to be related to the mismatch between what happened in the analogy and in the real-life scenario; the two situations did not concur sufficiently well with one another in her mind. This resulted in her reverting back to previous thinking from the end of analogy one. In effect she was making a judgement based on the fact that the two situations were too dissimilar to enable a robust link to be made. This caused her to engage in a twin-tracking process whereby she concluded that the most intelligible explanation was that the lack of movement implied a loss of momentum. She had rejected, or forgotten, her previous vague idea that the huge mass of the building would result in a very small amount of movement. This concept had evidently not been strongly embedded in her existing cognitive model. The link between momentum and the requirement in her mind for perceptible motion was evidently very strong. It could be argued that the idea that the very large mass of the building compensated for the lack of perceivable movement (which she mentioned in vague terms while thinking about the second analogy) was rather 'distant' from her core concepts about momentum, and had therefore not been connected robustly enough to withstand the attack from the cognitive conflict.

I: So, tell me what your thinking is then? What is your overall feel for it?

S58: What, in a number scale?

I: Aye, but first of all, do you think that momentum is or isn't being conserved here?

S58: I don't think it is being conserved.

I: So, you have changed round completely?

S58: Again.

I: Why?

S58: Because you can't, …, the bricks don't fall out, which, …, if you regard these as bricks, and that as the car, …, you kind of expect it to, because this has gained the momentum.

In an attempt to encourage her to formulate a reason for the difference in the behaviour in the two situations, she was reminded that the wall had mortar holding the bricks in place, and she was asked to consider whether or not this might explain the differences. Although she appeared to partially integrate this idea into her thought process, it did not give her a compelling enough reason to revise her conclusion because the connection between the concepts of momentum and motion was too strong.

I: So, does the fact that they are mortared in, does that have anything to do with the fact, from what you are saying the bricks don't fly out the other end, or is that irrelevant?

S58: It's probably, …, is quite important, because they can't move, because the mortar is holding them.

I: So, does that explain what is happening here versus here or not? Are you still thinking that this must be losing momentum because the bricks don't come out?

S58: I'm not sure.

Student 52 also reverted back to a prior answer by the end of this analogy because he could not reconcile the analogy with his recurring perception of a lack of motion in the wall after the collision. When he was asked at the end of the analogy to summarise his thoughts regarding the car and wall, he initially failed to include both the car and the building in his reckoning about the momentum after the collision. However, when he was challenged about this he adjusted his thinking. As a result of this he became more confident that momentum was conserved, and more confident that it was being transferred to the building as can be seen in the following extract.

I: So, tell me what you think is going on there, if anything? So give me a summary of what you are thinking at the moment? The car comes in, and what happens to the momentum? Before versus after, are you saying that it's conserved or not?

S52: Eh, …, it isn't conserved because momentum is going into the wall

I: Yeah but the total before versus the total after I'm not just talking about just the car, I'm talking abut the car and the wall as a together job

S52: Yeah, it is conserved.

I: How sure are you?

S52: Five.

I: It's gone up again why?

S52: Because I remember the equation $m_1u_1 + m_2 u_2$ = the total momentum

I: So, you are using the equation. What are you saying is happening to the momentum of the car then?

S52: Decreases after it hits the wall.

I: And what happens to the bit that goes away (for the want of a better phrase), where is it going? The bit that the car doesn't have anymore, in other words, where is it?

S52: Eh, …, in the wall.

I: How sure are you of that?

S52: Four or five.

I: Has that gone up again?

S52: Yeah.

He was then asked, immediately after this, to explain why he had become more confident. As he considered his answer to this question, he reverted back to his evidently deep-seated concept that the building could not move.

I: Why?

S52: Because, …, the car has a mass and a velocity and the wall has a mass and a velocity even though the velocity is zero.

I: So if it's zero, how do you end up with a momentum?

S52: Because the two masses and the two velocities right, the car has momentum and the wall has no momentum, because it's a multiplication of zero.

I: Is this before or after?

S52: Before, before the wall has no momentum and the car has momentum.

I: And what about after?

S52: After, eh, it would be, …, two masses x, …

I: Do you think there is any kind of motion in that wall?

S52: No.

I: After the car hits it.

S52: No.

I: None? So, explain, because you said a second ago that you thought it got momentum, how do you explain momentum and the wall, if there is no movement? Because those two statements seem to be contradicting each other.

S52: The wall has a mass and a velocity of zero, so that means the momentum equals zero.

I: Of the wall?

S52: Yes.

I: Is this after?

S52: Yes.

I: So, where is the momentum that the car's no longer got any more going? If it's not in the wall where is it going, in your opinion?

S52: Don't know. I've gone round in circles.

Although he appeared to have become more convinced about momentum being conserved in the target scenario, when he was interrogated about his underlying reasoning, his pre-conception regarding the non-movement of the building re-emerged. This casts doubt on the extent of his previous conceptual change. His thought process was clearly exhibiting twin-tracking, and he acknowledged at the end of this extract that he had become confused as he tried to decide which of the two competing ideas was the most intelligible. The new explanatory links that he made between the large mass and the correspondingly small velocity of an object as he considered both analogies two and three, appeared to have enabled him to make progress. Indeed, he was clearly arguing at the end of the third analogy that the building had gained some momentum from the car. He then became confused when he stated that the building would have a velocity of zero. It became apparent from this that he had been comparing the newly acquired concepts with his prior mental model, in which the building was too large to enable any movement. The new connections were evidently not robust or compelling enough to sever the pre-existing links in his mental schema. Arguably, this could have occurred because the new knowledge was still perceived as being too far removed from his existing ideas. Consequently, he could not make a strong enough link between them at this stage in order to displace his prior reasoning.

6.4.3 Non - changes resulting from interaction with analogy three

As discussed above, twelve students had not changed their belief-rating about conservation of energy in the target situation. Three of these students (4, 6 and 8) continued to state their prior opinion that momentum was not being conserved when the car struck the building. Students 4 and 8 continued to think that momentum was lost as it was changed into heat, sound and kinetic energy as a result of friction. Both students maintained their theory that some momentum would be transferred from the car to the building. Student 4 was still not able to give any explanation for this but student 8 maintained his theory that the transfer could be explained in terms of the building shaking slightly. The perceptions of both of these students were such that momentum and energy overlapped so much in their thinking that they could not separate them and none of the features of this analogy or the previous ones were sufficiently compelling to make them alter their existing schema.

Student 6 deduced that momentum was conserved in the analogy (belief-rating four) as a result of it being transferred from ball to ball, but only gave the idea a belief-rating of two. Despite this, he maintained his position that momentum was not conserved in the target situation. When asked to compare the third analogy with the target situation it became clear that he was comparing ideas and trying to decide which was the most plausible to him.

S6: I don't know. I keep changing my mind.

I: Why are you changing your mind? What is causing that?

S6: Just the way that they acted there. How the momentum, how I thought the momentum transferred.

I: In the analogy? So do you think that is going on here?

S6: I think I've changed my mind again. I think it transfers the momentum to the building then the momentum moves through the building and then it can't move it in the end so it comes back.

I: So you've come back to through the building and reflecting back? If I asked you here, total momentum before versus total momentum after including the building and the car, how would those two figures compare in your opinion?

S6: I don't think they would be equal because I just have an idea that it would lose momentum somewhere.

I: But you're not sure where.

S6: No.

I: So you see that as different from that, is that what you're saying?

S6: Yeah. Because that is different, in that that is bigger and it can't move. That car won't be able to move it.

At this point he attempted to merge the various facets of his thinking so far by devising a hybrid theory that momentum was transferred and reflected but also lost in the interaction. He was still unable to clearly articulate a mechanism for this perceived loss, but his reasoning (which came to light during analogy two) was based on the reduction in the magnitude of the velocity of both the ball-bearing after the collision with his hand, and the car after its collision with the building. The loss theory was also driven by his basic premise that the building could not gain momentum because he felt that it could not move as a result of its large mass. His comments above suggest that he was experiencing cognitive conflict and engaging in twin-tracking, caused by a realisation that his argument for loss of momentum was not entirely satisfactory and primarily based on instinctive reasoning. By the end of analogy two he had appeared to have begun to tentatively decide that the large mass resulted in a tiny amount of movement, but the explanatory connections made between this new knowledge and his existing mental model were evidently not sufficiently compelling to overcome his existing reasoning.

6.4.4 Positive conceptual changes resulting from interaction with analogy three

In contrast with students 4, 6 and 8, the most notable conceptual change was experienced by student 20 who reversed his opinion and ultimately came to the conclusion that momentum was being conserved by the end of the third analogy. The process by which he experienced this conceptual change was informative but not straightforward. He changed his mind several times as he experienced cognitive conflict. He decided quite quickly that momentum was conserved in the analogical situation (with a belief-rating of four) but it became clear that he thought that each ball kept some of the momentum that was transferred into it. After careful probing of his thinking, he ultimately decided, via a logic process which was driven by the visual evidence, that the momentum was passed from one ball-bearing to the next until it was all transferred to the fourth.

S20: These three have been together so the momentum is passed through these two but because there is a mass, …

I: So, ball one comes in with the momentum, tell me what happens to it.

S20: It hits ball two.

I: And does what with the momentum?

S20: Passes the momentum through to ball three which passes the momentum through to ball four but ball four has nothing pushing against it, so it moves.

I: So it heads off like that?

S20: Yeah, it heads off.

I: And does it take all the momentum that that had to start with?

S20: I don't think so. I think that some momentum was put into these two.

I: And stays there? Does it stay in those two?

S20: I think so.

I: How would you justify that?

S20: Because it has had to pass through these so there must have been some movement for this to hit that one and that to hit the other one.

I: But once it has hit that one, what happens to it? Once two hits three, what happens to it?

S20: The momentum is passed through to, …

I: Does two stop once it hits three?

S20: Yeah, two stops.

I: So, does that mean that it has got momentum in it still?

S20: It has lost momentum.

I: So, where is its momentum?

S20: In three.

I: And what happens to it when it hits four?

S20: It passes its momentum on and it stays, …

I: So tell me what you think is happening. Start from ball one to ball four, tell me what you think is happening.

S20: This ball hits ball two which passes momentum on to ball three, …

I: All of it?

S20: Yeah, it must because ball two is not moving after, and the same goes for ball three, and then it hits ball four which can move because it is not being pushed back.

This progress was short lived as he was unsure whether or not momentum was being conserved as it transferred from one ball-bearing to the next. He struggled to understand the transfer of momentum between the second and the third ball-bearing because neither of them moved as a consequence of the collision. In the end he resolved the problem when he was encouraged to re-examine the speed of the fourth ball-bearing after the collision, in comparison to the speed of the first before the collision.

S20: I think it [the speed of the fourth ball-bearing] is the same.

I: So what does that make you think?

S20: That momentum is conserved throughout the whole system.

I: How sure are you of that idea?

S20: Four or five I think now actually looking at the speeds.

I: What has changed your mind? What has convinced you?

S20: By looking at the speed that that is hitting that, they look roughly the same.

When he was asked to compare this analogy with the previous one he thought that the two ball-bearings that didn't noticeably move were similar to his hand, but that the fourth ball-bearing was different because it moved. He gave a similar response in relation to the building in the target situation as he felt that ball-bearings two and three behaved in a similar manner to the wall. The movement of the fourth ball-bearing did not appear to concern him. He then made progress in his thinking when he was guided a little to think about the structure of the wall.

S20: Only two of them, these two because they are not moving off. Like the wall they are stationary after they are hit.

I: Is the wall made up of bits in any way like that set are?

S20: Do you mean like rooms?

I: What is the wall made of?

S20: Bricks.

I: Do you think those balls represent the bricks in any way?

S20: Yes. I suppose you could say that.

I: Go on. Tell me what you are thinking.

S20: It is like this brick hits that brick and if there was nothing behind this one, it would push off so there must be momentum put into the wall. Yeah.

I: How convinced are you that the wall is getting momentum?

S20: Four or five.

I: It's gone up. Why has it gone up?

S20: I am just thinking it through logically.

I: Now how would you say the total of the car compares with the car and the brick wall after the collision? Is it conserved or not, in your opinion?

S20: Conserved.

I: You have changed your mind. Why?

S20: These other analogies have made me think about it.

I: So what is it made you think it is now conserved? Because before you were saying it was losing a wee bit. Why have you changed your mind? What is going on?

S20: From looking at this, because of the speed of this ball and the speed of the last ball leaving, to me they look roughly the same so that has made me think that there can't be momentum lost.

I: So why are you now thinking there isn't momentum here with the brick wall, whereas before you were saying that you were fairly sure that there was momentum going into the wall but you didn't think all of it was, you thought there was some getting lost?

S20: It was because that is not moving after it is hit whereas that is.

I: But you think there is enough similarity that you're saying you are more convinced that there is now momentum getting conserved here?

S20: Yeah.

I: How sure are you?

S20: About a four.

I: That's fairly sure. Is it this one that has caused you to think like that?

S20: Yeah.

This extract demonstrates that he had experienced conceptual change as a consequence of making connections between all three of the analogies that he had tackled up to this point. Rather than being concerned about the movement of the fourth ball-bearing in comparison to the behaviour of the building, he used visual cues from the analogical situation to reason out that momentum must be conserved in the analogy. He demonstrated by his response that he was able to use features of the analogy selectively in order to work out what he believed happened when the car hit the building, which is an important skill to develop in order to make successful use of an analogy. This extract in particular, also corroborates the arguments of Spiro et al. (1989) who, as discussed above, argue that the use of a series of carefully chosen, linked analogies can reduce the undesirable side-effects that a single analogy can cause. Student 20 was able to make appropriate use of the evidence provided by the fourth ball-bearing but was also successful in determining that its behaviour could not be mapped to the behaviour of the target, and consequently discounted it from his thinking about the need for perceptible motion for momentum to be considered as conserved.

In common with several other students, student 28 became slightly more convinced that momentum was being conserved in the target situation as his belief-rating rose by one point.

Ten students developed their ‘immoveable wall’ theory as a result of their experience with this analogy to include for the first time the concept that the momentum was being transferred through the wall of the building from one brick to the next, or in one case, from molecule to molecule. One example of this change in thinking was demonstrated by student 28 who had previously only stated vaguely that the momentum “passed through the bricks”. As he tried to make comparisons between the analogy and the target he initially mentioned that bricks on the far side of the wall would move. When he was asked if this idea was critical to his conclusion that momentum was conserved, his conclusion and related reasoning process demonstrated that he had experienced conceptual change. His reasoning was robust enough to cope with the challenge and enabled him to enunciate his new idea.

I: In terms of going back to this, the original car going into the brick wall, can you tell me any similarities or differences between this situation and this one?

S28: (Long pause).

I: Tell me what you are thinking.

S28: (Long pause). The two middle balls would act as the bricks.

I: In what way?

S28: That the car hit. But the bricks at the other side would have the momentum.

I: So, tell me what you think is happening to the momentum here with the bricks?

S28: The momentum would go through the wall and the bricks at the other side that the car hit would move off.

I: So you think there might be some damage on the outside edge of the wall possibly?

S28: Yeah.

I: What if there wasn’t? Would that ruin your story or would you still say that there was momentum getting transferred through the bricks? What happens if a brick doesn’t ping out that end? Does that ruin your thinking?

S28: There might not have been enough momentum to make it move.

I: Why would that be? What would stop it moving?

S28: It's connected to the rest of the bricks.

I: Using what?

S28: Cement.

I: So, it may or may not ping out but it wouldn't totally surprise you if something did? Is that what you're saying?

S28: Yeah.

I: So, tell me what you think is happening, the car comes in with momentum, it hits the wall, tell me the rest of the story.

S28: The momentum would go through the wall.

I: Brick by brick or the whole wall at once?

S28: Brick by brick.

I: Why do you think that?

S28: (Long pause).

I: What has made you think that? Because you did mention that earlier but is there anything in particular that is making you think that that is the case at the moment?

S28: That [pointing to the analogy], with the two middle balls.

I: Because you saw that? That's made you think that?

S28: Yeah.

I: How convinced are you that your theory is right? On that scale of one to six.

S28: A four.

I: It's gone up again. Why has it gone up?

S28: Because it seems reasonable.

I: Based on what?

S28: The momentum can make a stationary object move.

I: And has it got something to do with what you saw there? Is that helping you to think it through would you say?

S28: Yeah.

The conceptual change was primarily triggered by him making connections between the analogy and the target situation. The visual clues that he had considered and interpreted using a mixture of logical reasoning and judgements about the intelligibility of this new thinking as an explanatory tool were also triggering factors.

Five students exhibited a greater degree of conceptual change by revising their 'immoveable wall' theory to include both the idea of momentum being transferred from one brick (or molecule) to another as well as clearly discussing (for the first time) the concept that the large mass of the building would result in an imperceptible level of movement. For these students the cumulative effect of their analogical reasoning from analogies two and three was particularly noticeable. Student 35, who had really struggled during analogy one because of his lack of real understanding (see above), demonstrated this clearly when he was asked to state any similarities or differences that he thought there were between analogies two and three. He described the momentum being passed from his hand to his arm and possibly to the air on the other side of his body. This briefly suggested a possible return to his initially stated 'universalist' view of the transfer of momentum. However, he did not mention it again. When he was subsequently asked to describe how he thought the third analogy related to the target situation, he revised his theory to include the idea that momentum was transferred from one layer to the next, and he also began to include clear references to the relative masses and velocities of the various parts of the system, as shown below.

I: OK. What similarities or differences do you see between this and the car hitting the wall, or the building?

S35: Not any differences really. As long as you take the wall as hundreds of tiny little objects.

I: Explain what you mean by that.

S35: See if the wall was like, …

I: Given that it is a brick wall, you can see the wee bricks in it, is that what you're talking about?

S35: No, like even smaller, on an atomic scale, the energy and the momentum would pass through it, the only difference being in this one that none of it goes backwards.

I: So are you seeing these balls representing something?

S35: Yes.

I: What are they representing?

S35: Atoms.

I: So are you saying that the momentum is transferred from atom to atom to atom?

S35: Yes.

I: How sure are you that that's the case?

S35: Five.

I: What has given you that idea? You didn't mention that before.

S35: They are basically circular and they reminded me so I thought this might happen with atoms as well.

I: So, you are now saying that you think the reason that there is a transfer from the car to here is that at a very small scale there is a transfer of momentum through the atoms of the wall?

S35: Yeah.

I: Do you think the bricks are involved as well at a slightly bigger scale or not?

S35: On a slightly bigger scale, yes they would be.

I: So, you think there is a momentum transfer from one brick to the next to the next? Is that what you're saying?

S35: Yeah.

I: How sure are you of that?

S35: Well because these are balls, they are on a larger scale, they represent the atoms. Yes, it would have to represent everything.

When he was asked why the building did not appear to move when momentum was transferred to it, he mentioned the relationship between the large mass and the tiny movement of the building that he had previously hinted at when he was linking the second and third analogies.

I: How do you explain the whole wall doesn't move then?

S35: Its mass is huge compared to that of the car.

I: So why does that mean you don't see a lot of movement?

S35: The car can only transfer the amount of momentum it actually has.

I: So if it has a very large mass, what is the consequence of that in terms of its speed or its velocity?

S35: The faster the velocity is, the more likely it is to move the wall or damage the wall.

I: Because the wall has a huge mass, what is the consequence of that on its speed, the walls speed I'm talking about?

S35: It doesn't move.

I: At all?

S35: The speed doesn't change.

I: At all?

S35: Well, it would change on a tiny scale, on an atomic scale.

I: So you're saying that there is a tiny, tiny movement because it is a big mass? Is that what you're saying?

S35: Yes.

I: How much are you convinced of that?

S35: Very. Five.

He had clearly revised his mental model and theory regarding the wall and demonstrated several of the types of conceptual change which have already been discussed in relation to other students. In particular it can be seen that he had made connections between several physical and theoretical features of both the second and the third analogies, which appeared to both trigger and exemplify his new conceptual change.

Student 34 extended his ‘immoveable wall’ theory even more. When he was asked how he thought that the momentum was being transferred through the wall he described its progress in terms of the bricks. He then came up with an ingenious self-devised thought experiment in which he envisaged an object on wheels on the opposite side of the building moving as a consequence of the car’s impact. It would appear that in doing this, he was attempting to make connections with similar situations that he had previously seen or heard of in order to help him to work out what would happen in this less familiar scenario. He was then challenged to say what he thought would happen to the momentum if, as was more likely, none of the bricks were ejected from the far end of the building. This was asked in order to ascertain whether or not his theory was dependent on the wall acting in the same way as the ball-bearings in the analogy. At this point he decided that the momentum from the wall would ultimately be transferred to the Earth.

I: How is it moving through the wall?

S34: Through the bricks and that.

I: So, each brick?

S34: Yeah.

I: Is it doing anything similar to this? Brick by brick?

S34: Yeah, it is passing on momentum to it. Passing on momentum to each brick. Probably. I’ve never tried it but if you put something on wheels on the other side of the wall, I’m not sure but it might move. Like if you put a ball at the other side of the wall, it would move.

I: How sure are you of that?

S34: Four or a five probably. Probably a five.

I: Why do you think that?

S34: Because vibrations make things move.

I: Now, can you explain to me why you don't think, or maybe you do think, that bricks at the far end of this building don't pop out. Do you think they do or they wouldn't and if they don't, why not?

S34: They are cemented and it is stronger.

I: So where does the momentum ultimately end up, do you think?

S34: (Long pause).

I: If we have not got bricks pinging out the end, …

S34: If it hit is at a big enough force, it probably could ping out the end.

I: Let's assume it's not. A car hitting a building at 50 miles an hour is not likely to do that, so where is the momentum, assuming that doesn't happen, where does the momentum go?

S34: Probably into the ground.

I: How convinced are you that is true?

S34: Three.

This shows that by this point he had experienced conceptual change to a sufficient extent to enable him to realise that the momentum could be seen as being conserved and transferred at a universal scale, which included the car, the building and ultimately the Earth, to which the building was attached.

6.5 Analogy 4

The fourth analogy involved running a single ball-bearing into a piece of 'blu-tac' that was placed against the upright end of the wooden track that the ball-bearing ran on for the previous analogies. The student was also asked to place their hand behind the wooden upright section. The analogy was intended to help the students to reason that the ball-bearing's momentum was transferred to the 'blu-tac', followed by the wooden stand and then to their hand. By placing their hand at the end, they were able to feel the slight movement of the system that resulted from the impact. This tactile experience was intended to assist them in concluding that momentum was being conserved and transferred despite a lack of significant motion. 'Blu-tac' was chosen as the first layer for two reasons: it would visibly dent very slightly as a result of the impact; and because it was tacky it would be good at reducing the extent to which the ball-bearing rebounded, or stop it altogether.

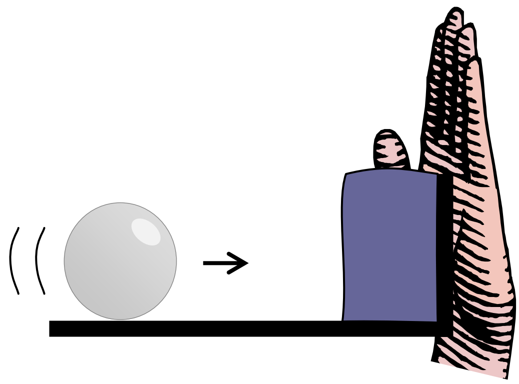


Figure 6.7: Analogy 4 - Ball running into 'blu-tac' and stopping.

The fourth analogy was rated as being particularly useful by fifteen of the students, although student 43 singled the analogy out as having caused her difficulty because she found that she was confused by the part played by the 'blu-tac' in the interaction. The overall level of conceptual change resulting from this analogy suggests that many of the students consolidated their thinking using this analogy as fifteen of the students maintained their prior belief-rating in the conservation of momentum and their 'immoveable wall' theory also remained unchanged. A total of seven students showed some positive conceptual change as a result of their interaction with the fourth analogy. Four students increased their belief-ratings by a small amount (one or half a point). Another three students maintained their belief-rating but added extra detail to their 'immoveable wall' theory.

In contrast with these positive changes, three students reduced their conservation belief-rating by one point. Two students went back to previously stated inaccurate ideas about momentum conservation, having made progress in the previous analogy. Students 4, 6 and 8 continued in their belief that momentum was not being conserved.

Figure 6.8 below, summarises the number of students who were stating each of the identified theories at the end of analogy three (figure 6.8a) and by the end of the fourth analogy (figure 6.8b). As before, figure 6.8a shows the same information as figure 6.6b in order to allow ready comparisons to be made between the overall numbers of students who held each theoretical stance at the end of successive analogies.

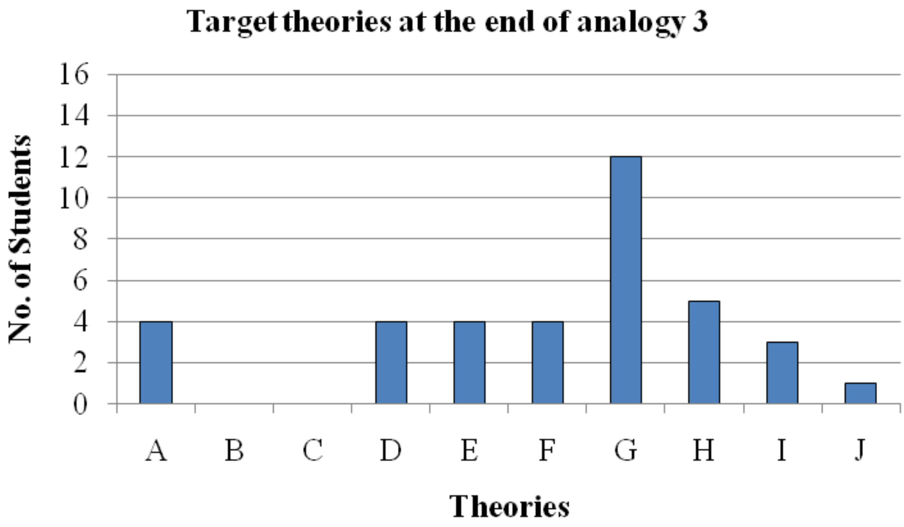


Figure 6.8a: Number of students stating each 'immoveable' wall theory at the end of analogy three.

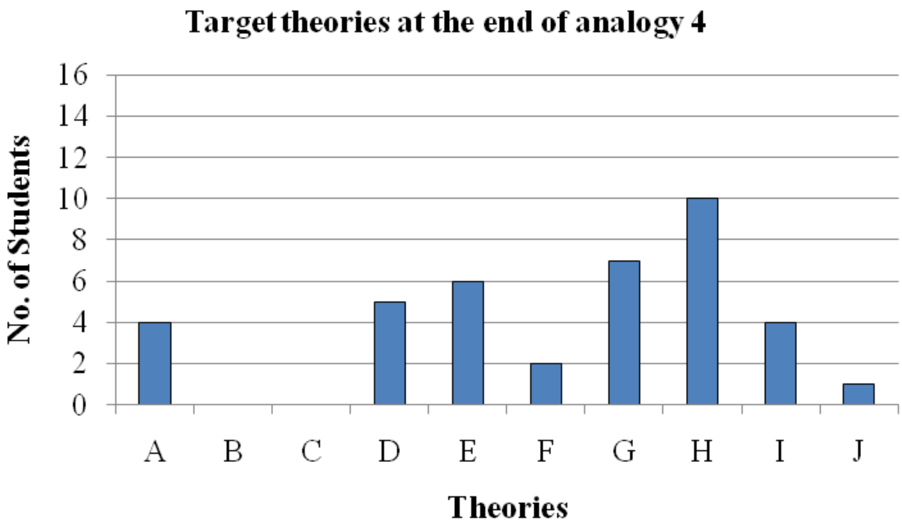


Figure 6.8b: Number of students stating each 'immoveable' wall theory at the end of analogy four.

6.5.1 Negative conceptual changes resulting from interaction with analogy four

The most obvious negative changes occurred in the thinking of students 7 and 20. Student 7 gave conflicting signals as she maintained her stance that momentum was conserved in the target situation but returned to the idea that some of the momentum was being converted into heat and sound energy which she had stated right at the beginning before seeing any of the analogies. It became clear from her statements that she was having difficulty in distinguishing between momentum being lost and being transferred as she tended to use these phrases as if they were synonymous. This is demonstrated in the following extract during which she was describing what she thought happened to the momentum in the analogy.

I: So, tell me the story of where the momentum is going. The ball comes in, tell me what happens.

S7: It loses momentum to the 'blu-tac' but then because they stick it is the momentum added together equals the momentum before.

I: So what happened to the momentum after the 'blu-tac' got it? Did it just disappear?

S7: It stayed.

I: It stayed in the 'blu-tac'? Does the fact that the wood moved your hand a bit or you could feel it moving against your hand, does that suggest anything to you?

S7: Some might have gone to my hand.

I: How did it get there?

S7: Through the wood.

I: So, you are saying that the momentum went from the ball to the 'blu-tac', from the 'blu-tac' to the wood and from the wood to your hand? How much do you believe that?

S7: About one?

I: Why?

S7: Because it just doesn't seem realistic.

I: Why?

S7: Because it has went all the way through there to my hand.

I: So why else does your hand move then? What is your alternative idea?

S7: The force of the ball.

I: So, something to do with the force but you're not sure if it has got anything to do with the momentum or not?

S7: Yeah.

Her obvious uncertainty about the transfer of momentum through the different materials was caused by two factors. She was struggling to understand how the momentum could transfer through the different layers of material to her hand, and she was thinking in terms of force rather than momentum. Her cognitive conflict regarding the concept that momentum had been transferred appeared to be triggered by her view that the analogy seemed unrealistic in some way. This in turn caused her to search for an alternative explanation for the movement of her hand that she had experienced. She resorted to using an existing, and potentially stronger and closer, mental link between force and movement as a means of explaining the situation. The link between the transfer of momentum and the motion of her hand could be considered to be insufficiently robust, or inter-connected, in her mind to give her confidence in its explanatory effectiveness. Having become less confident in the link between the movement and the transfer of momentum, she then partially changed her mind regarding the target situation. As can be seen in the extract below when she was discussing links between the analogy and the target scenario, her reasoning reverted back to another previously stated personal construct that some momentum might have been lost as a result of it being transformed into heat or sound.

S7: See when it hits, could it lose momentum to like heat and sound?

I: You tell me what you think?

S7: That maybe the momentum doesn't go into the building but when it hits the building it loses the momentum due to heat and sound.

I: Why have you decided to jump to that? What's going on in your head?

S7: I don't think you can transfer momentum into a building. It doesn't make any sense.

I: Why doesn't it make sense?

S7: I don't know. It just doesn't seem realistic.

I: What is unrealistic about it?

S7: That there is momentum in a building.

I: Why?

S7: I don't know.

I: So what has put you off? Up until now you have been saying momentum in the building and you're now going back to sound.

S7: It just seems better.

I: Because of what?

S7: It just makes more sense.

I: Did this analogy make you think of the sound and heat being released or is it something else that has made you go back to that?

S7: It maybe could lose momentum going into the building but I think some of it would be lost due to heat and sound.

I: So, a bit of both. How sure are you of that idea?

S7: About a two.

I How sure are you that the total momentum before is equal to the total after in this case?

S7: About a three.

She justified her change of thinking on the basis that she could not envisage the building gaining momentum, having previously decided that was the case. This shows that her prior mental model clearly made more sense to her and was remarkably resistant to change despite the apparent progress that she had made in the previous three analogies. It is also obvious that she was struggling to come to terms with this as she was engaging in twin-tracking, demonstrated by the fact that she was maintaining her position that momentum was being conserved while simultaneously arguing that some was becoming heat and sound energy. For her, this analogy had resulted in the resurfacing of prior, more interconnected pieces of knowledge, which caused her some difficulty that she could not, as yet, resolve.

As a result of analogy three, student 20 had changed to stating that momentum was conserved in the target scenario. During the fourth analogy he reverted back to stating that he thought that momentum was being lost. This came about as a consequence of him coming up with the idea that momentum was somehow being stored by the 'blu-tac' in the analogical situation.

I: How does the total momentum before compare with the total momentum after?

S20: It is less because it is not pushing my hand back a lot but it is pushing it back.

I: So where are you losing momentum?

S20: Is it in this piece of 'blu-tac'?

I: Why is that losing momentum?

S20: Is it not like a dampener?

I: So what is happening to the lost momentum?

S20: It is being stored in the 'blu-tac'?

I: How do you justify that?

S20: Because it is not pushing my hand back a lot. It must store momentum.

I: How does the mass of that lost compare with the mass of the ball?

S20: A lot more.

I: Including your hand? So you think overall between the mass and the speed there is a conservation? Does that mean that your momentum ends up the same?

S20: I'm not really understanding.

I: So the ball comes in with a mass and a speed, so it has got a momentum. By the time you take the mass of all of this stuff into consideration, you are saying it has got a smaller speed but does the bigger mass compensate for the smaller speed to give you the same answer?

S20: Yes.

I: Or do you still think there is some momentum getting stored somewhere or lost somewhere?

S20: It might be getting stored somewhere or getting lost somewhere.

I: Which do you think?

S20: It could be the bigger mass. It might actually be the bigger mass causing less momentum to be passed through.

I: Less speed?

S20: Yes.

I: So which one of those three options are you inclined to go for? Stored momentum, lost momentum or this thing about bigger mass, smaller speed?

S20: Bigger mass.

I: How sure are you?

S20: Four or five.

He was associating the lack of movement in his hand with a loss in momentum. This occurred despite him previously recognising (in a vague manner) during analogy two that the mass of his hand was linked to its lack of velocity. He was challenged regarding this as it was clear that he was struggling to decide between three possible explanations. At that point he appeared to settle fairly definitely on his previous thinking that the larger mass of the object being hot was consistent with the lack of movement while still having momentum conserved. However, he immediately contradicted this when he was asked to explain his thinking about the target scenario.

S20: The wall has a bigger mass than the car so when the car hits the wall, not as much momentum is being passed through as it originally started with.

I: So it is losing momentum?

S20: Yeah.

I: Is that different from what is going on here [in the analogy]?

S20: No, not really.

I: But you were saying here that you thought the momentum after was the same as before so, …

S20: No it's not the same, it is less because it is not pushing my hand back as much, it is pushing it slightly.

I: So the mass thing doesn't affect it that much?

S20: Yeah, because if there wasn't such a big mass here then it would push more.

I: So, it is the fact that there is a big wall here affecting how much it moves?

S20: Yeah, I think so.

I: Is the total momentum of the building the same as the momentum that the car has lost when it hits it? Or is there something getting lost to somewhere else?

S20: I am not sure. I think, …

I: What is your gut feeling on it?

S20: I am still thinking there is momentum lost somewhere.

I: To where?

S20: I'm not too sure.

I: Or to what might be a better question?

S20: It is just this feeling that I have got but I'm not sure.

In common with student 7, he appeared to be struggling to break the links which his pre-conceptions were based on. The new ideas that he had been working with were not sufficiently intelligible for him to really believe them or be able to use them as a fruitful explanatory tool. It could be argued that this was because the new ideas had not been perceived as sufficiently inter-connected with his existing mental schema to break the pre-existing links. It is none-the-less clear that the analogies had made him revise his previous assumptions to some extent which were causing him to experience cognitive conflict as he was evidently not convinced that his pre-existing theory was correct or intelligible when he admitted that he was basing his thoughts primarily on gut feeling.

Students 52, 57 and 63 reduced their conservation belief-rating by just one point. Two of these changes were not regarded as being significant as, when students 57 and

63 were asked why their rating had dropped slightly, it transpired that they had actually not significantly changed their mind, but simply could not remember what they had rated themselves at by the end of the previous analogy. Furthermore, their reasoning and immoveable wall theory had not changed either. The fourth analogy had genuinely caused student 52 to become less certain about conservation of momentum. He struggled to decide whether or not momentum was conserved when his hand was placed behind the wooden runner board, although he was sure that momentum was conserved when the board was allowed to move if his hand was not placed against it. When he was initially asked about the momentum in the analogy, he said that he thought that it was not conserved. He was then asked to explain his thinking, which resulted in the following discussion taking place.

S52: Because if I didn't have my hand there it would, it would, …, it would move away.

I: Try it and see. [Student tries the experiment without his hand in position]. Did the thing move?

S52: Yes.

I: So, was momentum conserved in that case?

S52: Yes.

I: Why is it conserved there and not when your hand was in the way?

S52: It was my hand acting as a barrier.

I: Did your hand end up getting any momentum?

S52: Yes, because it kind of moved back, it wasn't solid.

I: So, how did your hand end up with momentum?

S52: Because it travelled through.

I: From what?

S52: From the ball bearing to the 'blu-tac', to the wood to my hand

I: And in terms of the total momentum before versus the total momentum after how would they compare?

S52: The same.

I: Now, you've changed. A minute ago you said it wouldn't be the same? So is it because you didn't think that your hand was getting momentum?

S52: Yeah.

I: Are you now saying that you think it does? Or are you not sure?

S52: I'm not sure.

He was then encouraged to consider the small amount of movement that he had experienced in the group of objects (including his hand) that the ball-bearing had run into. This was done in an attempt to find out whether or not he could make a connection between the larger mass and the small amount of movement, and therefore deduce that momentum was being conserved.

I: Does the small amount of movement in the 'blu-tac' and the wood and your hand, does that account for the momentum no longer being in the ball?

S52: It could, yeah.

I: But you're not sure about that? Why aren't you sure about that?

S52: Because, …

It appeared that he was considering this link as a possibility, but he was unconvinced for reasons that he could not enunciate. This lack of intelligibility did not result in him going off the idea that momentum was conserved in the target scenario, but it appeared to make him a bit less sure of it since he down-graded his belief-rating by one point.

Students 4, 6 and 8 made no progress away from their thinking that momentum was not being conserved. Potential reasons for this became evident in the thinking of student 8 during this analogy, many of which were similar to the barriers demonstrated by students 4 and 6. He demonstrated that there were a number of factors which contributed to his inability to change his thinking. As discussed previously, he struggled to differentiate between momentum and energy. In addition, it became obvious during this analogy that the concepts of loss and transfer of momentum were overlapping in his thinking. As with many other students, it was evident that he had also not grasped the vectorial nature of momentum as he did not distinguish between movement in opposite directions when he talked about momentum being "given back" to both the ball-bearing and the car.

I: You have had a lot of momentum coming in. What happens to that momentum once it has hit the 'blu-tac'?

S8: It is lost to the 'blu-tac'.

I: Is it lost or transferred to it?

S8: Transferred.

I: OK. Go on.

S8: Some of it is still kept.

I: By the ball?

S8: Yeah, the ball.

I: Because it bounces back?

S8: Yeah.

I: And are you saying that all of it that doesn't get kept by the ball ends up in the 'blu-tac'?

S8: No. Some of it in the 'blu-tac' goes back to the wall [the wooden upright] as well.

I: But is that total the same as before that the ball came in with?

S8: No.

I: So what has happened to the bit that is not around anymore?

S8: It is being lost as energy.

I: What kind?

S8: Heat and sound.

I: Give me a rating for that idea.

S8: Four.

When he was asked to identify any similarities or differences between the fourth analogy and the previous one or the target, it also became evident that he was struggling to perceive any commonality, other than in terms of surface features. This made it very difficult for him to successfully make the intended links between features and behaviour of the analogy and the target, which consequently made progress impossible.

6.5.2 Positive conceptual changes resulting from interaction with analogy four

Four students slightly increased their belief-ratings in the idea of conservation of momentum. This was the only change for student 5 who did not adapt her 'immoveable wall' theory, or her belief-rating about it. Since her belief-rating only increased by half a point, it could easily be dismissed as a fluctuation resulting from the small, inevitable variations inherent in a repeating, self-estimated rating system where the participants may not remember what their previous rating was. However, when she was asked why her belief rating had increased she gave the following reason.

I: So what has made it go up?
S5: Just all the examples.

This shows that the cumulative effect of the analogies was effective in helping her to make connections in her mind about conservation of momentum in each of the analogies. Consequently, she had become more convinced that it was also true in the target scenario.

Students 48 and 64 increased their belief in conservation of momentum and adapted their 'immoveable wall' theories by adding, for the first time, the idea that the large mass of the building would account for the lack of perceivable movement. Student 41 increased his belief-rating in this same theory by one point and in conservation of energy by half a point. While considering this analogy, student 64 noticed the similarity between the analogy and the target of a smaller mass colliding with an object of greater mass in each case. This was the triggering factor for his conceptual change. It caused him to revise his existing theory about the momentum being passed through the brick layers in the building, by adding the idea that it would not move much because of its very large mass. His comments also show that this newly acknowledged connection also resulted in him experiencing an increased level of intelligibility and believability in the conservation of momentum for the target scenario.

I: Now how does that situation compare with the original of the car hitting the brick wall?
S64: It is pretty much the same.
I: Go on.
S64: With the ball hitting stationary object of greater mass and the car hitting the wall. That would make sense.
I: Because this small ball is hitting a bigger mass it is doing a similar thing?
S64: Yeah.

When he was asked at the end of the fourth analogy what had caused the changes to his theory, he freely acknowledged that these ideas had come “from the analogies”, which again suggest that the cumulative effect of the connections was particularly important. Student 48 gave identical reasons for her similar conceptual change. In addition, it is interesting to note that she subsequently made two comments which showed that she was making other connections between aspects of her theory and a self-devised thought experiment, as well as previous knowledge that she had gained from watching films.

I: Are you envisaging, you mentioned earlier something about a vibration, is that what you think?

S48: Just like, …, probably if you put a glass of water on the other side, and the water in it was still. Then if like, part of the glass was touching it, then if the water moved then it would kind of show, that there was like, …

I: Do you think that would happen if you did put a glass to the other side?

S48: Yeah.

I: How sure are you?

S48: Five

I: You seem reasonably convinced? Why are you convinced, because before you didn’t seem that sure?

S48: You see it in the movies as well, if something happens, it causes the whole house to shake.

Another three students maintained their belief-rating in conservation of momentum but added extra detail to their ‘immoveable wall’ theory. In a similar manner to students 48 and 64, the theory espoused by student 25 was extended as she clearly mentioned the link between the building’s large mass and its velocity for the first time, having previously only discussed this idea in relation to her hand in analogy two.

I: Remember before you were saying something about your hand, why it didn’t shoot off when the ball just hit is straight?

S25: Yeah, because I was bigger.

I: Is that still true here?

S25: Yeah.

I: So, because it is bigger, does that mean that it doesn't shoot off but it doesn't mean there is not momentum in it or what? What do you think?

S25: It is bigger.

I: So, by the time you take the mass into consideration and the velocity, are you saying that there is the same amount of momentum for something that is smaller that goes faster?

S25: Yeah.

This connection was only made as a result of some 'guided analogical reasoning' which was utilised because, just prior to this excerpt, she had briefly become unsure about whether or not she thought that momentum was being conserved because of the very small movement in the building. It is however clear from her statements that the links were made and this reassured her and bolstered her new thinking.

The reasoning of students 46 and 47 went even further as they began to think that the momentum would ultimately get transferred to the Earth in the target scenario. Although student 46 was very convinced that momentum was conserved in this analogy, he was initially less certain (belief-rating of three) that the momentum was passing all the way through to his hand. This cognitive conflict was caused by his perception of a lack of similarity between the behaviour of the final object in this analogy (his hand), in comparison with the very evident movement of the fourth ball-bearing in the previous analogy. He realised that the principle was the same in each case but he was struggling to justify the lack of his hand's movement. He partially resolved his difficulty when he was encouraged to think of a reason for the difference in the movement of the ball-bearing in the last analogy and this hand in this one. It was at this point that he deduced (by making comparisons) that the mass of his hand was relevant. This shows that he was making links between what he was seeing and the equation for momentum that he had been taught.

I: Why do you think it might be going through, in this one?

S46: 'Cause it would be the same principle, it's just different substances.

I: Uh huh. So is it the fact that it's different substances that puts you off, or what?

S46: It's just that the stationary bit at the end confuses me, I'm not,…

I: Well, is your hand completely stationary?

S46: Well no, not completely.

I: So, why would it be moving less than the ball was, for example?

S46: 'Cause of the much higher mass.

I: Because it's attached to your arm and things?

S46: Yeah.

It was clear from his subsequent comments that this new realisation had not entirely resolved his difficulty. He was therefore asked to repeat the experiment with the ball-bearing striking the 'blu-tac' at a higher velocity. This caused him to experience a greater degree of movement in his hand, at which point his belief-rating increased. This suggests that his conceptual change was caused by two different comparisons and resulting connections being made: firstly between the behaviour of analogies three and four; and secondly between his physical experience and his prior learning. When he was asked to compare the analogy with the target, he suggested another new idea.

I: How does this compare with the original of the car hitting the building? The brick building.

S46: It's pretty similar.

I: Go on.

S46: Like the car goes. Say that's the car [pointing to the ball-bearing], the car goes.

I: So, the ball's the car, right?

S46: Uh huh. The car goes into the wall, which is the 'blu-tac', and it gives way a little bit, and then it passes through to the rest of the building, which is the wooden bit, and then that's my hand as well.

I: So, all these represent different bits of the building, is that what you're saying?

S46: Yeah, like passing through.

I: So, how convinced are you that momentum is being conserved when the car hits the building?

S46: Six.

I: In terms of your theory about the momentum passing from the front, boom, boom, boom, right the way through, how convinced are you of that?

S46: Mmm. I'm not 100% convinced about that, it's just, because it's attached to, like firmly attached to the ground as well. So it might, …, move the ground.

These comments suggest that he had at least begun to make the conceptual leap towards viewing the transfer of momentum as occurring on a universal scale, whereby momentum is transferred to increasingly large objects, and thus never gets lost (see Bryce and MacMillan, 2009). Although it is not clear what triggered this thought in his mind, it is conceivable that it was the result of making comparisons with the movement of his hand.

Student 47 came to similar conclusions about the significance of the mass of the building and the idea that the momentum was ultimately transferred to the ground.

I: How does this analogy compare with the original of the car hitting the wall?

S47: Still kind of the same: there's the wall and the fact that it transfers through yet not moving through, so maybe something to do with the mass as well in that, and unequal masses.

I: Mmm hmm, go on. Tell me what you're thinking on that. What are you saying about the mass of the car versus the mass of the building?

S47: Say the building or the brick wall or whatever, it's [got] more mass.

I: And does that explain why it doesn't head off quickly, is that what you're thinking?

S47: Yeah.

She was then asked to state whether or not she thought that momentum was being conserved in the target situation, at which point she rated herself again at level four or five that momentum was being conserved. Her 'immoveable wall' theory was then explored.

I: Ok, your idea. Tell me what your idea is at the moment about what happens to the momentum of the car once it hits the building?

S47: That'll decrease and bounce back, but not with any great speed or distance.

I: And what happens to the momentum of the car that's disappeared, where's it gone?

S47: Travelling through the brick wall.

I: And how's that happening?

S47: Em, I still think it's still travelling through each brick backwards and backwards, maybe though different layers. It could travel down into the ground and it could move.

I: Why do you think it goes down in to the ground?

S47: Well when it gets through there, then there's nothing after that.

I: So, you think the ground might end up getting it?

S47: Might end up with it, or it could be somewhere changed to some form of kinetic energy, or, …

I: So, which do you think is more likely, the ground gets it, or it changes in to something else?

S47: The ground.

I: How sure are you of that?

S47: Still about four-ish.

Her idea about the momentum being transferred into the ground appeared to be a consequence of her seeing no other logically viable alternative, although as she considered her answer she displayed twin-tracking when she returned to her much earlier idea that the momentum could ultimately become kinetic energy. This is another example that demonstrates that prior thinking is hard to displace but her answers suggest that by the end of this analogy she was reasonably convinced that momentum was being conserved at a universal scale, as this seemed the most logical and believable idea to her, based on what she already knew and had experienced while interacting with the analogies.

Although the scale of the change in their thinking was clearly quite significant, the conceptual change exhibited by students 46 and 47 was not coded as involving a change in their 'generalised theory' in the way envisaged by Posner et al. (1982) in their 'accommodation' theory, the modification of the underlying 'mental theory' as described by Tiberghien (1994), or the revision of the 'framework theory' in the conceptual change model described by Vosniadou (1994). This approach was taken as it could not be reliably construed that they had necessarily altered their view of the way in which momentum would be transferred in any and every situation. This decision was arguably a little over cautious but it was felt that the students' comments were restricted to the situation involving the car and the building and so it could not be assumed that they had in fact changed their general mental schema at this point.

6.6 Analogy five

The final analogy in the sequence required the students to run a sponge ball initially into a piece of sponge which was placed against the wooden upright of the runner-board. In this analogy they did not place their hand against the apparatus. The sponge ball was chosen to allow the compression that the car would undergo in the collision with the building to be at least temporarily simulated, as the ball-bearings used up until that stage would not compress due to their relatively high density. The piece of sponge against the wooden upright section was chosen to continue the theme of different layers through which the momentum was transferred. It was also hoped that it would help the students to realise that there was momentum being transferred to the apparatus as the sponge was briefly compressed upon impact. Since the student's hand was not placed behind the apparatus, it was possible for them to see that the whole runner-board moved upon impact. This situation was intended to help the students to bridge to the concept that the momentum would ultimately be transferred from the building into the ground. Once this had been carried out, the experiment was repeated without the piece of sponge resting against the wooden upright as this was more representative of the target situation. It is interesting to note that many of the students asked to try this follow-up experiment without it being suggested to them as they were curious to find out what happened when the piece of sponge was removed.

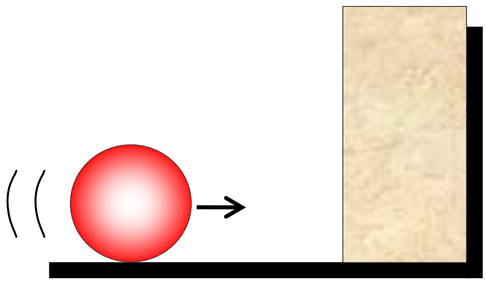


Figure 6.9: Analogy 5 - Sponge ball running into sponge and rebounding.

Not all of the students were able to examine this fifth analogy. As discussed in the methodology chapter, this was an unfortunate consequence of conducting some of the interviews during a student's lunch break. These time slots were used as some student volunteers were not available at the end of the school day and these times were the best alternative to avoid disrupting their timetabled lessons (which was part of the agreement made with the participating schools). In these circumstances, when the earlier part of an interview had become protracted, there was not always sufficient time for the fifth analogy to be worked through fully, in which case a decision was taken to jump directly to the final review section instead. This was the case for four of the thirty students.

Of the twenty six who did work through the fifth analogy, fourteen students showed no changes in their thinking. This included students 4, 6 and 8 who remained convinced that momentum was not conserved, while students 46 and 47 (discussed above) continued to state that momentum was ultimately transferred to the ground. Student 7 struggled to resolve her uncertainty about conservation of momentum. One student (S57) became slightly more convinced of conservation of momentum but did not change his ‘immoveable wall’ theory, while five students’ (S19, S22, S25, S28 and S62) belief in the conservation of momentum were unchanged but they developed their ‘immoveable wall’ theory. Five students (S40, 41, 43, 48 and 58) changed both aspects of their thinking as they increased their belief in conservation of momentum and developed their ‘immoveable wall’ theory. Twelve of the students mentioned that this was a particularly helpful analogy in the review section of the interview. Two of these students qualified this by saying that it was most helpful when the sponge ball collided directly with the wooden upright as they identified that it represented the target scenario more accurately. Student 40 made an interesting observation when he stated that the analogy helped him to ‘see’ that the earth would move in the target scenario.

Figure 6.10 below, summarises the number of students who were stating each of the identified theories at the end of analogy four (figure 6.10a) and by the end of the fifth analogy (figure 6.10b). Since four students did not do the fifth analogy, the answers given by them by the end of analogy four are not included in the figures for analogy five. Despite this, comparisons between the two charts show a clear shift as a consequence of the positive conceptual change experienced by the ten students during the fifth analogy. This resulted in an overall transition towards theories H and I in particular.

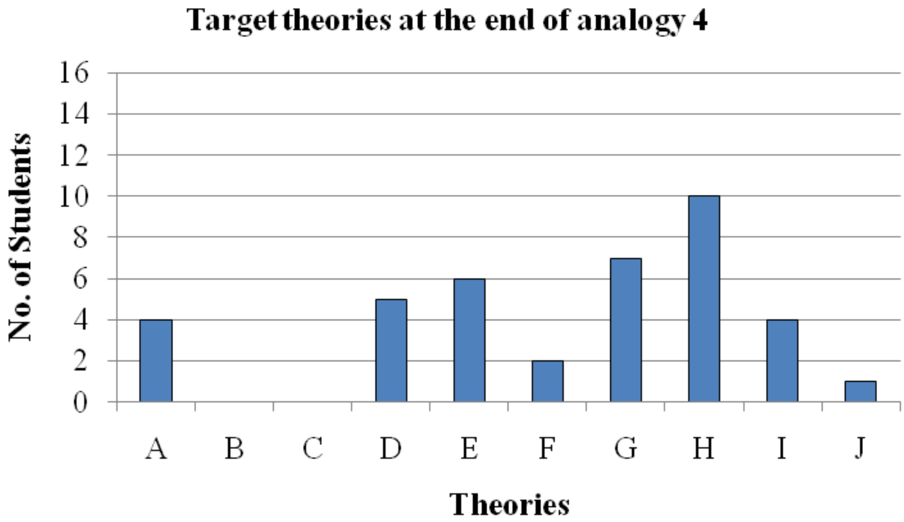


Figure 6.10a: Number of students stating each 'immoveable' wall theory at the end of analogy four.

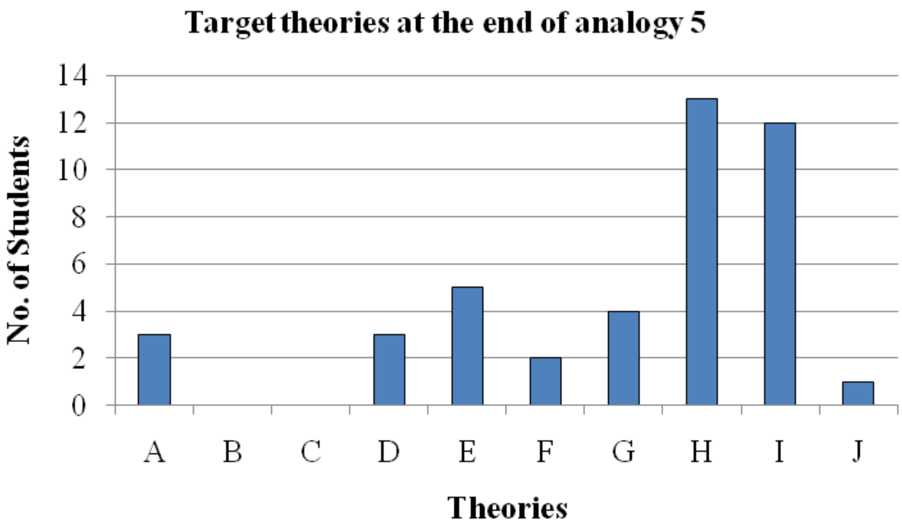


Figure 6.10b: Number of students stating each 'immoveable' wall theory at the end of analogy five.

6.6.1 Non - changes resulting from interaction with analogy five

For fourteen of the students this analogy appeared to simply confirm their prior thinking as they had become relatively secure in their ideas. Students 4, 6 and 8 continued to state that they thought that momentum was lost when the car struck the building. Their difficulties revolved around their inability to recognise the similarities between the analogy and the target. In addition to this, student 6 was still engaging in confused, single object thinking despite talking about the transfer of momentum, as is shown in the following extract when the analogy was being discussed.

I: Tell me what you are thinking here in terms of momentum.

S6: I think the sponge gives more momentum back to the ball.

I: So, how do you explain the wood moving? What is going on there?

S6: That is some of the momentum from the ball being transferred through the sponge and the wood.

I: So, tell me, do you think the total momentum at the end here is the same or different from the total momentum at the start?

S6: I think it would be a wee bit different.

I: Is that different from before or is it still the same story that you are thinking?

S6: I think it depends maybe on what material it hits. It looks the same but I don't think it is.

I: When you say it looks the same, what do you mean? What is happening to it that looks the same?

S6: No, actually I think it is different. Total momentum before is greater.

I: So there is a bit disappearing?

S6: Yeah.

I: Where to?

S6: I think in moving the wood back slightly.

I: Is the wood giving momentum to anything else do you think or is it just disappearing?

S6: I don't know.

These three students all struggled with the idea that the first object either "kept momentum" or was "given momentum back" when it rebounded. This shows that part of their difficulty in understanding the physics was that they misunderstood the vector nature of momentum and so they could not fully grasp how and why momentum was being transferred to the object that was being hit. As a consequence of this they were unable to comprehend that momentum was being conserved, as demonstrated by this extract from student 4.

S4: Em, …, this sponge ball collides with the sponge and it rebounds, …, eh, because, …, eh, the compression that presses in and gives it, eh, rebounding, force or energy, …, and it rebounds and goes back.

I: Ok, do it again and notice the wood and see if you notice anything. You know the wooden stand thing? Let's see if you notice anything.

S4: Sound, …

I: Anything else? Do it a wee bit faster.

S4: It moves.

I: It moves, right. So tell me what you think is happening in terms of momentum here. Do you think it's the same before and after or different before or after; the totals before and after?

S4: If there is no friction?

I: Assuming we are just taking it before it hits, yeah, so ignore the run in, yeah.

S4: So, momentum before, I think, would be greater than the momentum after

I: Why?

S4: Because, eh, …, it's an inelastic collision, …, or is it elastic? It's one where the ball rebounds, …, and, …, causes the second object to move in the other direction, so there is movement and, …, in both ways, the ball goes negative and that goes to the other direction, in a, …, velocity, …

I: So, what we have got here then? A situation where, …, what's happening, the momentum after in total is the same as it was before, or is it different?

S4: It's different, I think.

I: Is it more or less after than before in that case, in your opinion?

S4: The momentum after is less.

I: And how would you explain that?

S4: Because, …, the, …, I would explain that because the wooden plank didn't move as much as the ball was moving.

I: But did it move at all?

S4: It did move, but, …

I: So, where is the missing momentum gone?

S4: The missing momentum, that's like, …, the sound that's produced.

I: So, you're still saying about the sound?

S4: Yes.

I: How sure are you about that theory? Explaining about the missing momentum?

S4: Same. I would give it a three, I won't go more than four, for this momentum business.

I: Because you are not sure whether it's right or not?

S4: I'm not sure about the momentum and energy being the same.

His difficulties were also compounded by confusion about what an elastic collision was as well as having a poor grasp of the difference between momentum, energy and force.

6.6.2 Positive conceptual changes resulting from interaction with analogy five

As discussed above, student 7 had struggled with the concept of conservation of momentum at the end of the fourth analogy because she was comparing the concepts of momentum being transferred to the building with the idea that momentum was being lost as it became heat and sound energy. At the end of the fifth analogy she decided that, on balance, she was slightly more convinced that momentum was being conserved and gave the following explanation.

S7: I'll go for losing it to the building.

I: Now, give me a rating for that. How sure are you of that?

S7: Two.

I: Give me your heat and sound version. How would you rate that one?

S7: About a two as well.

I: So, they're competing equally but you can't say which one is winning?

S7: Yeah.

I: If I had to make you go for one or other what would you go for?

S7: The building.

I: Moving? Or the building getting momentum into it?

S7: Yeah.

I: Why?

S7: I don't know. Because it can't lose that much momentum to heat and sound so it just makes more sense.

Her final decision was based on the believability of one idea over the other, but it was not a resounding victory. Her use of the term "losing it to the building" suggests that she may have been struggling partly because she was not clearly thinking of the process as involving the transfer of momentum between objects.

Student 57 has become more convinced about conservation of momentum in the target scenario by the end of the fifth analogy. When he was asked if he thought that his rating had increased and why, he gave this reason.

> S57: Yeah, because you can see over the different experiments, …, you just sort of, …, I think because that's a picture and you are actually doing it, so you can see.

It is clear from this that he had found carrying out the experiments helpful but he had also been able to discern links between the different situations which convinced him more.

Of the five students who revised their 'immoveable' wall theory by the end of the fifth analogy, students 19 and 28 had added the concept that the large mass of the building accounted for the small degree of motion. During the fourth analogy, student 19 had been struggling to comprehend the idea that the building would move in some way. He continued to wrestle with this during his thinking about this analogy. He had previously rated his belief in conservation of momentum in the target scenario at "a two or a three", but by the end of this analogy he stated that it was at level two, having rated himself at a three for the analogical situation. It was therefore assumed that his belief rating was effectively unchanged. More positively, he returned to the idea that the greater mass of the wall could account for the tiny amount of movement, which he had first stated during analogy two. He was not at all sure of this, but felt that he had "no other reason" that he could think of as an explanation.

Student 28 also mentioned the idea of the relative masses of the car and the building as a new part of his reasoning. However, he then experienced a brief doubt about momentum disappearing when the car hit the building. He resolved this when he decided that the momentum was ultimately being transferred to the ground when he saw the link between the movement of the wooden runner board in the analogy and the possibility of the momentum being transferred to the ground.

I: Why do you think some of it must be disappearing somewhere? Is it because the whole wall doesn't move? Or is there something else about it?

S28: Part of the wall could move but the rest of the wall could hold that part of the wall in place.

I: So, where would the momentum go if that was the case? Does it all just go in a straight line or could it be spreading? What do you think? For example, when this came in there was momentum transferred to that and then to that and what happened to the momentum next?

S28: It went back into the ball.

I: And the bit that didn't did what?

S28: Moved the wood.

I: So, do you think there is anything similar going on here?

S28: (Long pause). Possibly.

I: So what might also be getting moved, maybe even very slightly?

S28: The ground.

He was initially quite unsure about this idea, possibly because he had been guided towards it, but he became more convinced during a subsequent discussion in which his new thinking regarding the significance of the relative masses of different objects was revisited. This implies, once again, that progress was being made on the basis of intelligible links between different pieces of knowledge being formed. The other three students (S22, S25 and S62) also concluded for the first time that the momentum was ultimately being transferred to the earth, although this was not clearly enunciated by students 22 and 62. Student 22 talked in terms of the ground becoming damaged, while student 62 mentioned the idea that the road might move. Both students mentioned this idea after they had observed that the whole runner board moved slightly when the sponge ball ran into it. This suggests that their conceptual change was triggered as a consequence of them connecting this behaviour in the analogical situation with the real-world scenario, even although it seemed a little far-fetched to them.

Student 25 gave a clearer indication of his thinking and seemed to be much more convinced because he had fully appreciated the significance of the large mass of the building and the earth in relation to their potential velocities as can be seen in the following extract.

I: Now, what do you think the runner board represents? The up and down bit represents the wall presumably.

S25: The road?

I: What did the runner board do when this hit that?

S25: What?

I: What did this bit do when the collision happened?

S25: It moved.

I: Now, do you think there is anything going on when you hit the car into this building, to the ground, do you think it does anything similar?

S25: It might get some momentum as well but it is not going to move because it is too big.

I: So, what is ultimately getting the momentum? Where is it ultimately going?

S25: The wall.

I: And then the wall is attached to the ground so is it gaining momentum? Is that what you're saying? The ground is part of planet earth. Are you saying that you think when a car hits a wall, the earth gets a wee bit of extra momentum?

S25: Yeah, but I don't think it is going to be anything you could particularly feel.

I: Why not?

S25: It's not big enough.

I: Because what's not big enough?

S25: The momentum in it.

I: Why can you not tell that the earth is getting this momentum, if that's what you're saying is going on?

S25: The momentum is too small.

I: For it to make a noticeable difference, is that what you mean?

S25: Yeah.

Although the student did not introduce the suggestion about the ground moving himself, he did determine the analogous relationship between the base of the runner-board and the ground on his own, and he readily concluded for himself that he thought that the ground would gain momentum.

The five students (S40, 41, 43, 48 and 58) who increased their belief in conservation of momentum and developed their ‘immoveable wall’ theory all concluded by the end of the analogy that the momentum that was transferred to the building would ultimately be transferred to the ground. In each case, the movement of the runner board when the sponge ball collided with it was instrumental in them adding this feature to their theory. This new level of explanatory power in their theory also had the effect of slightly increasing their belief in the conservation of momentum in the target scenario.

6.7 Final target theories

After completing the sequence of analogies, the students were asked to summarise their target theory to give what they considered to be their final ideas. For all but one of the thirty students, their answers remained the same. Student 2 added the idea that the momentum would ultimately be transferred to the ground. This came about as a result of her noticing the movement of the track and connecting that to her thinking about momentum and energy. This resulted in her transferring her knowledge of physics to her thinking about the target scenario.

I: Let's do a wee summary, right? You're saying here that you think momentum is being conserved, and what's your ultimate reason for coming up with that? How would you argue that to someone who didn't understand that, what would you be saying to them?

S2: Because it can't just disappear off to nowhere.

I: So, where's it going?

S2: Like, to either, …, staying in the car or in the brick wall, possibly into the ground, but not too sure on that one.

I: Tell me about the ground bit?

S2: No, it would probably not go into the ground.

I: Why, what's your thinking, why did you suddenly think 'ground'?

S2: I don't know, because if some of it's lost, …

I: And is it lost?

S2: No.

I: But you think that some of it might be ultimately going into the ground?

S2: Possibly, just because it seems very similar to, …, the momentum seems quite similar to kinetic energy, and that would go into the ground.

I: Now, in terms of you coming up with that answer, what are you giving it, 1 to 6?

S2: About 4.

Her belief rating of a four is arguably a little optimistic given her apparent change of mind when she was asked to talk about her idea about the ground. However, her subsequent thinking suggests that she had decided that that the momentum transferred into the ground. This conceptual change occurred as a consequence of her making connections between what she felt would happen to some of the kinetic energy and where the momentum would go.

Figure 6.11 below, shows the number of students who were stating each of the identified theories as their final theory.

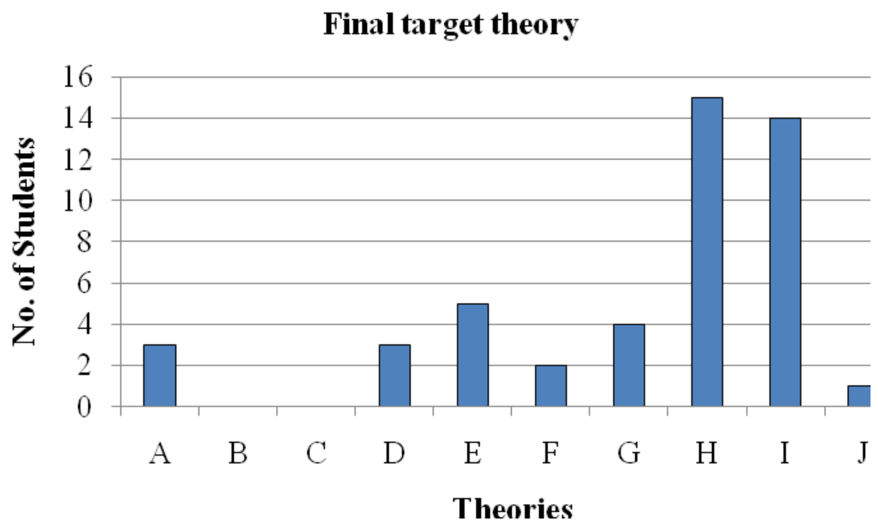


Figure 6.11: Number of students stating each ‘immoveable’ wall theory as their final answer about the target scenario.

6.8 Extension question

By the end of the 'immoveable' object analogical sequence, a total of fourteen of the thirty students were stating a belief (with various degrees of certainty and clarity) in the idea that the momentum transferred from the car to the building was ultimately transferred to the ground.

In the extension question the students were asked to try to explain how momentum could be considered to be conserved in the situation where they started running from a standing start. This question was asked to ascertain whether or not the students could apply their new thinking to a different situation in order to demonstrate the extent and robustness of the conceptual change that they had experienced as a result of their interaction with the analogical sequence. Because of time constraints on many of the interviews, it was not possible to ask every student the extension question as it was scheduled to be asked at the very end of the interview. In total, seventeen of the thirty students gave an answer.

Three of the seventeen students either stated that they could not explain how momentum was conserved in the extension scenario, while students 4, 22 and 58 gave incorrect answers in which they linked momentum and energy together in inappropriate ways. Student 22 tried to rationalise what he thought happened by giving this answer to the question.

> S22: It's about energy changing into momentum.

Student 58 gave a very similar response.

> S58: You are pushing off, you are giving, you are transferring, …, potential energy into kinetic, which then gives you the momentum.

As discussed above, student 4 had stated consistently throughout the analogical sequence that he thought that momentum was not conserved in the target scenario. He was unsuccessful in answering the extension question because he felt that momentum was being gained by the person moving forward but linked this to the idea that energy was "being lost" and the idea that "the friction pushes in the opposite direction". It is clear from the answers given by both these students that the concepts of momentum, energy and force all significantly overlapped in their thinking which meant that they used the terms in the wrong context and consequently failed to grasp the underlying physics in this new situation, at least in terms of the way in which momentum would be conserved.

Student 7 had a final 'immoveable wall' theory in which she said that momentum was conserved because some of it was transferred to the wall although she did not give a detailed mechanism for this. She had also decided that some of the momentum was converted into heat and sound energy in the target scenario. Her attempt to answer the extension question was a self-confessed guess. She thought that the runner was gaining momentum "from the road" but was unable to elaborate on this, although it is notable that she did not invoke any link between the momentum gained and energy on this occasion.

Of the ten students who gave an answer that was in line with the accepted scientific response to the extension question, only two had not ultimately decided that the momentum was transferred to the ground in the target scenario by the end of the fifth analogy. Student 51 had decided by that stage that momentum was transferred to the building by a process which involved vibrations that travelled through the layers of brick. She linked this idea to the new situation as she stated that she thought that the ground might vibrate as the person moved away from their starting point, but she was not very convinced that her idea was correct.

Student 1 had only concluded that the momentum from the car would have been transferred from brick to brick through the building. When faced with the extension question, she initially talked about force and gravity as she tried to come up with some ideas. She then made what appeared to be a spontaneous break-through, but the reason for this became evident as she talked through her idea more.

S1: It is, are you talking about gravity or is it like, well if you are walking along the ground then you have friction, so maybe because of the fact the ground is getting some of the momentum.

I: The ground is getting your momentum?

S1: Yeah, because, when you are going over like, [shows the interviewer a walking motion].

I: When you push back?

S1: Yeah.

I: So, what's gaining momentum? When you say you are going forwards, what's the trade off?

S1: The ground, and the friction of the foot and the ground.

I: So, you are saying the ground is gaining momentum?

S1: Well, ..., I suppose, but you will, …, I mean if you are walking in gravel or grass, or something like that then you would be able to see the gravel moving, which means they are getting momentum.

I: So, let's say that its concrete, it was a street, there is no bits moving, do you still think that true?

S1: Yeah, I would say so.

I: So what's moving? You obviously are but what else is moving because you seem to be saying that something else needs to move?

S1: It doesn't need to move, because I mean obviously, you know, the world, and then me. So that means that there is not exactly going to be, like, if you had one of those wee ball-bearings and you hit it against a brick wall, it's not exactly going to have a huge impact on it is it?

I: But does it move slightly? The wall? Although you can't maybe see it.

S1: Yeah, you can't see it, yeah, I suppose.

I: Do you think it is moving though?

S1: Probably.

I: So, when you are walking what is happening? In your words something about the earth, what's happening, even at a very small level maybe?

S1: So small that you couldn't even see it or calculate it or anything.

I: What do you think is going on?

S1: The earth is gaining momentum.

I: In which direction?

S1: The opposite to the way I am walking.

After the initial spontaneous generation of the idea, there appeared to be several triggers for her conceptual change at this stage. She made connections with prior everyday experiences (like seeing gravel moving in the opposite direction when someone was walking) as well as with the experience that she had in thinking through some of the analogies. She also made progress as a consequence of transferring an application of learned physics to the situation. This was evident when she talked about the movement of the building and the earth being tiny because of their large mass. This showed that she had also realised the significance of the relative values of mass and velocity in calculating a momentum for the first time in the interview. She had certainly changed her specific theory as a result of her thinking and had shown conceptual change in terms of making connections between new thinking and the analogy, prior learning and prior experiences. It could also be argued that she had experienced changes to her 'general' theory as she had transferred her thinking to a new situation and appeared to be generalising her reasoning, which suggests that she may have changed her underlying theory about the way in which most things 'work' in relation to the conservation of momentum.

Students 2, 25, 34,40, 47, 48, 63 and 64 had all stated their belief in a universal level view of momentum transfer by the end of the fifth analogy, whereby momentum was transferred from the car, to the building and then to the ground. Each of them transferred this same theoretical stance to the new situation that the extension question presented them with. Students 25 and 47 were very unsure of this idea, while three of this group rated their belief in the idea that the ground would gain momentum in the opposite direction from the runner at a level three, showing that they were reasonably convinced about their stance. In comparison, students 40, 48 and 64 were very confident, rating themselves at level five or six and having expressed their idea clearly, confidently and without hesitation.

This scenario required students to transfer their personal construct to a situation in which the conservation of momentum necessitated the movement of two objects in opposite directions, unlike the target situation connected with the analogical sequence. In addition, the extension question required an understanding of momentum being gained by an apparently highly 'immoveable' object (the earth). Since they successfully made this transfer, it could be argued that they fulfilled the criteria for demonstrating the most rigorous level of conceptual change described as 'accommodation' by Posner et al. (1982) in terms of the replacement of a learner's 'central concepts'; 'meaningful learning' by Ausubel (2000) in which learners change their ‘cognitive structure’; the modification of the ‘mental model’ and the underlying ‘theory’ in Tiberghien’s (1994) modelling theory; and the modification of the deeply held ‘framework theory’ described in the ‘theory restructuring’ approach proposed by Vosniadou (1994). It can also be seen from many of the arguments above that this conceptual change clearly involved (and was triggered by) the making of connections between the target scenario, the extension situation, and certain aspects of the analogies that each of the students had been examining. The formation of these links culminated in the resultant theories becoming increasingly intelligible, believable and fruitful to each of these students.

6.9 The effectiveness of the 'immoveable' object sequence

It is evident from the data that has been analysed in this chapter that the 'immoveable' object sequence was very effective in causing conceptual change for many students, while for a few students it helped very little, or in some cases appeared to be counter-productive.

Figure 6.12 below, illustrates the shifts that occurred in the theoretical stances of the thirty students throughout the sequence. It is evident from the chart that the students' theoretical stances had changed during the sequence. Increasing numbers of students decided that momentum was being transferred to the wall and that the building's large mass resulted in a very small movement (theory H). This shift coincided with a reduction in the number of students who felt that momentum was lost when the car collided with the building (theory A), and a decrease in the number of students who thought that the momentum was transferred to the building but were unclear about how this could be explained (theory D). The increasing number of students that developed a 'universalist' view of momentum, whereby they considered the car's momentum to have been ultimately transferred to the Earth (theory I) over the course of the sequence of analogies, is also evident from the results illustrated in figure 6.12.

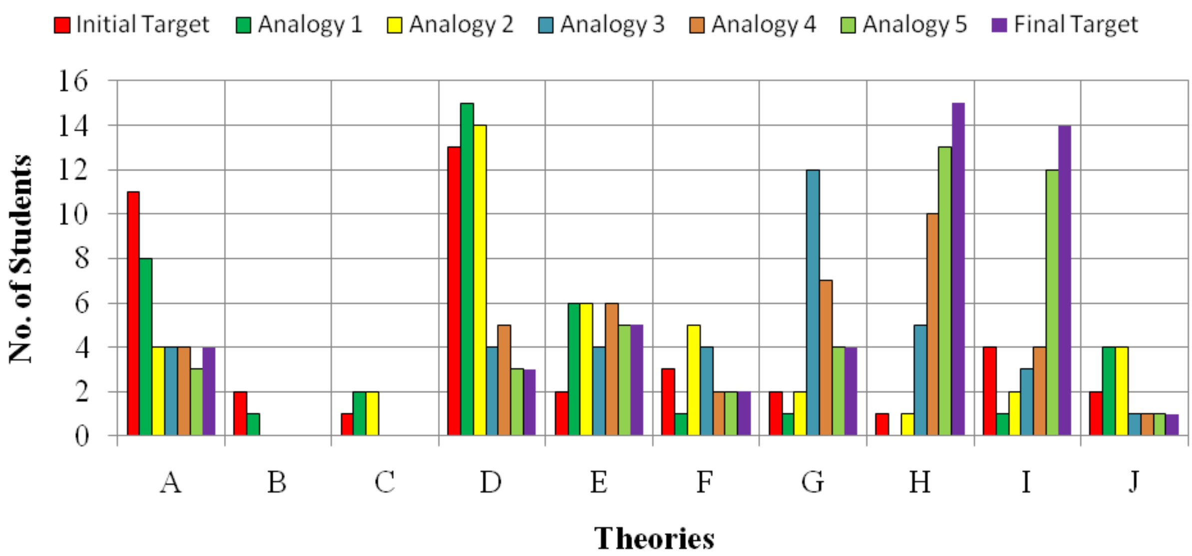


Figure 6.12: Number of students stating each 'immoveable' wall theory at each stage of the 'immoveable' object analogical sequence.

Not all of the students experienced positive conceptual change. Students 4 and 8 did not find the sequence beneficial as they did not change their views in any tangible manner throughout the process. Students 6 and 20 had initially stated that momentum was conserved in the target scenario but by the end of the bridging sequence had decided that momentum was being lost. Despite this negative effect, it is notable that by the end of the process they had both also concluded that momentum was being transferred to the building, which neither of them had clearly stated prior to working through the analogies. It could therefore be argued that they made limited progress in some respects as a consequence of their engagement with the sequence. It has been argued above, that the lack of conceptual change experienced by each of these students was primarily caused by them being unable to make connections between the target situation that they were thinking about, and the relevant features of the different analogies. In the case of the two students whose thinking moved away from the accepted answer, their confusion was similarly caused by their inability to perceive and make connections between the relevant aspects of the sequence and the target.

However the entries in table 6.1, and the chart in figure 6.12, clearly demonstrate that the majority of the students did experience positive conceptual change through engaging with the analogical sequence and their associated thinking, and that these changes could be tracked and analysed. This evidence suggests that the sequence was successful in promoting conceptual change in students across the entire ability range of candidates who attempted the Higher Physics syllabus (measured in terms of their performance in the Higher Physics examination). The most dramatic changes across the sequence occurred for students 25, 47 and 48 who had initially stated that, in their opinion, momentum was not being conserved in the target situation, but by the end of the sequence all three had developed their theory to the point where they were clearly stating that they considered momentum to be conserved at the ‘universal’ level. In addition, all three successfully transferred their thinking to the extension question, although students 25 and 47 were somewhat unsure about the correctness of their answer.

Chapter 7

Findings 4: The elastic / inelastic collision sequence

The questions regarding what the students knew and understood about momentum and kinetic energy prior to engaging with the analogical sequence took up a sizeable proportion of the interview time for this sequence. This was because there were a number of issues that had to be explored in some depth in order to ascertain what each student knew prior to working with this set of analogies. The outcomes of these discussions have been reviewed in sections 5.1 to 5.3 of chapter 5. This chapter will therefore examine the ways in which the analogies themselves influenced the students' thinking and learning. Unfortunately, due to time constraints on several of the interviews, not all of the students were able to complete all four of the analogies. However, all of the interviews that are included in the sample for analysis had worked through at least the first three analogies. Any interviews that had not got as far as including analogy 3 were discounted as only having been partially completed. It was for this reason that interviews 38 and 39 were not included in the final sample.

7.1 Overview of elastic / inelastic sequence results

Table 7.1 below shows the initial and final theories that students gave, which they felt explained why kinetic energy was lost in an inelastic collision between two Pasco carts which were collided in such a way that contact was made between them. Each student's self-assessed belief rating, prior to engaging with the analogical sequence and at the end of the sequence is also shown. The theories given by the students were grouped into six main categories in order to enable an analysis of the theories and changes to them to be tracked and analysed. As with the immoveable object sequence, it can be seen that some students made considerable progress over the course of thinking through the analogies, while some made little or no progress. In common with table 6.1 in the previous chapter, the arrows after each 'final theory' entry in the table indicates where a student' theory became more in line with the accepted theory [↑]; less in line with the accepted theory [↓], or did not change [↔]. An identical system is used to indicate increases, decreases or no changes to a student's belief rating in their theory.

No.	Higher Grade	Initial Theory	Belief Rating	Final Theory	Belief Rating
9	D	Sound – vibrations	3 / 4	Sound – vibrations [↔]	4 / 5 [↑]
10	F	Sound – collision	5	Sound – vibrations [↑]	5 [↔]
11	A	Sound & heat - collision	5	Sound & heat-vibrations [↑]	4 [↓]
12	F	Sound – collision, unsure	2	Sound – collision, unsure [↔]	1 [↓]
13	A	Sound & heat – collision forces & friction	2	Sound & heat-forces [↔]	? [↓]
14	C	Sound – collision	3	Sound – vibrations [↑]	5 [↑]
15	A	Sound – collision	4	Sound & heat - vibrations [↑]	3 / 4 [↓]
16	B	Sound – collision	5/6	Sound – vibrations [↑]	4 / 5 [↓]
17	B	Sound – collision	?	Molecules hitting [↑] (density of molecules)	3 [↑]
18	A	Sound & heat - collision Rubbing	6	Sound & heat – contact, rubbing & vibrations [↑]	6 [↔]
23	C	Sound – collision	?	Sound – vibrations [↑]	4 [↑]
24	C	Sound – collision	?	Sound – vibrations [↑]	4 [↑]
26	B	Sound – collision	?	Sound – vibrations [↑]	5 [↑]
27	F	Sound – collision	?	Sound – vibrations [↑]	5 [↑]
30	B	Sound – collision	?	Sound – vibrations [↑]	5 / 6 [↑]
31	B	Sound & heat – vibrations & friction (Velcro)	6	Sound – vibrations [↑]	6 [↔]

32	F(WD)	Sound – collision	?	Sound & heat - vibrations [↑]	5 [↑]
36	C	Sound – collision	?	Sound – vibrations [↑]	5 [↑]
37	A	Sound - atom vibrations	5/6	Sound - atom vibrations [↔]	6 [↑]
42	A	Sound – vibrations	4	Sound – vibrations [↔]	4 / 5 [↑]
45	F	Potential to kinetic to sound – collision	?	Potential to kinetic to sound – collision, unsure [↓]	? [↔]
49	A	Sound & heat - collision	?	Sound – vibrations [↑]	5 / 6 [↑]
50	A	Sound & heat – compressions	5	Sound & heat – compressions [↔]	5 [↔]
54	A	Sound – vibrations	4	Sound – vibrations [↔]	5 [↑]
55	C	Sound & heat - collision	?	Sound – vibrations [↑]	4 [↑]
56	C	Sound & heat - collision	?	Sound – vibrations [↑]	4 [↑]
59	A	Sound – collision or incomplete transfer	2	Sound – vibrations [↑]	5 [↑]
60	A	Sound – collision	?	Sound – vibrations [↑]	5 [↑]
61	A	Sound – vibrations	5	Sound – vibrations [↔]	4 [↓]
65	C	Sound – collision	5	Sound – vibrations [↑]	3 / 4 [↓]

Table 7.1: Initial and final non-conservation of kinetic energy theories in an inelastic collision and belief ratings for each student.

The entries in the initial and final theory columns of the table relate to explanations that each student gave for the loss of kinetic energy in the inelastic collision that constituted the target scenario for this sequence, in which the two PASCO carts collided ‘magnet to Velcro’, releasing sound and a small amount of heat energy as a consequence. This theory will be referred to as their ‘loss theory’ hereafter.

The initial theory column shows the explanation that was given by each of the participating students prior to working through this analogical sequence, while the final theory column summarises their theoretical stance after they had worked through the set of analogies. Where an entry is ‘sound - collision’, ‘sound or heat – collision’ or ‘sound & heat – collision’ these indicate that the student had thought that some of the kinetic energy was being converted to sound, sound or heat, or sound and heat. Furthermore, it indicated that they could only identify that this was happening as a consequence of the collision between the two carts, but they did not, or could not, enunciate a more developed mechanism or reason for this. The initial ‘loss theory’ entry for student 59 indicates that he initially stated two ideas. He thought that that the production of sound energy was either a consequence of the collision taking place, or that there had been an incomplete transfer of the kinetic energy, but he did not elaborate on this second idea.

It can be seen from the entries in table 7.1 that, by the end of their engagement with the analogies, a greater number of the students had developed more detailed 'loss theories' that went beyond this basic stance of merely stating that the conversion of energy was a consequence of the collision. Some students attributed the conversion of kinetic energy to heat and/or sound because they felt that the two carts rubbed together in some way when they made contact. This 'loss theory' was indicated by inclusion of the word 'rubbing' in their entry in the table. Similarly, some students thought that the mechanism for the conversion was contact between the vehicles, friction between the vehicles, or compressions that travelled through the structure of one or other cart. Each of these views is indicated by the inclusion of the words 'contact', 'friction' or 'compressions' after the type of energy (or energies) which the student indicated that the kinetic energy was converted into. In his final 'loss theory', student 17 described the molecules of each cart hitting one another, making them move, and hence changing their relative spacing. This was recorded by entering 'molecules hitting (density of molecules)'. Student 45 considered sound to have been produced through a process whereby potential energy was converted to kinetic energy and then to sound, but the only explanation that she could identify was that a collision had occurred. This idea was recorded as 'potential to kinetic to sound - collision'. By the end of the sequence she was unsure of these ideas and so the word 'unsure' was added to indicate this uncertainty. The entry 'sound – vibrations' was used when a student stated that the collision resulted in some of the kinetic energy being converted into sound energy as a consequence of small vibrations which had occurred in the structure of both carts. An entry of 'sound & heat – vibrations', shows that the student had stated that kinetic energy had been converted into both sound and heat as a consequence of these vibrations. The final theory given by student 37 was similar to these ideas, but she went a little further, in that she discussed the idea that a vibration travelled through the atoms of each cart. In addition to the vibration concept, student 13 also included the idea that the force exerted between the two carts was partially responsible for the conversion of kinetic energy and so this is included in the entry for his final theory.

The success, or otherwise, of each of the analogies in encouraging successful conceptual change for the students who examined this sequence of bridging analogies is examined below. Each of the analogies in this sequence was intended to help the students to realise that the heat and sound energy that was produced when the two PASCO carts made physical contact was a consequence of the vibrations that were set up throughout the structure of both carts. By the end of this sequence it was hoped that the students would be able to return to the elastic collision example (that had been discussed before the target scenario) and be able to state clearly and concisely that no kinetic energy was lost in that collision because no physical contact took place and therefore no vibrations occurred. This discussion was intended to serve the same purpose as the extension question in the 'immoveable object' interviews, as it required the students to use the ideas that they had developed during the analogical sequence to attempt an explanation for a scenario other than the one that they had been working on.

Many of the comments regarding the types and triggers of conceptual changes that occurred are similar to those for the first sequence discussed above. The discussion of these arguments in relation to this sequence will therefore be rather more curtailed.

7.2 Analogy one

This analogy was intended to enable the students to associate the production of sound energy with the vibrations that occurred when they struck the tuning fork with the hammer. By touching the tuning fork, the students were able to determine that it vibrated after it was struck and they could easily hear the sound that was produced. It was also easy for them to find out that it stopped making a sound when they touched the tuning fork and that this also stopped the vibrations. Although momentum would be conserved in this situation, and kinetic energy would not, this was the most distant analogy in the sequence as it does not appear, at first glance, to be particularly similar to the target situation.

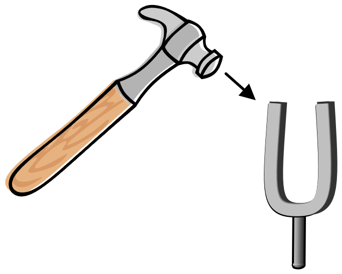


Figure 7.1: Analogy 1 - Tuning fork and hammer

All but two of the students were content that momentum was conserved in this analogy, although some were initially unsure. Students 18 and 24 did not think that momentum was conserved in the analogy, while student 42 appeared to have become slightly less convinced of this in the target scenario as a consequence of examining this analogy. Student 12 was uncertain about the conservation of momentum and although he was not sure, he thought that kinetic energy was not conserved in the analogy or the target situation. As a result of this analogy, student 56 had changed his answer completely regarding conservation of momentum as he had initially stated that he considered momentum to be lost in the target situation.

Twenty nine of the students were of the opinion that kinetic energy was lost in the collision between the hammer and the tuning fork, although student 61 initially thought that kinetic energy was gained as a result of the collision, but ultimately decided that some of it was converted into sound. Student 50 was very confused about whether or not kinetic energy was lost or gained in the analogy and ultimately failed to come to a conclusion.

Despite being the most distant analogy in the sequence, it caused the greatest number of positive conceptual changes. One student (S14) experienced positive conceptual change by increasing his belief rating in the loss of kinetic energy in the target scenario, without changing his actual ‘loss theory’. A total of seventeen students altered their ‘loss theory’ towards one that was more in line with the accepted version.

Nine students experienced no noticeable change in their ideas. Five of them continued to state the sound was produced because of the collision between the carts but were unable to develop their explanation beyond this basic level. Another four students (S9, S37, S42 and S54) had stated at the outset that they thought sound energy was released as a consequence of vibrations in the carts when they collided, and they maintained this theoretical stance.

Two students experienced negative conceptual change in relation to their ‘loss theory’ as a result of their interaction with this analogy, as their theory became less detailed, which suggested that they had become less sure of their stance.

Figure 7.2 below contains two charts which summarise the theories given by the thirty students prior to engaging with the analogies and after working with the first analogy. These theories are the students’ attempts to explain why kinetic energy is not conserved in the inelastic collision between the two PASCO carts when they struck one another Velcro to magnet in the target scenario. Each theory was allocated a code (see table 7.2) in order to make the charts easier to read. Figure 7.2a shows the number of students who stated each theory prior to working through any of the analogies from the bridging sequence; and figure 8.2b shows how many students were enunciating each theory after working through the first analogy. The difference between the two charts enables the overall level of conceptual change that resulted from the thirty students' interactions with the first analogy to be easily gauged.

Inelastic kinetic energy loss theory	**Theory Code**
Kinetic energy not lost	A
Kinetic energy lost but not sure why	B
Kinetic energy lost as sound due to collision	C
Kinetic energy lost as sound & heat due to collision	D
Kinetic energy lost as sound due to vibrations from collision	E
Kinetic energy lost as sound & heat due to vibrations from collision	F
Other	G

Table 7.2: Codes for the inelastic kinetic energy loss theories expressed by students which are in the charts showing the numbers of students who enunciated each theory at the end of each analogy in the sequence.

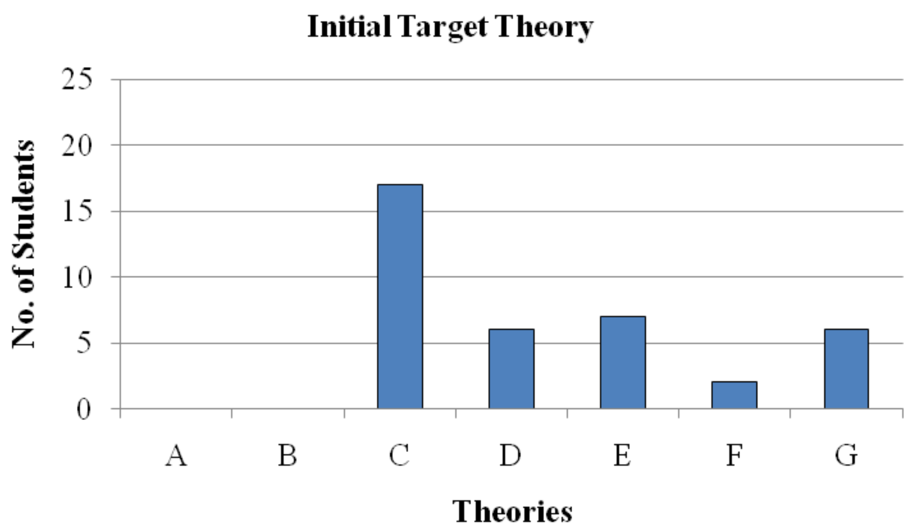


Figure 7.2a: Number of students stating each kinetic energy loss theory prior to working with the analogies.

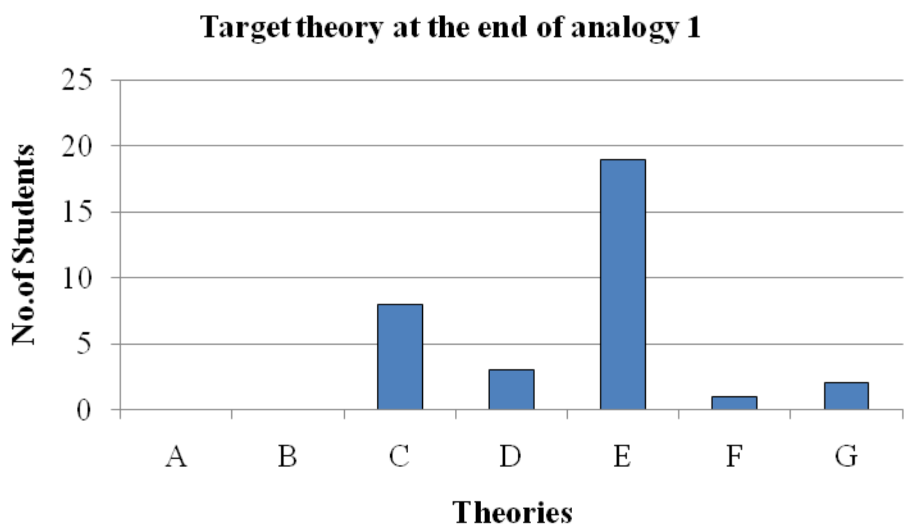


Figure 7.2b: Number of students stating each kinetic energy loss theory at the end of analogy one.

7.2.1 Conceptual difficulties caused by interaction with analogy one

The main difficulty encountered by students in dealing with this analogy was deciding whether or not they thought that momentum was being conserved in the collision. This dilemma was caused in the minds of several students (including many of those who clearly experienced conceptual change) as a consequence of the tuning fork not moving much (other than vibrating) after it was struck by the hammer. In common with the immoveable object sequence, some students had difficulty in appreciating that the tuning fork was part of a bigger entity that included their hand and arm. The larger mass of this set of objects meant that they had little appreciable velocity afterwards. This issue was exacerbated by the difference in behaviour in comparison with the second cart in the target scenario that had moved off with an appreciable velocity after it was struck by the first cart.

Student 12 was very unsure about whether or not he thought momentum was conserved based on the fact that the tuning fork didn't move very much. He was unwilling to commit himself either way. He was also unable to state any similarities between the analogy and the target scenario. Students 18 and 24 concluded that momentum was not being conserved in the analogy on the basis that the tuning fork didn't really move after the collision as the second cart had in the target scenario. This extract from student 24 demonstrates the difficulty of these students.

I: So are you saying momentum is or isn't conserved in that collision?
S24: Gut feeling, I would say no. Just because of the way I'm thinking about it.
I: What is putting you off thinking that?
S24: Because these cars are moving like, and that is rooted to the spot.
I: So because that is not moving?
S24: Because it is not moving as much.
I: So that is making you not sure?
S24: Yeah. I know there are vibrations and all that but I just don't think, ...

Neither of these students expressed an opinion about conservation of momentum in the target situation when they were they stating what they thought were the similarities or difference between the analogy and the target scenario, although prior to working on the analogy, both had initially stated that they thought that it was conserved in the target.

Student 42 appeared to have become slightly less convinced of conservation of momentum in the target scenario having been unsure of the movement of the tuning fork in the analogy. When he was asked why this was the case, he admitted that he was primarily basing his answer on the fact that he had been told by his teacher that this was always true. He said that he was actually not very sure and that his decision was based partly on guesswork. This meant that his originally stated belief-rating of a six was more likely to have been an over-estimate on his part. His interaction with the analogy in fact highlighted that he had not really fully grasped how conservation of momentum worked in real-world scenarios.

Student 50 demonstrated an interesting struggle to decide whether or not he thought that kinetic energy was being lost in the analogical situation. His difficulty was based on his perception that the tuning fork moved quite quickly after the collision. Initially he thought that there would be an overall gain in kinetic energy because the velocity of the tuning fork afterwards would be higher as a result of its smaller mass. This resulted in him concluding that the kinetic energy would increase because of the effects of squaring the larger velocity ($\frac{1}{2}mv^2$).

I: And in terms of kinetic energy before and after what are you saying?

S50: Kinetic energy, I don't think it would be conserved 'cause this is lighter so it would be moving at more velocity.

I: So you're saying what?

S50: Because again it's the same with the car, it's because velocity affects kinetic energy more, I'm saying it wouldn't be conserved and I think it would be higher.

I: After?

S50: Yeah.

I: Where's the extra coming from?

S50: The increased velocity.

I: But how are you creating that energy? From what?

S50: Because the mass is, of this [the tuning fork], is less than the mass of that [the hammer].

When it was pointed out to him that both the hammer and the tuning fork moved after the collision, he changed his mind completely, which showed that he was not consistently applying logic to the situation.

I: But there's two objects moving after.

S50: They’re moving the same way. Well, kinetic energy may be less then ’cause mass has increased, the velocity will decrease, so kinetic energy will be less.

I: Caused by what? Because you’ve not changed from saying its more to it’s less.

S50: I know, yeah, ’cause I was thinking that that would be bouncing back.

I: Well.

S50: Yeah, it’s going, it’s following through.

I: Either way the hammer moves afterwards doesn’t it?

S50: Yeah, if it moves, if it goes back the kinetic energy of this is greater, if it goes through the kinetic energy will be smaller.

I: Why the difference depending on whether this bounces?

S50: Because that’ll affect the weight and the speed going that way, so will affect the momentum going that way, and the momentum beforehand going towards the tuning fork has to be the same as afterwards.

I: In terms of kinetic energy though, why does the direction that the hammer’s going in matter?

S50: Because it affects the velocity of the tuning fork, which in turn affects the kinetic energy.

His main difficulty was that although he had a clear grasp of the kinetic energy equation, he misused it because of a misunderstanding about the significance and use of the direction of motion of the hammer after the collision. He was treating the kinetic energy as a vector quantity. It is clear from this that he was not adept at applying his knowledge of kinetic energy correctly in this situation as he found the change in direction of the hammer confusing. Despite this problem he continued to state that momentum was conserved in the target scenario throughout the entire interview. A few seconds later he reverted back to stating that there would be a gain in the amount of kinetic energy based on the increase in the velocity of the tuning fork. When he was challenged to explain where the extra kinetic energy would come from, he started to discuss a new idea that kinetic energy would be converted into heat and sound energy and said that the increase in kinetic energy was caused by elastic potential energy being changed into kinetic energy. This shows that he was searching for ways to resolve his cognitive conflict using pieces of knowledge that he had previously acquired but he struggled to work out a satisfactory way to link the different pieces together in an intelligible way.

Student 61 initially thought that kinetic energy was gained as a result of the collision but decided ultimately that it was lost. His initial reasoning was that the force of the collision caused vibrations. He reasoned, as shown below, that this meant that there was extra kinetic energy produced which was converted into sound energy.

S61: I would say more after but the fork starts to lose energy

I: As what?

S61: Sound?

I: So, does that suggest that you have got more or less kinetic energy once the collision has happened?

S61: More.

I: Why? If there is sound and there wasn't sound before, where is the sound coming from?

S61: Does the kinetic energy cause the sound energy?

I: Explain what you are thinking.

S61: Because the kinetic energy causes the particles to vibrate.

I: So, you are saying that, the kinetic energy, the vibrations causes sound, is that what are you saying?

S61: Yeah.

I: So, is the system losing kinetic energy, when sound is produced or gaining?

S61: Eh, …, not quite sure because, …, it's the kinetic energy that is causing the sound but, the sound is there because it has kinetic energy.

I: So, are kinetic energy and sound energy the same?

S61: … No, but I think they are related.

I: So if, when we are talking here, are you saying total kinetic energy before the collision, versus the total kinetic energy after, just in terms of the kinetic energy, so what are you saying? About the total before versus the total after of kinetic energy?

S61: There is more after.

I: How do you explain that? Where is that extra coming from?

S61: It's the extra coming from the sound energy then.

I: So, what has allowed the sound energy to be produced?

S61: The collision.

I: And is that creating energy? Is that what you are thinking?

S61: It's causing the force that is being exerted, it's causing the particles to move, so, …, and have energy.

He subsequently changed his mind when he was asked to rate his belief in this idea and decided that he was rather unsure about it. He subsequently decided that sound energy was released when the particles in the tuning fork collided with one another, such that kinetic energy was transformed into sound energy.

I: Well what is it that is causing the sound? Tell me what your ideas about what is causing the sound?

S61: The particles in the tuning fork having kinetic energy.

I: And how does that give them sound? Or how does that result in sound, should I say?

S61: They collide with each other and, eh, …, inside the tuning fork.

I: And that does what?

S61: Releases sound energy.

I: So it's releasing sound energy?

S61: Yeah. It's transferring it from kinetic to sound energy.

I: So, what does that make you think about the total amount of kinetic, before and after?

S61: It's lower because it's being transferred into energy of another form.

I: Ok, so that's different from what you said a couple of minutes ago, why have you changed your mind?

S61: Because, ..., I don't see another way of how the energy can just be produced.

I: So, why can't you see another way, what is the block to that, in your mind?

S61: There is nothing else, to cause the energy being produced.

I: Other than what?

S61: The collisions with the hammer.

I: So, where is the sound coming from?

S61: It's coming from kinetic energy, which is passed into the, …, tuning fork and then it's transformed into sound energy?

I: So, what are you now saying about the total kinetic energy, before versus after? How do they compare?

S61: I think it's the same until, …, the kinetic energy and the tuning fork, starts to change it into sound energy.

I: And then what happens?

S61: The kinetic energy after starts to drop.

I: How sure are you that you are right?

S61: Four.

I: So, you're a bit surer now of this idea than you were of the other version?

S61: Yeah.

The end of this extract shows that he had been 'twin-tracking' between the two ideas. In the end he decided that his final explanation was more intelligible as he was able to link it with other pre-existing ideas that he had about how sound was produced. He had also come to his conclusion partly as a result of having a lack of plausible alternatives.

7.2.2 Negative conceptual change resulting from interaction with analogy one

Student 31 and student 61 were the two students who experienced negative conceptual change as their 'loss theory' became less precise, which suggested that they had become unsure of their prior reasoning. This assumption is perhaps less valid in the case of student 31 for the following reasons.

Student 31 had mentioned that kinetic energy would be converted into sound and heat as a result of vibrations from the collision when she discussed the target scenario prior to embarking on the analogies. During this initial discussion she had stated that heat would have been produced because of friction between the Velcro pad and the other cart. By the end of analogy one, she had changed her answer slightly in that she no longer mentioned friction or the conversion of energy into heat energy but only discussed the conversion to sound energy (as shown in the extract below). It is possible that this was caused by the emphasis on the release of sound energy in the analogy, rather than an actual down-grading of her theory.

I: What about the kinetic energy, before and after?

S31: Probably be less.

I: When?

S31: After it struck it.

I: Why? What's your reasoning?

S31: Because it's being lost through the sound energy.

I: And why is there sound energy being lost?

S31: Because the momentum is being passed on to the particles of air and they all move.

I: So, what is the tuning fork doing that is causing the sound?

S31: It's vibrating and moving.

Her initial reasoning for the conversion into sound was consistent with her pre-analogy view as she repeated her earlier assertion that the release of sound energy was linked (in her thinking) with the transfer of momentum to the air particles that surrounded the vibrating object. It is however also obvious, that she made the link between vibrations and the production of sound very evident in her final statement.

When she was then asked to describe the similarities or differences that she thought existed between the analogy and the target situation, it became clear that she was highly convinced that sound energy was released as a consequence of vibrations. Her level of certainty was checked by asking her to consider that the carts were solid objects, in order to ascertain whether or not this worried her.

I: Ok, so what differences or similarities do you see between that analogy and the collision you have just done with the two trolleys, which would help to explain it to someone else?

S31: After one of them hitting, …, the other, they both move still.

I: So, tell me what you think is going on with the trolley collision? Red trolley comes in, …

S31: They both vibrate a bit afterwards.

I: Despite the fact that they are solid objects? Are you quite happy with that?

S31: Yeah, because solid objects can vibrate as well.

I: How sure are you?

S31: A six.

Her 'loss theory' remained well articulated and her confidence in it had remained unchanged. She had lost the prior references to friction and heat energy but, as argued above, this may have been simply because the discussion about the analogy had focused on the sound that she could hear. In addition, the lack of any rough surfaces on the hammer or the tuning fork may partially account for her not revisiting her previous thoughts about friction and the resultant conversion of energy to heat.

Student 61 exhibited a clearer downgrading in his ‘loss theory’ by the end of the first analogy. Prior to encountering the analogies he gave the following explanation for the loss of kinetic energy in the target inelastic collision.

I: So, in terms of the total before versus the total kinetic energy after, what would you say is going on?

S61: I would say that some of it is possibly lost.

I: Lost as what?

S61: … Heat possibly from friction, if there is any.

I: Ok, anything else?

S61: Eh, …, sound when the two collided.

I: Sound. Now why is there sound produced, whereas in the last one, if you try it again, have ago, you didn’t mention sound there, is there any sound there?

S61: No.

I: So, why have we got sound being lost in one and not in the other?

S61: Because in the second one, the two cars hit each other but, this one is forced apart by the magnets.

I: And why does, in your words, hitting each other, make a difference? Why does that matter?

S61: Because they are touching each other.

I: And what is the consequence of that?

S61: Some of the molecules of each car come into contact with, …, ones in the other

I: And so why does that cause a loss of sound energy, as you have mentioned?

S61: … They start vibrating.

I: What do?

S61: Some of the particles

I: How sure are you of that idea?

S61: A five.

I: Pretty sure?

S61: Yeah.

As discussed above in the conceptual difficulties section, he had struggled to decide whether or not he thought kinetic energy was being lost in the analogy and ultimately decided that it was lost because the tuning fork changed it into sound energy. When he was then asked to explain what he thought was happening in the target situation at the end of the first analogy, he gave this answer.

I: So, what's your current story then about kinetic energy before and after for the trolleys?

S61: I would say that they are lower after, than before.

I: Give me a belief rating on that? How much do you believe that is true?

S61: Five.

I: And why is sound being released?

S61: Because of the same idea as the tuning fork, …, that the, …, particles in each car have kinetic energy and, …, transform into sound.

I: And why does it transform into sound and not stay as kinetic energy, any ideas?

S61: Eh, …, is it because they have too much energy and they are trying to release it.

I: Ok, so in terms of your theory about the sound being produced, because the kinetic energy some of it becomes sound, what are you giving that?

S61: A four.

His statements show that he was making connections between the analogy and the target situation. The negative influence of this was that, having struggled to understand what was happening in the analogy, he defaulted to merely stating that the kinetic energy of the carts' molecules was converted into sound energy. He had lost the part of his theory that explained the production of the sound, specifically in terms of the vibration of molecules. It is possible that he was still thinking in terms of the molecules vibrating but since he did not mention it, it was assumed that he was not. The problem was that he overlooked the obvious idea that the tuning fork produced sound as a consequence of the vibration in its arms, which is an idea that he was very likely to have been introduced to in science lessons in previous years, and which he had mentioned before engaging with this analogy. The data from this section of the interview highlights some of the negative effects of cognitive conflict. It suggests that it is possible for students to fail to make links with prior learning and to take cognisance of relatively obvious physical clues in a situation as a consequence of underlying cognitive conflict because it triggers incoherent thought processes that divert or possibly overwhelm their reasoning. In this case, the cognitive conflict of student 61 became evident as a result of the in-depth interview process, but often it is not obvious in everyday classroom interactions with students.

7.2.3 Non-changes resulting from interaction with analogy one

Prior to being introduced to the first analogy, students 9, 37, 42 and 54 all stated that some kinetic energy would be converted to sound energy in the target scenario because there would be vibrations in the carts as a consequence of the physical contact between them. In all four cases they appeared to be basing their thinking on prior teaching or knowledge that they had on the topic. When asked how sure he was about the vibrations when initially discussing the target situation, student 9 said this.

I: How sure are you of this vibrations idea?
S9: Three or four, because that is how sound is produced, through vibrations.

Student 54 also showed that she already knew that there was a link between sound production and vibrations when she made the following statement regarding the inelastic collision.

S54: I know that vibrations must be caused for sound to happen, so, …
I: Based on what? How do you know that?
S54: Well sound is vibration.
I: And how do you know that?
S54: Because, I don’t know, it’s just kind of, been a fact.

Students 37 and 42 did not indicate their reason for stating that vibrations were responsible for the release of sound energy, but it is reasonable to assume that they were basing their thoughts on previous teaching that they had received on the topic. All four of these students maintained their ‘loss theory’ throughout the sequence, although all of them became slightly more convinced that they were correct as each of the analogies confirmed their original thoughts.

The four students who maintained their basic view that sound energy was produced in the target scenario because of the collision had similar difficulties to those who made negative progress in using the first analogy. Two of the students did however make progress when they were examining analogies later in the sequence, while the other two failed to progress their 'loss theory' throughout the entire sequence.

Students 12 and 45 (both of whom were at the lower end of the ability spectrum as they both ultimately failed the Higher course) made no progress in relation to their 'loss theory' as a result of this analogy or any of the others in the sequence. Student 45 believed that momentum was conserved in the analogy almost entirely on the basis of what she had previously been told by her teacher or had read in textbooks. In effect she had experienced conceptual change in the past simply as a consequence of what Tiberghien termed 'social rules'. It became apparent during this sequence that she did not understand the reasons behind conservation of momentum. She simply accepted it as being true because that was what she had been told. More positively, she realised that the tuning fork produced sound as a result of the vibrations that occurred, but she was unable to relate this to the target situation in any way. Student 12 failed to make progress as a consequence of encountering several difficulties. He found the analogy hard to comprehend and claimed that the target scenario was easier to understand in terms of the kinetic energy being lost as a result of the collision. His failure to associate the vibrations in the tuning fork with the sound that it produced also caused him to experience confusion. He was ultimately very unsure about whether or not kinetic energy was conserved in the analogy and admitted to merely guessing that it was not.

I: So, in terms of the kinetic energy that the hammer had before the collision, tell me what has happened to that kinetic energy total by the time the collision has happened.

S12: I would probably say it has gone down because there is energy lost through sound.

I: So, you are now saying that you think energy is being lost, kinetic energy, by being changed into sound? Is that what you're saying?

S12: Yeah, I think so.

I: How convinced are you?

S12: One.

I: Not sure at all?

S12: No.

I: Why are you not sure?

S12: I'm just a bit confused.

I: Why are you confused, would you say?

S12: It is just a different situation with the hammer and the tuning fork. I think it is a bit easier to understand through the carts.

I: You think they are easier to understand?

S12: Yeah.

The end result was that he failed to make any meaningful connections between the analogy and the target and therefore made no progress in belief-ratings or his 'loss theory'.

I: OK. Now what do you think? Any comparisons you would make between that and the previous example? How do you think this analogy compares with this?

S12: This one is a bit more confusing I would say because the carts move, they are the same weight, same mass. This is just a bit odd.

Although they made progress later in the sequence, students 15 and 59 made no progress through the use of the first analogy. Like the others, student 15 was initially unable to link the production of sound with the vibrations in the analogy. He only succeeded after the vibrations and the sound were made more obvious by striking the tuning fork on the desk and placing its end on the desk to amplify the sound.

I: Now is there a link there between the vibration and the sound?

S15: I don't know. No.

I: Think back to first year. Did you learn anything about sound?

S15: It doesn't make that loud a sound but it still vibrates if I hit it off that [the desk].

I: But it does make some sound does it?

S15: I can't hear anything.

I: If I do that? [Places the end of the tuning fork on the desk].

S15: I mean it doesn't make a sound on collision.

I: That's true, but is there a sound coming from that?

S15: Yeah.

I: So is there a link between vibration and sound?

S15: There must be.

I: Why are you saying there must be?

S15: Because it is a tuning fork, and it is getting sound and it is making sound, and to do that it vibrates.

I: So you are saying that the sound is caused by the vibrations? Is that what you're saying? Or is the sound being caused by something else?

S15: The vibrations cause the sound.

From this interaction, it could be deduced that he had struggled to understand the link between the vibration and the sound because the sound level and the magnitude of the vibrations, when he struck the tuning fork with the hammer, had been insufficient to convince him. The encouragement to consider what he had been taught about sound in first year science appeared to make no difference, but the increased levels of sound and vibration did make him much more convinced. Having made this connection in the analogical situation, he then failed to associate the production of sound in the target situation with vibrations. He evidently perceived the two situations as being dissimilar. It could be argued that the idea that vibrations could have occurred in the carts was too 'cognitively distant' from the analogy to enable any causal connection to be made. He therefore continued to explain the loss of sound energy as being a consequence of the contact between the carts.

Student 59 (a very able student) had only rated himself at a belief-rating of two that kinetic energy was lost in the target scenario. This only came about after a rather protracted discussion about the movement of both carts after the collision, as opposed to only one cart moving beforehand. This had resulted in him wrongly deducing that kinetic energy had been gained in the collision. He eventually concluded that the production of sound energy in the collision (which he initially considered to have a negligible magnitude or significance) meant that kinetic energy could not be conserved. His 'loss theory' at that stage was linked to the production of sound because of the collision and changes in the velocities of the two carts. He subsequently linked the vibration of the tuning fork, and then the air molecules around it, with the production of sound in the analogy. Like the other three students who did not alter their 'loss theory', he was unable to see any connections between the analogy and the target and gave the following reason for this.

S59: I'm not sure how I would relate the two, they are both kind of, ... Would you say something about how, …, that velocity, … No, I don't know how to relate them, because they are sort of two different ideas, because that continues to move forwards and that actually moves backwards.

The surface features of the two situations were too dissimilar to enable him to connect the thinking from the analogy to the target scenario. This finding once again exemplifies the assertion of Spiro et al. (1989) that students can directly (or indirectly) focus on misleading properties of an analogy. The rebound of the hammer was actually caused by the student's own wrist action rather than being a direct consequence of the collision with the tuning fork. However this dissimilarity worried this student (as well as some others) sufficiently to dissuade him from seeing enough similarities between the two situations to enable progress to occur at this stage.

7.2.4 Positive conceptual change resulting from interaction with analogy one

Student 56 experienced a significant change in his thinking about conservation of momentum in the target situation by the end of the first analogy. His initial thinking, prior to the sequence, was that momentum was lost when the two carts collided. By the end of the first analogy, he had decided that momentum was being conserved and rated his belief at level four, having rated his previous non-conservation idea at level three. He had initially stated that momentum was not being conserved as he thought that it was converted into sound energy when the carts collided. The change in his thinking was initiated during his interaction with the analogical situation, as shown in the extract below.

I: So tell me, the total momentum before versus the total momentum after, given that then you have a hammer and a tuning fork involved after, both have some sort of movement going on. How do you think those totals compare, of momentum?

S56: I reckon it would be equal.

I: Why?

S56: Because, …, the kinetic energy is given off, ..., the movement energy doesn’t change into sound like that, it’s the kinetic energy that changes into the sound

I: So you are saying that momentum isn’t becoming sound?

S56: No.

I: It’s the kinetic energy?

S56: It’s the kinetic energy that is becoming sound.

I: How sure are you that you are right?

S56: Four.

I: Now that seems slightly different than what you were saying before because, when you were doing this Velcro to magnet, you were talking about momentum becoming sound energy. Have you changed your mind?

S56: Yeah.

I: Why?

S56: Because, both of them can’t become sound energy, because they are not the same thing, they’re different, because kinetic energy and momentum aren’t the same thing.

I: What’s led you to that conclusion? Because I think you have changed what you are saying. Why do you think that now? Because five minutes ago you weren’t saying that.

S56: Because, probably the different examples.

I: So, by doing this, it’s made you think more, has it?

S56: Yeah.

The triggers for this change were coded as ‘faulty logic recognition’ and ‘making connections’ with the analogy. He had realised, as a consequence of thinking about the analogy, that momentum could not become sound as it was not the same as kinetic energy.

A few minutes later he was asked to describe what he thought was happening in terms of momentum in the target situation. He exhibited clear evidence of ‘twin-tracking’ between conservation and non-conservation, but ultimately settled on conservation of momentum in the target situation as well, as a result of the process shown below.

I: What about in terms of momentum – are there similarities or differences? In terms of what is going on with the momentum?

S56: Hmm.

I: Before versus after and things like that?

S56: I don't really know. It's hard.

I: Well, what were you saying about the momentum of the hammer and the tuning fork, before versus after, how did you say they were comparing?

S56: Pretty equal.

I: And what were you saying about the trolleys?

S56: In what situation of the trolleys?

I: With the Velcro to magnet.

S56: After is smaller, the before is greater than the after.

I: Now that's different from what you said two minutes ago.

S56: I know.

I: Are you comparing two of the ideas, or are you trying to work out which one is true?

S56: Yeah.

I: Because you seem to be jumping between the two regularly.

S56: Yeah.

I: So, tell me what you think is happening here in the trolleys then, you are struggling to see much comparison, so tell me in terms of momentum what you think is happening here?

S56: Here?

I: Yeah, with the trolleys Velcro to magnet?

S56: Well based on that, after that experiment, the momentum is conserved.

I: So you have gone back to that again?

S56: Yeah, if you added up afterwards, if you added up the movement of this one is moving at and the red one is moving at.

I: The red one, yeah.

S56: Like if you added them both up, I reckon it's going to be the same as before.

I: How sure are you, because you seem to be jumping back and forward in that?

S56: About a four now.

By connecting what had occurred in the analogy to what happened in the target scenario, he decided that the two situations were very similar and therefore he transferred his theory about momentum across.

This transfer of concepts, from analogy to target, did not occur in relation to his kinetic energy ‘loss theory’, despite the fact that he had made it very clear during his thinking about the analogy that sound was produced as a result of vibrations in the tuning fork, as shown in this extract from an earlier section of the interview about analogy one.

I: So why does a tuning fork make a sound, why was it making a sound?

S56: Because of the vibration.

I: So how would you convince someone that it was the vibration that was making the sound?

S56: The laws of physics, that’s the way sound works, it comes from the vibrations and the sound waves and sound energy.

Although he had clearly connected the production of the sound with the vibrations in the analogy, he did not mention this when he was asked about the target scenario. His answer was consistent with his original theory about the transformation of kinetic energy into sound and heat. He also repeated that this was a consequence of the collision rather than describing vibrations. The link between sound and vibrations was not sufficiently evident in the target scenario to encourage him to change his ‘loss theory’ at this stage.

Student 14 experienced positive conceptual change in three ways. He increased his belief-rating in the loss of kinetic energy, as well his belief-rating in the conservation of momentum, in the target scenario. He was also one of the seventeen students who developed the detail of their ‘loss theory’ such that it bore more similarity to the accepted version. As can be seen in the extracts below, these changes were triggered by the connections that he made between the analogy and the target scenario. Having initially given a vague ‘loss theory’ in that he merely stated that the sound was produced as a consequence of the collision, he gave a more detailed answer by the end of this analogy.

S14: There was some given off to sound energy but the rest was kept within kinetic energy.

I: And why was there sound given off there?

S14: Because of the vibrating. So, when that hits off that there is a small vibration which causes sound.

I: Vibration where?

S14: You can't see it. Maybe not a vibration but when they hit, …

I: So what do you think is vibrating?

S14: Not vibrating but like when they hit each other, the two ends of the car, I don't think it is a vibration but it is a, …

I: Why don't you think they are vibrating?

S14: I don't know, I can't see if it is. It would be so small a vibration anyway.

I: But do you think there might be?

S14: Yeah, I think there would be some vibration. In most things you hit, if there are two bits that hit each other there would be vibrations.

I: OK. Give me a rating on how much you are convinced that kinetic energy is not conserved now.

S14: When I did this?

I: With the trolleys.

S14: Five.

I: It's gone up. Why?

S14: Because I proved with the analogy that it helped me see what happens. I am convinced of the vibration.

I: How convinced are you that there is a vibration in the trolleys?

S14: Four from your suggestive tone.

I: I'm not trying to suggest anything, deliberately. I'm trying to not suggest. I want you to tell me what you think.

S14: Yeah, five.

I: Why are you giving it a five?

S14: Because that is what I have learnt in class and I've proved it with this so I backed it up with this.

It is evident from the above extract that he was initially unsure about vibrations occurring in the colliding carts because he could not see any movement in the structures. Despite this, he made it clear in his final statement, that he had become convinced that the sound was being produced as a result of vibrations. There were two triggers for this change. He made use of the visual and tactile evidence from the analogy, and he linked what he had previously learned with what he had just experienced. His use of the term 'proved' is noteworthy as it suggests that he viewed the analogy as having given him definitive evidence that there would be vibrations in the carts. It could be argued that this change was partly encouraged by the implicit encouragement that he felt had been given by the interviewer. However, the reply that he was given attempted to dissuade him of this impression and it is also notable that he increased his belief-rating in the new ‘loss theory’ after that discussion, which suggests that he had genuinely become more convinced.

Before moving on to the second analogy, he was asked to discuss his thoughts about the momentum in the analogy. His belief-rating in the conservation of momentum in this scenario was higher than it had initially been for the target situation. This increase was largely a consequence of the idea becoming more logical to him. He was able give a fairly coherent argument in terms of the previously discussed impulse equation, and he could not envisage any other more plausible explanation.

> I: Tell me about the momentum there. Tell me what you think is going on with the momentum between the hammer and the tuning fork.
>
> S14: It is conserved.
>
> I: How sure are you?
>
> S14: Five.
>
> I: Why?
>
> S14: Because there is really nowhere else that the momentum, momentum is force times time.
>
> I: The change in momentum?
>
> S14: Yeah, the change in momentum is force times time so when you hit this, the time you take to hit it and the force at which you hit it transfers on to the fork. There is not really any other way. There is nowhere for it to go.

Unfortunately, this increased belief-rating was not asked about in relation to the target scenario at this point but later questioning, after other analogies in the sequence, showed that he had transferred this greater belief to his thinking about the target as well.

Student 16 had made less progress by the end of this section of the interview, although he had one similar outcome to student 14. He had been unable to articulate a reason for the loss of sound energy other than there having been physical contact between the carts prior to working with the analogies. Like student 14, he had concluded that sound was being produced in the analogy because of the vibrations in the tuning fork, but he did not convincingly transfer this thinking to the target scenario. When he was asked how the analogy and the target compared, he mentioned that “vibrations are carried through by the momentum” but it was unclear whether or not he was referring to the carts. Since he had not specifically mentioned this idea when he was asked about similarities or differences between the reasons for the sound production in each case, it cannot be assumed that he had connected the two pieces of knowledge in the target. Like student 14, the ‘conceptual distance’ between the knowledge about vibrations and the production of sound was too great in the case of the target situation to enable him to confidently connect the concepts. He rated himself as a four or a five for conservation of momentum in the target scenario by the end of this section, but this showed that he had become slightly less convinced. The reason for this slight reduction was that he found it harder to see that momentum was being transferred from the hammer to the tuning fork and so he was less convinced that it was being conserved.

> S16: Because in the cars it is a lot more noticeable, you can see there is momentum getting passed through from one car to the other whereas with the hammer and the tuning fork it is a lot harder to see.

As discussed in the ‘conceptual difficulties’ section above, it is evident that he was one of the students for whom the first analogy had made things slightly less clear regarding the conservation of momentum.

Of the other fifteen students who changed their ‘loss theory’ from the vague notion that the sound was being released simply because of the collision, fourteen came to the conclusion that the sound was being produced as a consequence of vibrations in the carts. There could be two explanations for this. It is possible that the first analogy simply reminded them of previous teaching that they had received about the connection between heat, sound and vibrations. This was partially true for student 27 who was the only member of this group to explicitly state that he remembered being taught about the need for vibrations for the creation of sound. Alternatively, they could have experienced conceptual change as a result of thinking through the first analogy, and the other analogies could be seen as having helped them to confirm their new thinking. In many cases it was likely to have been a combination of the two possibilities, but connections were being made regardless of which option was the cause.

The latter of the two possibilities is consistent with the fact that each of them appeared to connect the vibrations with the production of sound as a consequence of their physical interaction with the first analogy. They had been encouraged to touch the vibrating tuning fork. It was only at that point, when they noticed that the sound stopped when the tuning fork ceased vibrating, that they really made the connection between the knowledge that the tuning fork produced sound and that it vibrated. Students 10 and 26 made it very obvious that this was the cause of their progress. Student 26 had been explicitly asked if he could remember being taught a link between the two things and said that he didn't think that they were linked. However he made the link when he was asked to try the experiment again.

I: So has the vibration got anything to do with the sound?

S26: No. I don't know.

I: Think back to first year or second year. Has vibration got anything to do with sound?

S26: No.

I: So why, if I touch this, if you touch that straight after, why does the sound stop?

S26: Because it has stopped vibrating.

I: So is there a link between those?

S26: Yeah.

I: What is the link?

S26: The vibrations link with the sound.

I: Do they cause the sound?

S26: Yeah.

I: How do you know that? How would you justify that?

S26: Because the molecules, whatever is colliding is causing a sound and vibration and as they collide it vibrates causing a sound.

I: So you're saying the vibration is what is causing the sound ultimately is it?

S26: Yeah.

I: And how could you prove that to me by doing something? What could you do to prove that to me?

S26: Hit it.

Although his thinking was guided in relation to the vibrations and the sound by careful questioning, it is evident that he had made the connection between the two for himself. This meant that he was then able to link this new idea with the target situation.

Student 10 had a similar experience as he interacted with the analogy.

I: Why are we getting sound?

S10: Because they are touching each other.

I: What is making the sound happen? If you tap it again. You can tap it a bit harder if you like and then touch the tuning fork.

S10: What is making the sound?

I: Yes. Why is there sound being produced at all?

S10: I don't know.

I: Tap the tuning fork a bit harder. [Student taps tuning fork with hammer]. Now touch it.

S10: To use up some of the energy?

I: Let me tap if for you a second. Touch it and listen as you touch it. Do you notice something when you touch it? Do it fairly quickly after I have hit it. What happened when you touched it there?

S10: You feel it vibrating.

I: And what happened to the sound when you touched it?

S10: The sound stops.

I: So does that suggest anything to you? What is causing the sound to be produced? In other words why is the tuning fork making a sound?

S10: I don't know how to explain.

I: When you touched it, what happened?

S10: The sound stops.

I: And what else stopped?

S10: The vibrating.

I: Do you think there is a link there?

S10: Yeah.

I: Go on.

S10: Between me touching it and them stopping?

I: Well the sound and the vibration. Is there a link? Or is that just pure chance?

S10: Well the energy is changing to sound and vibration. Sound and kinetic.

I: What is causing the sound to be produced? What is making the sound from the tuning fork?

S10: The vibrations.

This discussion demonstrates that he only made the connection as a result of his interaction with the analogy and the guided questions. As he did not state that he had simply remembered a previous connection between the two, he appeared to have made the connection for the first time in his own thinking at this point.

Some of the students gave an indication of the reason for their change of thinking when they were reconsidering the target scenario after working through the analogy. Student 27 gave a well considered reason for his change of theory that clearly demonstrated that he had conceptually connected the analogy and the target.

S27: They hit so they vibrate which causes the sound.

I: So, what are you saying is vibrating?

S27: The front of the blue one and the back of the red car.

I: Give me a rating, one to six of how sure you are of that.

S27: Four.

I: Why have you decided on that? Because a minute or two ago you didn't really have an idea what was causing it?

S27: Because with the hammer and tuning fork you can feel the vibrations so if you were quick enough you could probably feel the vibrations after those two collide.

I: So, what would you say to someone that said: Well I can't see that vibrating, so how do you know?

S27: Because it will be a quite small vibration because the sound only lasts as long as contact.

I: But you think, despite the fact that you can't see it, that there is a vibration going on there.

S27: Yeah.

Student 13 went further than the others as he decided that both sound and heat were being produced as a consequence of vibrations in the carts.

I: Is there any link between what caused the sound here [in the analogy] and what you think is causing the sound here [when the carts collide]?

S13: Yeah, it is the same kind of thing, is it not? So the exact same thing will happen so there will be a degree of heat produced where I hit it as well from the collision.

I: What is causing the sound?

S13: The vibration and kinetic energy.

I: And do you think there is anything similar going on here [when the carts collide]?

S13: Yeah, there will be a vibration there as well that will create the sound.

I: Where would this vibration be?

S13: In the air. Surrounding the collision.

I: Caused by what?

S13: The kinetic energy of the collision being transferred to the air.

I: So is it just the air round it that is vibrating would you say?

S13: The cars will do it is as well, sort of. The sound that you will hear will be through the air vibrating.

I: But you are saying that you think the trolleys are vibrating?

S13: I think they will and that will make it go through the air.

I: How sure are you of that theory?

S13: Not very. About three.

I: So what is making you not sure?

S13: I am just not sure. I could be wrong.

Although he was rather cautious of the correctness of his newly extended theory, it was clear that he had experienced conceptual change in the terms discussed by several of the theoretical positions. His conceptual change was coded as being an example of several types: Ausubel's 'meaningful learning'; diSessa's concept of 'complex system building'; Brown and Clement's 'explanatory model construction'; Tiberghien's 'modelling theory' (at the level of specific objects and events only); Vosniadou's theory restructuring explanation (at the level of objects & properties only); and 'making connections' between his new thinking and the analogy, as well as prior learning in Physics. In addition, the fourteen students who came to the conclusion that sound energy was produced by vibrations that occurred when the carts collided were coded as exhibiting these same conceptual change categories. In particular, they all made progress by virtue of making connections between the behaviour of the tuning fork and the carts in the target scenario. These identified categories are the same as those exhibited in the thinking of several students whose reasoning was analysed in relation to the 'immoveable object' sequence in the previous chapter.

7.3 Analogy two

The second analogy made use of the same tuning fork that was used in the first analogy. This was done to encourage the students to realise that the same vibration process was occurring in this analogy. By placing their hand on the rubber ball, it was also hoped that they would be able to feel the slight vibrations that were set up in it as a consequence of the collision. It was hoped that this would enable them to deduce that both objects involved in a collision of this type vibrate.

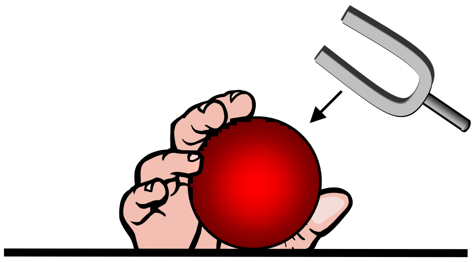


Figure 7.3: Analogy 2 - Touching a rubber ball which is being struck with a tuning fork.

Several of the students were rather uncertain about the ball vibrating after it was stuck by the tuning fork, mainly because the vibrations were not very obvious. However, in terms of momentum conservation, a number of students (including students 11, 27 and 56, who all had different outcomes in using this analogy) came to the conclusion that momentum was transferred through the ball and then into the table. This showed that they were considering momentum conservation on a large scale, somewhat akin to with the universal scale discussed in relation to the 'immoveable object' sequence above. The negative side of this for student 27 was that, although he mentioned the idea that momentum might be transferred to the desk, he struggled to really accept it and so his belief-rating in conservation of momentum dropped to a two for the analogy, but remained at level four for the target scenario.

Nine students maintained their loss theory but had become more convinced of it, while one student (S17) became slightly less sure of his. Two students developed the detail of their theories, while another two developed their theory and increased their belief-rating

Fourteen students did not change their theory or their belief rating although ten of them were already talking about vibrations. Two of this group were students 12 and 45 who did not alter their opinions throughout the sequence.

Figure 7.4 below, summarises the number of students who were stating each of the identified theories at the end of analogy one (figure 7.4a) and by the end of the second analogy (figure 7.4b). As with the charts in the previous chapter, this enables comparisons to be made readily between the overall numbers of students who held each theoretical stance at the end of the successive analogies.

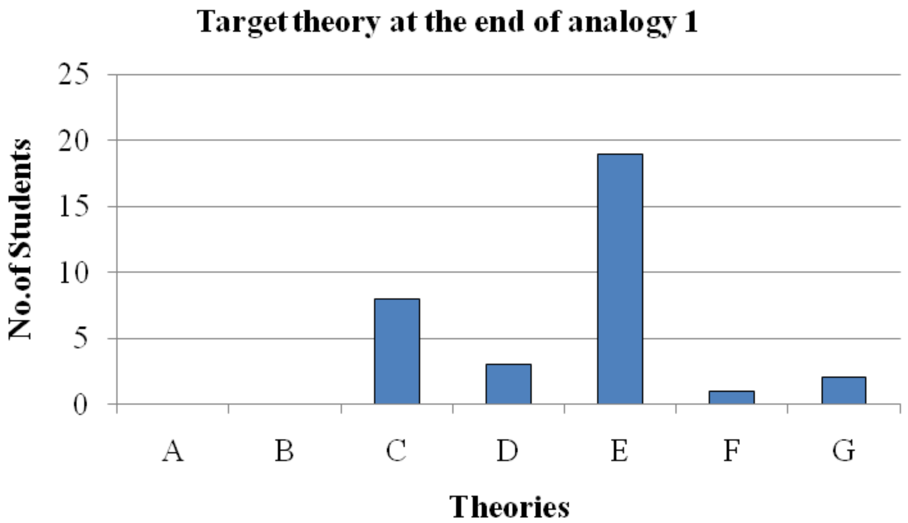


Figure 7.4a: Number of students stating each kinetic energy loss theory at the end of analogy one.

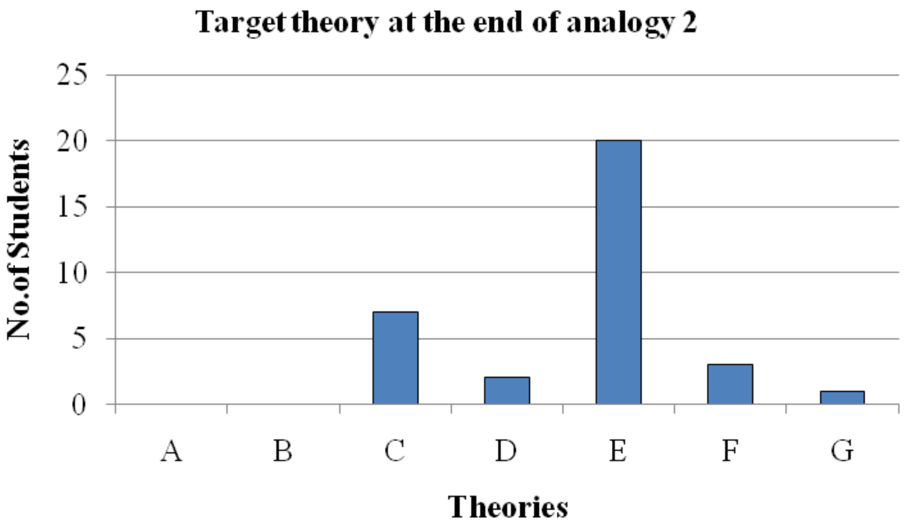


Figure 7.4b: Number of students stating each kinetic energy loss theory at the end of analogy two.

7.3.1 Negative conceptual change resulting from interaction with analogy two

Two students reverted back to an earlier version of their 'loss theory' as an explanation for the loss of kinetic energy in the target scenario by the end of the second analogy. Student 18 regressed in his 'loss theory', while student 56 progressed his 'loss theory' in relation to the analogy but regressed in terms of the target. In both cases their difficulty was caused by a failure to connect what they were seeing and thinking in relation to the analogy with what they thought happened when the two PASCO carts collided.

Student 18 continued to think that momentum was not conserved in the second analogy having said the same about the first and having struggled to decide that it was in the in the target scenario prior to studying the sequence. In terms of kinetic energy, he was of the opinion that kinetic energy was lost through conversion to sound and heat in the second analogy and he made connections between the first and second analogies about vibrations being the cause of this.

I: Do you see any links between that [the first analogy] and this analogy? Any similarities or differences?

S18: Sound, and that one only moves a little bit. It doesn't move as fast as the hammer and as long as the hammer if you let it go on and this is the same. It just dies off.

I: And what about the reason for the loss of sound energy?

S18: The vibration.

I: In both?

S18: Yeah.

However, when it came to comparing the second analogy with the target he reverted back to stating that the sound energy was being caused purely by the contact between the surfaces, rather than by vibrations that he had unequivocally mentioned in connection with the two analogies.

I: Now what similarities would you draw for somebody between this [the second analogy] and this [the target scenario]?

S18: That is two surfaces contacting and there is nothing from stopping it. This there is a table and the energy is passed on to the table and then it will stop some of the energy.

I: What are the similarities between the two though?

S18: Energy is being lost through sound.

I: And is the reason for the loss of energy the same or different?

S18: The same.

I: So, what is your story about the reason for the loss of sound?

S18: Because of the contact. The contact is made and sound is produced because of the contact.

I: A second ago interestingly, when I said that, you said that the sound was produced here because of vibration, so are you seeing that as different to that?

S18: Well it has contact and there is a sound, some, and then because this is a kind of ball which vibrates all over, the energy is passed in through it.

I: So you see them as a bit different?

S18: Yes.

Although he did not state a reason for it, it is arguable that this difficulty was caused by him being unable to see any vibrations in the body of either cart, while he could see or feel the vibrations in both of the analogical situations. This suggests that he had struggled to make the theoretical connection between the vibrations and the sound and heat when the carts collided and that his initial idea about contact and rubbing surfaces was proving to be resistant to change.

Student 56 clearly linked the production of sound energy with vibrations in both of the analogies for the first time. Despite making this progress, he did not make this connection with the target. However, unlike student 18, he did indicate a reason for his thinking, as follows.

I: Why is there sound given off in the two trolleys?

S56: Because of the collision between the surfaces.

I: So, why are we getting sound there? How does that cause sound?

S56: Not quite sure, because I can see the vibrations ,and you know that in the tuning fork, that you know that's what its suppose to do, and it just gives off energy, eh sound, because it collides.

I: You don't see the vibration as being similar?

S56: No.

I: Why not?

S56: Just because it's not a loose object, it's not used to vibrating.

In a similar manner to that argued for student 18, he struggled to connect his vibration theory for the analogies with the target situation because he could not envisage the bodies of the carts vibrating. He justified this lack of vibration on their inability to move in that way due to the hardness (i.e. lack of 'looseness') of their structure, which meant that they were not designed to vibrate, unlike the tuning fork or the rubber ball. This apparently deeply held perception of the surface features of the carts blocked the transfer of his theory to the target scenario, despite the cognitive connection having been obvious to him in the analogies.

Student 17 became less convinced about his primary 'loss theory' during this part of the sequence, as he reduced his belief-rating in it by one point. During analogy one, he had briefly considered the possibility of vibrations causing the sound that was produced in the target scenario, having been reasonably sure that this was the case in the analogy but had ultimately decided, by a small margin, that the collision was the cause. By the end of the second analogy, he no longer mentioned the idea of vibrations, although he had become less sure of his primary theory that the sound was being produced when the carts collided because the plastic molecules were hitting each other. In addition, he was arguing that the sound level was linked to how densely packed the molecules were in each material. He stated that the rubber ball made less sound than the plastic carts because he thought that the rubber was less dense. He did not indicate why he had become less sure of his theory, but it could conceivably have been as a result of the cognitive conflict that he was experiencing as he attempted to integrate his thinking about the significance of the vibrations that he was experiencing in the two analogies.

7.3.2 Non-changes resulting from interaction with analogy two

Twelve students did not change their theory or their belief rating although eight of them were already talking about vibrations. Two of the twelve were students 12 and 45 who did not alter their opinions throughout the sequence.

The collision theory that student 15 had suggested from the beginning of the interview was unchanged as a consequence of studying this analogy. He also reduced his belief-rating in conservation of momentum for the analogical situation by one point to a two. The reason that he gave for this was an honest reflection of his thinking.

I: Why are you not sure?
S15: Because again it can't be proved. We are just assuming this because we are told. In the classroom you are just told.
I: Does it make sense, sort of, to you though? In what way does it make sense?
S15: I don't believe that all the momentum can be moved from one place to the other. There has to be somehow that a little bit is lost, even if it is a tiny amount.
I: Lost to what?
S15: Anything, like energy or the surroundings or whatever.

His belief was based on what he had been told but his stronger lack of trust in that was his innate feeling that momentum could not be completely conserved. Despite being a very able student, he had been unable to argue for the concept of conservation of momentum using the impulse equation and Newton's Third Law.

He had difficulty in detecting any vibrations on the rubber ball in the analogy which meant that he did not have the opportunity to link this idea with the previous analogy or the target. When he was asked to explain why he thought that sound was produced in the target scenario he again simply referred to what he had been taught, and thus showed that he was primarily following what Tiberghien (1994) called 'social rules' in her 'modelling' theory.

S15: Just the same as the hammer. The reason is that it hits and makes a sound. Sound energy is lost. It is the same as that hitting.
I: And why is there sound being made?
S15: The collision. You always ask that but I don't know.
I: I'm trying to see if you can work out a mechanism for sound being made.
S15: We have just been told that because it hits. They don't do it in detail.

This is somewhat surprising given that he was a very able student (grade A) who would have been capable of thinking for himself, but was obviously frustrated by his inability to come up with a better reason for what was happening at this stage, other than the fact that a collision had occurred.

In common with his reasoning about the first analogy, student 55 discussed the idea of vibrations causing the sound in the second analogy. Despite this, he maintained his version of events in the target scenario that the sound was being produced as a consequence of the collision. Part of his difficulty was that he struggled to perceive that more apparently solid objects (like the rubber ball) could vibrate because he felt very little movement when he hit it with the tuning fork (which he readily accepted vibrated in each analogy). Consequently, he was unable to transfer the concept of vibrations to the situation in which the two carts made contact with one another. This resulted in him reverting back to his contact theory for the target scenario.

Eight of the students had previously come to the conclusion that vibrations in the carts were responsible for the dissipation of heat and/or sound from the carts. However several of these students said that they found the second analogy useful as it confirmed their thinking that vibrations were involved. One such example was student 50 who said this about his thinking by the end of the second analogy.

I: And the vibrations being the cause? What are you rating that as?
S50: Five probably, because I can't prove it but I'm pretty sure.
I: Why are you pretty sure?
S50: 'Cause it's the most likely explanation.
I: Has it got anything to do with what you've been doing, or just because that's what you think?
S50: Well what we've been doing here kind of confirms it, as the tuning fork, because the tuning fork when you stopped it the sound, when you stop the movement the sound, you stop the vibration of the tuning fork. That would be like a big version of the molecule in the trolleys vibrating.

In the case of students 12 and 45, they did not make progress as they thought that the second analogy simply backed up what they were already thinking. This meant that they failed to recognise the significance of the vibrations and connect them with the dissipation of sound energy in the analogies or the target scenario. For them, the two ideas of the vibrations and the sound were too cognitively distant to enable them to make a connection between them, and so they failed to make any progress.

7.3.3 Positive conceptual change resulting from interaction with analogy two

Students 14, 23, 27, 32, 36, 49, 54, 60 and 61 all left their 'loss theory' unchanged but had become more convinced of it. The main reason for this increased confidence was that they made connections between the concept of vibrations and analogy two. Students 36 and 49 explicitly stated that the connections that they made between the vibrations in the analogy and their 'loss theory' had increased their confidence. The following extract from student 49 demonstrates this.

S49: The two cars vibrate against one another.
I: When do they vibrate?
S49: During the collision.
I: As a result of the collision do you mean?
S49: Yeah.
I: When they hit?
S49: Yeah.
I: How sure are you of that?
S49: Four.
I: That's gone up, has it? Was it a three before?
S49: I think so.
I: So why, well I'm assuming that you're a bit more convinced that you're right, why?
S49: 'Cause of this thing; I noticed how both things vibrate afterwards. So you'd think when those two cars hit they'd do the same thing.
I: And how convinced are you that you're right on that theory?
S49: Eh, …, four or five.

Students 23 and 27 felt that both of the analogies that they had examined contributed to the increase in their belief-rating because they perceived that both demonstrated the vibration principle.

S27: Because the collision causes vibrations.

I: In one trolley or both trolleys?

S27: Both trolleys.

I: How sure are you of that?

S27: Five or a six.

I: It's gone up. Why?

S27: Because since I felt the rubber ball vibrating and the tuning fork vibrating, I think the collisions cause both objects to vibrate.

I: So, has this analogy made you surer?

S27: Yeah.

I: Why?

S27: Because it is easier to see when there are two objects that you can check afterwards, or feel as you are doing it, if they are vibrating or not.

S23: Due to the vibrations during the collision.

I: How sure are you of that?

S23: Four.

I: Has that gone up a wee bit?

S23: Yeah, I think so.

I: Why has it gone up a wee bit?

S23: Because we found out that during these two collisions, the vibrations make sound.

I: So, that has got you a wee bit more convinced it was maybe vibrations here?

S23 Yeah.

Student 60 increased his belief-rating because he felt that the second analogy bore a greater level of similarity to the target than the first analogy had. This enabled him to gain greater confidence in the connections that he had made already.

S60: Because, …, eh, …, the, …, the vibra-, …, yeah, the vibrations cause a sound.

I: So, there is a vibration going on?

S60: Yeah.

I: How sure are you that you are right?

S60: A four, I think.

I: That's gone up a wee bit, has it?

S60: Yeah.

I: Why?

S60: Because, …, eh, …, in the second analogy, …, there was less of a, …, it was a bit more similar to, …, the trolley collision.

I: How come?

S60: Because of the, …, the shorter sound, …, like the time of the sound, was shorter, the time you can hear the sound for was shorter.

I: So, that convinces you that, there is something more similar going on there does it?

S60: Yeah.

Students 11 and 24 developed their 'loss theories' as a result of thinking about analogy two, while two students 16 and 59 developed their theories and also increased their belief-ratings in them.

Student 11 added the loss of heat energy to his existing theory that sound would be lost as a consequence of vibrations in the carts. He had spontaneously added the idea of heat being produced in the analogy, possibly because he had described the movement of molecules, which may have triggered the idea of heat being produced by association with what he had been taught, although there was no direct evidence for this in his statements. He went on to describe molecules colliding and therefore sending vibrations through both carts in the target scenario.

I: And how would you explain that being produced? The heat and the sound being produced from what you've just been doing.

S11: The impact of the molecules will just have a chain reaction so it can't be destroyed.

I: So, what kind of chain reaction are you talking about?

S11: The molecules will hit and keep sending vibrations across.

I: How sure are you that that is true in the trolley situation at the moment?

S11: Four.

This idea shows that he had developed his initial idea of the collision being responsible for the loss of kinetic energy by adding new features from the analogies, such that his 'loss theory' became increasingly detailed and articulate.

Student 24 made some progress as he started to consider for the first time that vibrations in both of the carts were the cause of the kinetic energy being converted to sound. This was triggered by his consideration of the analogy as he tried to decide whether he thought that this was caused by the contact between the ball and the tuning fork or the resultant vibrations. He then engaged in a twin-tracking thought process as he wrestled to decide between these two explanatory options in relation to the target.

I: Tell me what your thinking is at the moment with this collision here then.

S24: With the sound?

I: Yeah.

S24: The contact. When they touch they make a sound. It is moving.

I: So the sound is being caused here by what?

S24: It can't be caused by the contact because they are touching [demonstrates ball and tuning fork touching] and no sound.

I: So what do you think?

S24: Movement, contact, sound. Because of the movement there is sound.

I: But if there is movement there, there is no sound. [Demonstrates moving tuning fork through the air].

S24: If it is moving prior to the contact then, …

I: So what is it that is happening during the contact that is causing the sound? Do you see a link between what happened there [hammer and tuning fork] and what happened here [tuning fork and rubber ball] or what happened here [target scenario]?

S24: Kind of.

I: What do you think the link is?

S24: The vibrations.

I: Tell me more.

S24: I don't see where you are getting vibrations from.

I: In this?

S24: Yeah. But I suppose you just count that as one big vibration but I don't know.

I: Do you think the actual trolleys are or aren't vibrating?

S24: Maybe very slightly because of the way they're running along the track.

I: Do you think there is a vibration in the trolleys caused by the collision?

S24: Yeah.

I: How convinced do you think you are of that idea?
S24: Three.

Although he found the concept of vibrations difficult as he could not see the trolleys vibrating, he did make eventual progress which was coded as being triggered by a mixture three things. His experience of the analogies was clearly involved; he engaged in faulty logic recognition about contact and movement being the only possible causes of the sound (which was partly guided by the interviewer); and he made a clear connection, in terms of vibrations, between the different analogies, the target scenario and his existing mental model. This demonstrates that conceptual change is often initiated by several key factors. In common with several of the other conceptual change examples discussed above, his conceptual change was coded as being an example of several types: Ausubel's 'meaningful learning'; diSessa's concept of 'complex system building'; Brown and Clement's 'explanatory model construction'; Tiberghien's 'modelling theory' (at the level of specific objects and events only); Vosniadou's theory restructuring explanation (at the level of objects & properties only); and 'making connections' between his new thinking and the analogy, as well as his existing mental model.

The idea that sound and vibrations were linked had only been mentioned by student 16 in relation to the first analogy but not the target. By the end of the second analogy he had added the vibrations concept into his 'loss theory' for the target scenario and his confidence rating in the idea had risen by one point to level two. Like student 24, he struggled to decide whether he thought that the sound was caused just by the collision or by any resulting vibrations. The eventual changes in his thinking were triggered by faulty logic recognition, his attempts to resolve his cognitive conflict and making connections between the analogies and prior learning. This process was initiated when he was asked to state any similarities or differences that he thought there were between the second analogy, the first analogy and the target scenario.

S16: There is, …, all the collisions are giving off sound so in all of them kinetic energy must be getting lost due to the fact that the only energy before is kinetic energy and if there is sound being given off there has got to be some of that kinetic energy used up.

I: So, you think that is the same for all three situations?

S16: Yeah.

I: What about the reason why? Is the reason why the same in all three situations or do you think the reasons are different?

S16: I don’t know why the reasons.

I: But do you think they are the same or different?

S16: I would imagine they were the same.

I: And what do you think, if we went back to the first one, what did you think the reason was there? Hammer and tuning fork.

S16: The tuning fork is vibrating though.

I: Is that what is making the sound?

S16: No, the collision is making the sound. No, in fact not in the tuning fork. After the collision, the tuning fork vibrating will make the noise whereas in the car it will be the collision that will make the noise.

The above extract demonstrates that as he thought through what happened to the tuning fork in the analogy, he self-corrected his faulty thinking. Likewise, it is clear that he had not initially connected the vibrations with the carts, but he then recognised that this reasoning was also possibly faulty, which led to some progress as shown below.

I: Why the difference?

S16: Because the car won’t be vibrating. I’m not sure in fact.

I: Why are you not sure? What are you not sure about?

S16: I’m not sure about why the sound is given off in the hammer to the tuning fork compared to the car to the [other] car.

I: But you think they are different? Or do you think they might be the same?

S16: I’m not sure. I think they might be the same.

I: OK. Give me a rating for that. You are obviously comparing things. What are you doing in your head?

S16: I’m comparing. I’m wondering if the reason the sound is given off from the tuning fork, from the hammer to the tuning fork, is the same. I’m wondering if it is the same reason when sound is given off from the car to the [other] car.

I: So why are you saying there is sound being produced here?

S16: Why? Because of the vibrations that are given off by the tuning fork.

I: And why do you think it is happening here?

S16: Because of the collision that takes place.

I: So what bit are you not sure about in terms of the similarity?

S16: In theory, I would think it would be the same reason why the sound is given off.

I: So, what are you struggling about with this one?

S16: I'm just not sure generally why sound is given off.

I: But here you are saying you think it is to do with the vibrations of the tuning fork but you are not sure if it is the same reason here?

S16: I think it is to do with the collision where there is energy lost so it is given off in sound. I don't think that is a reason, I think it is an explanation.

This last statement suggests that he realised at this point that his loss theory was lacking some necessary extra detail, which required a resolution as it was causing him some consternation. His earlier statement about "comparing" clearly shows that he was trying to resolve his difficulties by making connections. He continued in these attempts as he sought to think through the missing details in his 'loss theory'.

I: So what do you think is going on here that is causing sound to be given off?

S16: A loss in energy.

I: Caused by?

S16: The loss of energy from this one overall because the sound is given off.

I: Are you struggling to take on board that there is any vibration here? Is that what it is?

S16: Yes.

I: So you are not sure if there are vibrations there or not?

S16: I don't think that is what is making that.

I: The sound in this case? But you think it is here?

S16: Yeah, but there might be smaller vibrations there that I'm not noticing.

I: How likely do you think that is?

S16: I don't think it is likely.

I: Give me a rating.

S16: One or two.

Although he was evidently still struggling to accept that there might have been vibrations in the carts, he was becoming slightly more convinced of the possibility.

This gradual change process was occurring because he had decided that it was the cause in both of the analogies and so he was beginning to make connections between the different situations in his mental schema. His conceptual change therefore displayed features of several of the theoretical stances discussed above in relation to other students. Making connections between different situations was clearly a strong influence in student 16's thinking in relation to the conservation of momentum as well. Prior to the above discussions about kinetic energy, he had made the following statements to back up his clear belief (at level "four or five") that momentum was being conserved in the second analogy.

S16: Because in the cars, if the momentum equals the same in that, then surely it must equal the same in other circumstances not with trolleys.

I: Now you have said something interesting, 'it must'. Why must it?

S16: Just because the objects are different, it doesn't necessarily mean that the units will be different, like just because the two objects are different it will be the exact same idea.

It can be seen from this that the cognitive connections between different situations and pieces of knowledge was instrumental in both triggering conceptual change as well as justifying the intelligibility of his thinking.

In a similar manner, student 59 added for the first time in the target situation, the idea that vibrations were causing sound energy to be dissipated. This detail was added to his original theory which had only included the idea that the sound was caused by the collision. His belief-rating for his newly expanded theory rose by two points. When asked why this was the case, he gave the following answer.

I: So, this theory that you have got then, about them colliding and sound given off, because there are particles vibrating, how convinced are you that that theory that you have got is right?

S59: About a 5.

I: Fairly sure?

S59: Yeah.

I: Why are you so sure?

S59: Just because, it seems to, …, it just seems right.

I: Why, because you didn't mention it before?

S59: Because it kind of makes sense with the tuning fork, when it's vibrating the air particles, it is creating a sound so, so if they hit each other, then, …, that movement of that compacting of air particles would make a sound.

As with previous examples, his increasing level of intelligibility and belief in his theory was triggered and exemplified by the connections that he was making between the different situations that he was considering.

7.4 Analogy three

The rubber ball that was used in the previous analogy was re-utilised in this scenario. This set-up had more visual links with the target scenario as it involved one object rolling horizontally into another. The water filled balloon clearly shook when the rubber ball collided with it. This was chosen in order to re-emphasise the idea that vibrations were occurring as a consequence of the collision, using one of the objects from the previous situation.

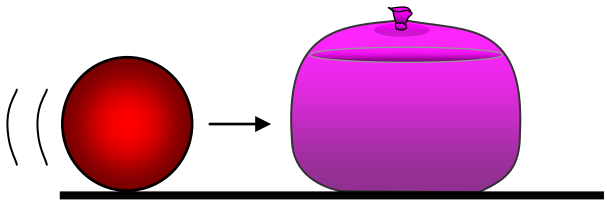


Figure 7.5: Analogy 3 - Rubber ball and water filled balloon

The majority of students (twenty one out of thirty) maintained their previous 'loss theory' by the end of this analogy. Students 12, 17 and 45 continued, as before, to think that the sound was produced purely as a consequence of the collision between the two carts, while a total of eighteen students continued in their prior belief that some of the kinetic energy was converted to sound energy (and in some cases, heat energy) as a consequence of vibrations in the body of each of the carts. Student 13 experienced negative conceptual change in that he no longer mentioned his previous idea about the vibrations being the cause of the released sound energy in the target scenario. Negative conceptual change was also exhibited by student 59 who had changed his mind about conservation of momentum in the target situation despite being reasonably sure that it was conserved in the analogy. Seven students experienced positive conceptual change as their 'loss theories' became more detailed (and in the case of students 9 and 32, more plausible to them).

Some students voiced concerns in this analogy that the water filled balloon did not roll away when the ball struck it. They could clearly see that it wobbled, but it worried some that it did not move off. Although this did not cause widespread conceptual difficulties, it caused three of the students who were in the group who had not changed their ‘loss theories’ to have doubts about conservation of momentum in the analogical situation. One of the three decided that momentum was being lost in the analogy, while the other two were unsure about the conservation of momentum in the analogy, but decided in the end that they thought that it was conserved. Despite these concerns, all three students maintained their view that momentum was conserved in the target scenario. Student 24 (who reverted back to a previous loss theory’ during this analogy) was also not convinced that momentum was conserved in the analogy although he could not give a reason for this. When he was asked to explain his thinking about the target scenario, he decided that momentum was not being conserved there either. The reason for this was not directly associated with his problem in the analogy. Instead, he was unable to see how the total momentum afterwards could be the same as the total before, based on the idea that there were two objects moving slowly after the collision but only one was moving beforehand.

Figure 7.6 below, summarises the number of students who were stating each of the identified theories at the end of analogy two (figure 7.6a) and by the end of the third analogy (figure 7.6b). As before, figure 7.6a contains the same information as figure 7.4b. It is shown again here to enable the change in overall numbers of students who held each theoretical stance to be seen easily.

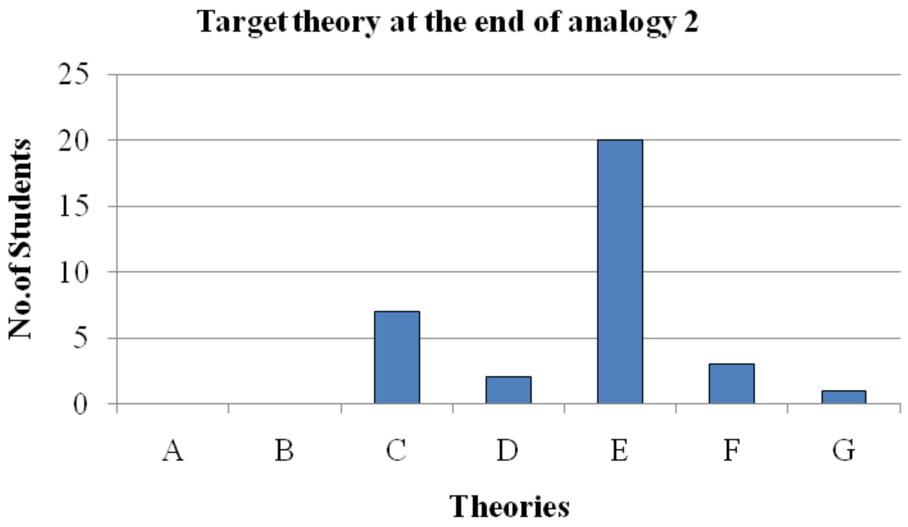


Figure 7.6a: Number of students stating each kinetic energy loss theory at the end of analogy two.

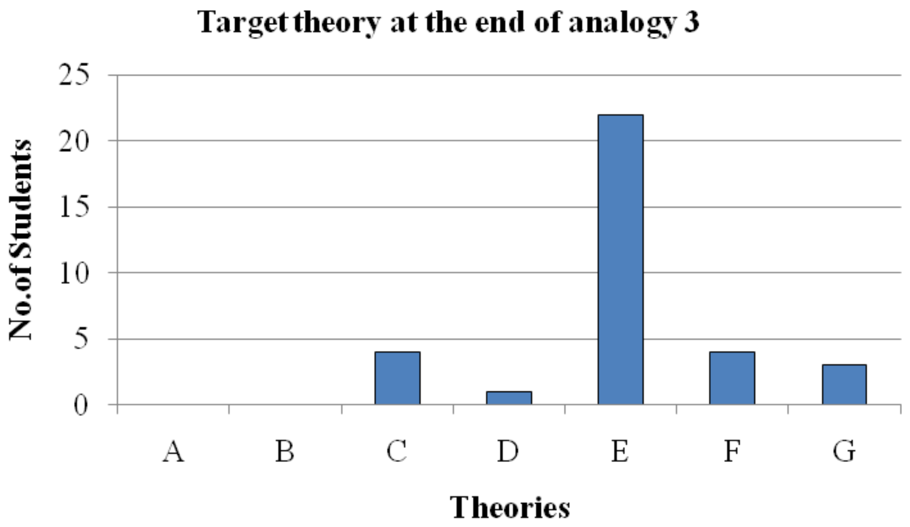


Figure 7.6b: Number of students stating each kinetic energy loss theory at the end of analogy three.

7.4.1 Negative conceptual change resulting from interaction with analogy three

Student 59 went off the idea that momentum was conserved in the target scenario at the end of the third analogy. The reason for this was that he rekindled his view that momentum and the kinetic energy were very similar to one another. It also became apparent that his difficulty was caused by him having a very ‘velocity-centric’ view of momentum as shown by the extract from the discussion below.

I: So what is going on in terms of momentum in that collision of the trolleys? What’s your current story about that?

S59: This seems like it’s, …, the, …, slightly lost and not the same.

I: Why?

S59: Just due to the fact that, …, overall there would be a slight loss of, …, energy which would relate to velocity being lost, so it would never, if this energy is being lost in the collision it would never mean that it would be the same as the start and afterwards.

I: So the fact that it’s losing energy, means that it’s losing momentum as well, is that what you’re saying?

S59: Yes.

I: So, how does that link back to the previous thing about the forces being equal and stuff though?

S59: Eh, …, not very much.

I: So a bit confused about that?

S59: Yeah.

Despite the attempt to get him to return to his previous reasoning about Newton’s Third Law and impulse, he could not see that link and admitted that he was confused at this point, although he switched his answer back to conservation by the end of the next analogy. His difficulty at this point did not appear to have been caused by the analogy, but was primarily triggered by an over-emphasis on one aspect of the system which resulted in him experiencing transient cognitive conflict.

By the end of the third analogy, student 13 had changed his ‘loss theory’ back to a version that did not overtly include the concept of vibrations in the carts. The vibrations in the balloon did not figure in his thinking. Instead, while thinking about the analogy, he returned to considering the forces acting on the rubber ball and the balloon as being the best explanation for the production of the sound.

I: Now, why is there heat and sound being produced? What’s going on that’s causing that heat and sound to be produced?

S13: Energy is being transferred from one to the other.

I: But you can’t think of a mechanism?

S13: No.

I: Now, compare that with the one before where we had the tuning fork hitting the ball. How do they compare? Similarities or differences?

S13: The tuning fork and the ball, this has movement, like noticeable movement in both things before and after but there is nothing to stop the balloon moving at all, so it moves a bit before it goes back to its original shape.

I: In terms of the sound and heat being produced, do you think there is a link as to why that is being produced?

S13: Because I think if the force of the thing that is being hit with something is greater than the thing that is hitting it, then heat and sound will be produced.

I: So, if the force is bigger than what?

S13: If the force of the balloon is bigger than the force of the ball then the total energy cannot be conserved.

I: How sure are you of that idea?

S13: I'm pretty sure of that one. Four or five.

I: Any particular physics reason for that idea that you can think of?

S13: It seems to make sense.

It was clear from this exchange that he was not thinking in terms of Newton's Third Law as he seemed to be saying that the force exerted by the two objects in the collision on each other could be different. He then transferred this incorrect idea to the target scenario. This was his final 'loss theory' as time restrictions meant that he was unable to examine the final analogy. This final version had been his original theory, prior to working with the analogies. He had appeared to be making progress during the previous two sections of the interview, but in the end his original conceptual model appeared to overwhelm his new thoughts. This switch back was triggered when he was unable to think of a mechanism for the heat and sound loss that he was convinced was occurring in the third analogy. He therefore reverted back to his original explanation which had not been superseded, despite the appearance that it had. This example re-emphasises the fact that producing real conceptual change is often difficult due to the strong influence of pre-existing, inaccurate or incomplete conceptual models with all the strong internal links that 'prove' that they are correct in the mind of a learner. The connections that he had started to make with the new theory were evidently not robust enough and so they did not have the cognitive ‘strength’, and therefore lacked a sufficient level of plausibility to sever and replace the existing links.

7.4.2 Non-changes resulting from interaction with analogy three

As mentioned above, most of the non-changes were for students who were settled in their belief that kinetic energy was lost in the target scenario because vibrations in the body of the carts resulted in the conversion of some of the incoming cart’s kinetic energy into sound and/or heat energy. These students were coded as having shown examples of ‘derivative learning’ described by Ausubel (2000), whereby the analogy supported and exemplified their existing ideas, as opposed to changing them.

Students 12 and 45 continued to perceive the conversion of kinetic energy into sound energy as being a consequence of contact between the different objects. For them, the presence of vibrations in the third analogy was not a compelling enough reason for them to include the idea in their ‘loss theory’. They were not able to connect the knowledge of the vibrations with their knowledge of the sound production because the two ideas were still too ‘cognitively distant’ from one another in their minds, despite the repetition in each analogous scenario. Both students only noticed what were coded as being ‘surface’ level similarities between the analogies and the target. They saw that the analogies were similar to the target because they all involved two objects coming into contact with one another, but they were unable to perceive the ‘deeper’, theoretical similarities regarding the significance of the vibrations. This lack of connectivity resulted in their inability to experience conceptual change.

Student 17 had similar difficulties as he was unable to appreciate the link between the vibrations and the sound in all of the different analogies and consequently relate that to the target scenario. As discussed previously, he had appeared to make the connection during the first analogy but the connection was short lived. When he was directly asked if he thought that the vibrations were linked to the sound that was being produced in the third analogy, his answer was an unequivocal “No”. He had abandoned the earlier connection that had appeared to be forming as the interconnection between the two things was not robust enough in his mind to convince him that it was true. He was also content to base his reasoning on the surface similarities between the different situations. For him, the deeper similarities were also not clear enough or plausible enough for him to experience conceptual change.

Student 24 demonstrated continued 'twin-tracking' in his theory. He had made progress in the previous analogy by adding the idea that vibrations might be responsible for the production of sound to existing theory that the movement leading to the collision was responsible. When he was asked why sound was being released in the third analogy, he initially reverted back to his first theory as he struggled to see similarities between this analogy and the previous one.

I: Why does it create sound?

S24: Because of the movement before the contact that I was explaining before.

I: So, because the ball is moving before it hits that, is that why there is sound?

S24: Yeah.

I: So, how does that compare with the one before where it was the tuning fork and the ball or the hammer and the tuning fork?

S24: Actually then, it doesn't really, …

I: Do you think there is a link there?

S24: I think it is just in general, movement, contact, …

I: So, movement contact means there is sound?

S24: I think so.

I: Do you think there is any link to the vibration that was going on?

S24: Yes.

I: But you are not sure about it?

S24: I think it has got something to do with the air or something like that as well, it makes a sound as well.

I: And what is happening…

S24: The vibration does something to the air and causes it to make a sound.

Although he included the idea about vibrations, it was evident that his dominant theory was the one in which the contact was the primary cause of the sound.

However, when he was asked about the target scenario, his 'loss theory' became an equal hybrid of both, although his instinctive reaction was to mention the contact theory first.

I: Why is sound being created?

S24: Because of the contact between, …

I: And what does that cause?

S24: Movement from the car moving to get into contact with the other car, it causes sound energy.

I: And why is sound energy being produced?

S24: Vibrations from the collision in the air making sound.

When he was asked to state which of the two ideas he was more content with as an explanation, he said that both were equally valid in his thinking.

I: What about your story about contact and some kind of vibrations going on?

S24: Four.

I: Are you more sure of the contact bit or the vibration bit?

S24: Three for each.

I: So they are about even?

S24: Yeah.

This suggests that his prior theory was still strongly influencing his thinking. The connection that he had made between the sound and the vibrations was not strong enough to completely replace his pre-existing mental model.

7.4.3 Positive conceptual change resulting from interaction with analogy three

Seven students experienced positive conceptual change during this section of the interview. Students 9 and 32 added the idea that heat was being produced as a result of vibrations to their existing theory about the link between sound and vibrations. In addition, their belief ratings in their theory about the target scenario increased slightly. Student 32 added the idea of heat to her story because she noticed that the balloon in the analogy rubbed against the table as it moved. She therefore reasoned that there would be friction which would result in heat being produced.

I: And why is it being lost or how is it being lost first?

S32: To sound and heat and friction.

I: And why is that happening?

S32: Because the table has friction, when you hit the balloon it makes a sound so it will vibrate, so that will have some.

This shows that her experience of the third analogy had a direct influence on her thinking. Her new thinking was then transferred to the target scenario. She demonstrated this when she gave a clear and concise explanation when she was asked to explain why she thought sound and heat were being released in the target situation.

I: Why is the sound and the heat being produced?

S32: Because it is hitting off each other and making vibrations.

I: Does that explain the heat?

S32: Well kind of, because if you hit off something it can get warmer.

I: Do the vibrations explain the heat at all?

S32: Yeah, because if they keep on moving they are producing heat.

I: How convinced are you that in this collision we are losing kinetic energy?

S32: Six.

I: In terms of your story about the vibrations explaining that, whether it be sound or heat, how convinced are you of that?

S32: Five.

I: So that has gone up a bit. Why has it gone up?

S32: Because it makes more sense.

I: Why does it now make more sense?

S32: Because I can see it.

I: Can you see the vibrations now?

S32: No, but I can see how it can be done.

Her last comments in this extract clearly show that she had experienced conceptual change as a result of connecting what she could literally see in the analogies with what she thought she could 'see' happening in her mind's eye regarding the target. Her conceptual change was triggered by three factors: the visual clues that she had seen; making connections between the analogy and the target; and the experience of working with the analogy. Her conceptual change, in relation to the addition of the transition of energy to heat, met the criteria for being classed as an example of the types discussed in relation to previous examples: Ausubel's 'meaningful learning'; diSessa's concept of 'complex system building'; Brown and Clement's 'explanatory model construction'; Tiberghien's 'modelling theory' (at the level of specific objects and events only); Vosniadou's theory restructuring explanation (at the level of objects and properties only); and 'making connections' between her new thinking and the analogy, her existing mental model and her previous learning in Physics. In addition to adding a new feature to his 'loss theory, student 9 had become more convinced that momentum was conserved in this analogy than he had been in the second one. He gave a similar reason to student 32 for this when he said that he could 'see' it better in this case, and he was able to back up his assertion with a logical and coherent argument for conservation. His reason for adding heat to his previous answer was very similar to that given by student 32.

S9: You are losing some to sound and heat when the ball connects.

I: So where is the heat coming from? You didn't mention heat before, heat is new. What do you think is causing the heat?

S9: Friction between the balloon and the surface it is on because it would move if there wasn't any friction.

When he was asked to explain any similarities or differences between this analogy and the target, he identified several key features which demonstrated that he had transferred theoretical ideas from one situation to the other.

S9: Energy is kept in the ball. The ball bounces off the water balloon, bounces back. Some is transferred to the water balloon. It moves slightly but there is some lost to friction and heat caused by friction and sound.

I: Is that similar [to the target scenario] in any way?

S9: There is not as much friction in the trolley as there was in the balloon.

I: Are you still saying there is energy lost in that collision with the trolleys?

S9: Yeah.

I: Because of what?

S9: Sound.

I: And why is there sound being produced?

S9: Because of the vibrations when the two make contact.

I: And how sure are you of that idea?

S9: Still five.

I: Has this helped to think of that in any way?

S9: Yeah, it’s the same kind of thing. I think it is because this has, it is on a greater surface, whereas the wheels are thin.

I: So, that is why there is more friction here?

S9: Yeah.

He was able to identify the key difference between the analogy and the target in terms of the different surface areas in contact with the ground which he used to explain the differing amounts of heat that would be produced through friction in each. This explanation showed that he had made a connection in the way in which he thought heat would be produced in both cases. Although he did not directly associate the production of heat with the vibrations at this point, he went on to say that he had become more convinced of his vibration idea because he could see the balloon vibrating. This demonstrates again that the triggers for conceptual change were visual clues, making connections and the experience of the analogy.

Student 15 changed his theory for the first time in the sequence as a result of studying the third analogy. Having previously stated that the sound was merely a consequence of the collision, he changed to stating that sound was caused by vibrations in the carts. This change was directly triggered by his consideration of the previous analogies along with the third one after being asked if he thought that the sound was linked to the vibrations. This resulted in him connecting the key idea of the vibrations from all three situations which he had previously not noticed. (He was the student who had been frustrated about not being able to recognise any connections during the previous analogies, as discussed above). He then proceeded to connect this idea with what he thought happened in the target scenario.

S15: Yeah, it will lose some through sound.

I: Why is it losing sound?

S15: Because it is colliding. Are you going to take me back to these two?

I: Yes. Go on.

S15: The collision makes the noise. I don’t know how to explain it further than that.

I: Was there any link between the vibration and the sound do you think?

S15: For?

I: Any of the collisions.

S15: Sound energy?

I: Yes, that is being produced.

S15: Vibration must take up some energy to do so.

I: And what is the vibration doing? Is it making the sound or is the vibration a different issue?

S15: Because of the tuning fork it makes me think it was making the sound.

I: So, do you think there is anything going on here that is similar?

S15: The hitting of the two might cause a wee vibration to make the sound.

I: In the trolleys? What makes you think that might be true?

S15: Because the tuning fork.

He had clearly changed his thinking as a result of these newly realised connections. Making these connections was both the trigger and the evidence that conceptual change had happened for student 15.

Although he did not introduce something new to his ‘loss theory’, student 61 experienced conceptual change with this analogy as it resulted in him returning to his original theory about sound being caused by vibrations in the carts, having regressed to merely stating that it was caused by contact at the end of the previous two analogies. His experience of seeing the balloon vibrate when the rubber ball collided with it brought about this change in his thinking. He made this obvious when he was asked to explain where the idea about the vibrations had come from.

S61: That’s just how sound is produced, particles, …, move, or just particles vibrating.

I: So, what particles do you think are vibrating?

S61: Ones that are, …, on the surface of the two objects.

I: And you are saying that produces sound?

S61: I'm saying that it causes it, …., yeah.

I: So how sure are you that that is correct?

S61: A four.

I: Fairly sure?

S61: Yeah.

His initial statement suggests that the link with vibrations was a core idea that he had about sound anyway, but it is notable that he had not mentioned this during the first two analogies. A sceptical view of this would be that this analogy had merely reminded him of this idea. However, when he was subsequently asked to say what he thought was happening in the target scenario he confirmed that conceptual change had taken place in his 'loss theory' because he linked the 'deep' similarities for the first time with the target since he started the analogy sequence, and was fairly convinced that he was correct.

S61: There is less kinetic energy after the collision.
I: And why is there less kinetic energy after the collision?
S61: Because of the sound created.
I: And so, what is your current story about how the sound is created?
S61: The kinetic energy causes the particles to vibrate.
I: In the trolleys?
S61: Eh, yeah, but then they cause, …, particles in the air to vibrate.

Student 18 connected the sound with vibrations in this analogy, having not mentioned it at the end of analogy two. This occurred when he was asked whether or not he felt that kinetic energy was being lost in the collision between the rubber ball and the balloon.

S18: Yes, there is energy being lost.
I: As what?
S18: As the vibration in the balloon because of the liquid inside, not all energy is transferred into movement of the ball moving forward, the liquid has vibrations inside and the vibrations uses some and the energy is passed on from the ball.
I: What is that energy being given out as if it is being lost?
S18: Vibration. Kinetic again, but then it is not the kinetic that would move the ball or the balloon forward.
I: Is there any other kind of energy being given off?
S18: I would think sound maybe.

Having made this link, he immediately reverted back once again to his contact theory when he was asked to compare the analogy to the target situation. This shows that he was struggling to assimilate this vibration idea into his thinking.

I: In terms of this analogy and here [the target scenario], what similarities and differences would you be drawing?

S18: Differences, this moved back and not all energy was passed on. Similarities, energy was lost through sound.

I: And why is sound being produced here do you think?

S18: Because of the contact.

I: How sure are you of that?

S18: Six.

It is evident from this that he was most convinced by the contact argument in relation to the target. He had however changed his thinking about the link between the sound and the vibration in the analogy and so some progress had been made. As time restrictions meant that there was insufficient time for him to go through the final analogy, he was asked the extension question about the magnet to magnet version of the collision immediately after this point. His answer showed that he had in fact integrated the vibration idea into his final 'loss theory' despite it not appearing in his answer about the target scenario at this point. His final version was a hybrid of all of his previous versions, as will be seen below in the analysis of his answers to the extension question.

Students 55 and 56 both mentioned the idea of vibrations in relation to the target for the first time, having previously only mentioned it as being true in the analogies prior to this. Student 55 said that she "just thought of it" when she was asked where her idea of the vibrations had come from. This suggests that the analogy caused her to generate the idea having seen the balloon obviously vibrating. She was then able to relate this to the target situation, which resulted in her 'loss theory being altered.

S55: The Velcro and I think the magnet, …, eh, …, the Velcro and the, …, the particles would move when hitting the magnet so, ...

I: So, what particles are you talking about here?

S55: … The magnet and the, eh, the Velcro so, …, so like, when they vibrate against each other then, ...

I: So, when you are saying when the Velcro and the magnet come together, or are you saying when the trolleys come together, are you talking about the Velcro and the magnet or the trolleys?

S55: Well both, …, when the trolleys, …, hit each other, the plastic will vibrate against each other so, that causes, ...

I: That causes the sound, is that what you are saying?

S55: Yeah.

I: How sure are you that you are right?

S55: A three.

Student 56 had overtly rejected the idea that the sound was caused by vibrations at the end of the second analogy but changed his mind as a result of this analogy. He first linked the production of sound with the vibrations in the water-filled balloon. He then went on to link them to the loss of sound energy in the target scenario.

I: Why is it not conserved?

S56: The kinetic energy?

I: Yeah.

S56: Because it’s given off as sound energy, because it’s given of as another form and that needs to come from somewhere.

I: Ok, so why is it given off sound energy?

S56: Because the collision causes it to, you know, the vibration in the collision causes sound energy.

I: So, are you saying that there are vibrations here, with the trolleys?

S56: Yeah, there would be vibrations in there between the surfaces.

When he was quizzed about why he was now linking them, the following discussion took place.

I: Now a minute ago you said you didn’t think there were vibrations?

S56: Well, I've changed my mind.

I: Why?

S56: Because the other examples changed my thinking.

I: Why?

S56: Because it happens in every other example, that vibrations cause the sound so it must be vibration.

I: How sure are you that that’s true?

S56: Four.

The cumulative effect of the similarities in all three analogies had clearly influenced his thinking by this point such that conceptual change occurred when he successfully made the connection between all of the situations.

7.5 Analogy four

This analogy was the most similar to the target scenario which is why it was used as the final part of the sequence. It was included to encourage the students to think through what they thought happened when two solid objects collided with one another. Having considered the idea that vibrations had occurred in each of the previous analogies, the students were challenged by this analogy to consider whether or not they thought that a similar process was occurring when they could not see or feel any vibrations. Since sound (and a little heat) was produced as a result of the vibrations set up because of the contact between the two ball-bearings, this collision can be considered as being slightly inelastic because not all of the kinetic energy is conserved.

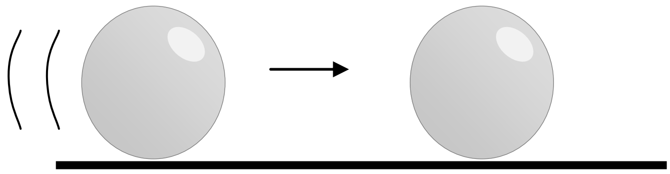


Figure 7.7: Analogy 4 – Ball-bearings colliding (slightly) inelastically

A total of eighteen students worked through this analogy. The other twelve students had insufficient time to do this example as a consequence of the time slot that they had volunteered for and their interview taking up most of the available time. Of these twelve students, seven of them were students whose ‘loss theories’ were very stable as they had not altered during analogies two or three, as discussed above. These twelve students jumped straight to the sequence review and the extension question at the end of analogy three.

The vast majority of the students who did this analogy found that it confirmed their prior thinking rather than changing it. Out of the eighteen students who did examine the fourth analogy, sixteen of them left their ‘loss theory’ unchanged. Thirteen of this group had already concluded that internal vibrations were causing the production of sound energy in the carts, while three had already decided that both sound and heat were being produced as a consequence of internal vibrations in the carts. There were however some changes in the belief-ratings about the ‘loss theory’ for six of these students. Four of them increased their belief-ratings, while two of them reduced their rating slightly. Two students experienced negative conceptual change during this analogy as they changed their ‘loss theories’ by reducing the level of information that they gave at the end of this section of the interview.

Figure 7.8 on the next page, summarises the number of students who were stating each of the identified theories at the end of analogy three (figure 7.8a) and by the end of the fourth analogy (figure 7.8b). Since twelve students did not do the fourth analogy, the answers given by them by the end of analogy three are not included in the figures for analogy four. This reduction in overall numbers accounts for the apparent decrease in the number of students stating of the several theories.

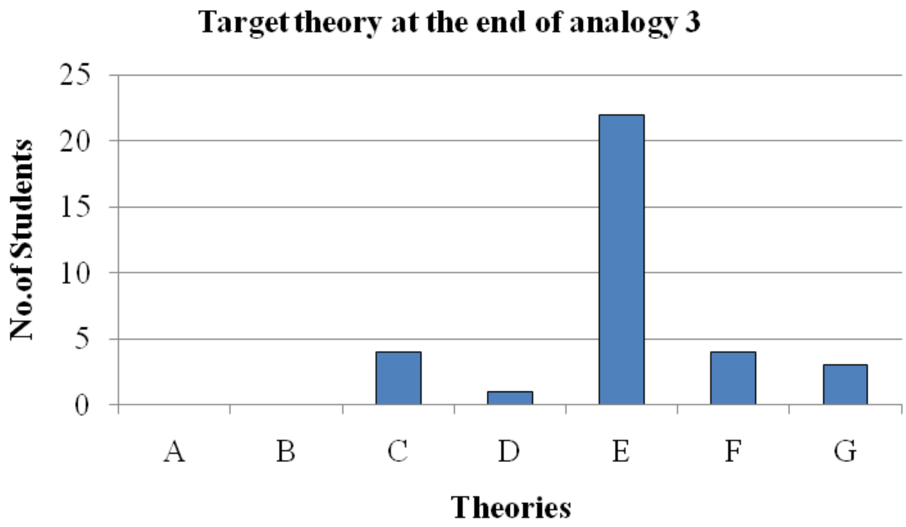


Figure 7.8a: Number of students stating each kinetic energy loss theory at the end of analogy three.

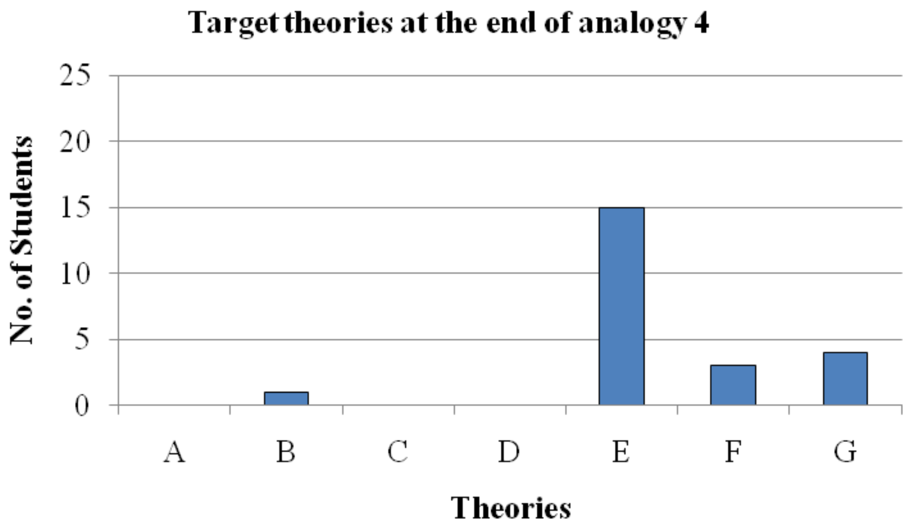


Figure 7.8b: Number of students stating each kinetic energy loss theory at the end of analogy four.

7.5.1 Negative conceptual change resulting from interaction with analogy four

Students 14 and 61 both decreased their belief-rating in the 'loss theory' that they had developed by one point at the end of the fourth analogy. Despite this apparent reduction, both students were able to give clear and concise versions of their 'loss theory' and so the reductions could be a result of them not remembering their previous values. Neither student gave the impression that they were less convinced. In fact, if anything, student 14 appeared to be more convinced, as this extract demonstrates.

S14: The kinetic energy before the collision is not equal to the kinetic energy after the collision because some kinetic energy is transferred into sound energy because of the vibrations caused between the two cars in the collision.

I: And how sure are you of this vibration, despite the fact that you can't see it?

S14: Four.

I: Why are you so sure?

S14: Just because I can't think of any other reason. We've been discussing it for a while and I seem to be picking up the vibes that that is the correct answer.

In reply to his impression that he was 'picking up vibes' that he was correct, the interviewer re-emphasised that he may, or may not, be correct. This reminder did not cause student 14 to alter his belief-rating which suggests that it was primarily based on the fact that this represented the most plausible theory for him.

Students 9 and 45 reduced the complexity of their respective loss theories by the end of this analogy. Student 9 only dropped the reference to heat being produced in the collision but maintained his theory about the vibrations causing the sound energy to be produced. It is not clear whether or not this was a result of him going off the idea or simply a case of him forgetting to mention the production of heat in the analogy and then the target. In either case, his loss theory was almost the same apart from this slight alteration. Student 45 changed from stating that some of the kinetic energy was converted into sound energy as a consequence of the collision, to stating that he was unsure whether or not the kinetic energy was being lost. The reason for his confusion was that he started to think about potential energy in the initially stationary cart being converted into sound energy. Throughout the rest of the sequence he had been consistently stating that some of the kinetic energy was converted into sound as a result of the collision. This change of thinking did not appear to have been brought about by any of the features of the fourth analogy, and so it was coded as being spontaneously produced. It shows that he had failed to really understand what was going on in the target scenario throughout the interview, partly because he did not comprehend the basics of the different types of energy that were involved. His lack of progress was also linked to his inability to connect the repeating features of each analogy with one another or with the target scenario.

7.5.2 Positive conceptual change resulting from interaction with analogy four

Three students increased their 'loss theory' belief-ratings by one point, while student 49 increased his rating marginally from a five to a "five or six". Students 49 and 56 did not give a reason for their increased belief rating or acknowledge that it had increased. As with the students whose rating decreased, it could be suggested that the increase was not significant and could have been because they could not remember the previous value that they gave. In contrast, students 55 and 60 did acknowledge the increase in their ratings and gave the following reasons for doing so.

I: So, how sure are you that you have the right answer there?
S55: A four.
I: Fairly sure, are you more sure now than you were before?
S55: Yeah.
I: Why?
S55: Taking all the other ideas, …, eh, …
I: Analogies?
S55: Yeah.
I: Why have they helped?
S55: Eh, …, just like the different materials against the other ones, a the hammer and the tuning fork.
I: But the fact they are all different, how does that not put you off, how come you're saying that has made you think more strongly, this answer, how come; they are not all the same materials?
S55: Yeah …
I: So how come?
S55: The different, …, the different materials present different sounds and, …, if there is more, if there are solid objects they produce a harder sound.

Her answer strongly suggests that her experience with the successive analogies had encouraged her to think along similar lines. It is notable, as discussed above, that her 'loss theory' had evolved from what she had been seeing in the analogies and that her theory regarding the target scenario had been less advanced than her theory about the analogies prior to the third analogy. Up until that point in the sequence she had recognised the vibrations in the analogous situations, but had not transferred that theoretical concept to the target, preferring instead to suggest that the sound was merely caused by the collision between the carts. This evidence of conceptual change was therefore consistent with the reasoning that she gave for this final increase in belief-rating.

Student 60 also indicated that he had increased his belief-rating as a direct consequence of the cumulative effect of the analogies.

I: How sure are you that what you have come up with is correct?

S60: Probably maybe about a 5

I: Now, I think that has gone up a wee bit. Why has that increased?

S60: Because the analogies, seem to all have the same conclusion in that, …, when there was a collision, there was eh, …, a vibration causing a sound.

It was obvious from his statements that he had become more convinced as he perceived that the series of analogies all confirmed his current thinking and this therefore encouraged him to become more confident. In essence, the first analogy triggered the formation of a theoretical connection between the analogy and the target. In addition, he subsequently made connections between each of the analogies such that each one served to confirm his new 'loss theory' and therefore his belief-rating steadily rose from a three to a five by the end of the sequence.

7.6 Final target theories

After completing the sequence of analogies, the students were asked to summarise their target theory to give what they considered to be their final ideas. None of the thirty students altered their answers at this stage of the interview. Figure 7.9 shows the number of students who were stating each of the theories. These figures include the answers given by all thirty students. This explains why the number of students who are shown to be stating that they consider that some of the kinetic energy of the first cart is converted to sound energy due to vibrations from the collision (theory E) appears to have risen quite sharply in comparison with the number of students stating the same thing at the end of the fourth analogy.

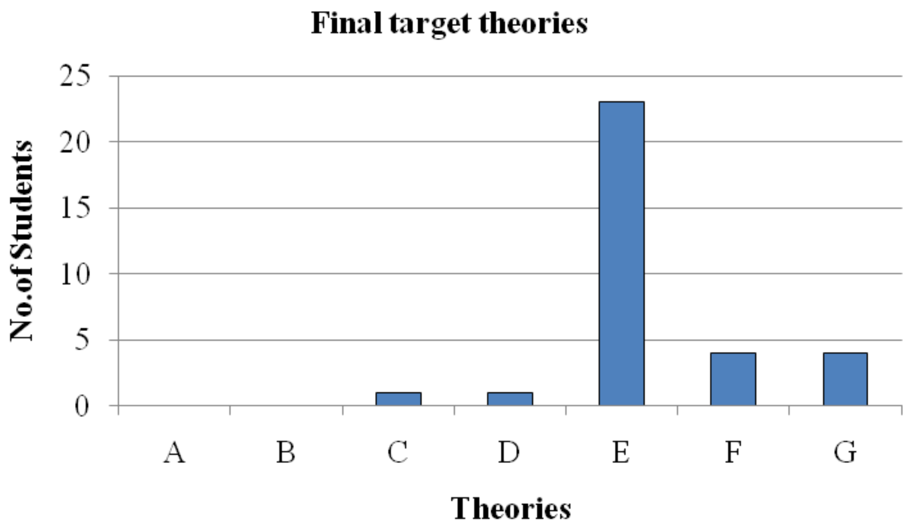


Figure 7.9: Number of students stating each kinetic energy loss theory as their final answer about the target scenario.

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7.7 Extension question

The extension question required the students to return to the original elastic collision in which the two PASCO carts ‘collided’ magnet to magnet. The potential disadvantage of this choice was that the students had already met this scenario at the beginning of the interview. However, this was chosen as it would enable each student to demonstrate whether or not they had really understood and believed the idea that the internal vibrations were fundamental to the loss of kinetic energy in the inelastic collision. It would have been much easier for them to attribute the lack of sound to the obvious lack of physical contact, rather than argue in terms of their newly formed ‘loss theory’. Consequently, this situation deliberately assessed the students’ resolve in adhering to their new theory, rather than returning to their initial version. This would therefore indicate whether or not conceptual change had really occurred as well as testing the students’ ability to transfer their new thinking to a situation that differed from the one that they had discussed throughout the majority of the interview.

Three students were not asked the extension question due to a lack of time. Four students attributed the conservation of momentum in the magnet to magnet collision to the lack of contact. Twenty three students stated that absence of physical contact meant that there was a lack of vibrations in the two carts, which meant that no kinetic energy was converted into heat and/or sound energy. Some initially mentioned just the lack of contact and went on to state the connection with the internal vibrations when they were asked about the significance of no contact occurring.

Of the four students who gave the ‘lack of contact’ answer to the extension question, student 12 was the only one who had consistently stated throughout the sequence that he thought sound was released purely as a consequence of the collision. He had given no indication that he had changed his ‘loss theory’ to include the role of internal vibrations. His answer to the extension question was therefore consistent with his prior thinking and confirmed that no perceivable conceptual change had occurred for him as a result of working with the analogical sequence. The other three students from this group had discussed the idea of vibrations in connection with the target scenario at some point during the analogies. Student 13 had discussed the vibrations theory at the end of analogies one and two, but he had omitted the idea at the end of analogy three, preferring instead to attribute the production of sound energy to the forces between the carts, and the heat loss to the friction created between them. As discussed previously, student 17 had only mentioned the idea of vibrations at the end of the first analogy before changing his idea to molecules hitting each other. In both cases their answers to the extension question confirmed that they had not made the connection between the vibrations and the release of heat or sound energy. Student 13 had made little progress other than to justify the conversion of kinetic energy as being a consequence of the forces exerted by the carts on one another during the collision. However, he did not appear to have been concerned by the fact that the elastic collision also involved the exertion of equal and opposite forces on both carts, and yet no heat or sound was produced. This suggests that he had not really understood the underlying Physics that the analogies were intended to help him to appreciate. Student 17 had appreciated the need for contact but in the end he only changed his theory by describing this contact at a molecular level. His answer to the extension question showed that he had not really experienced conceptual change or that, at best, it had been transient as the connections that he had made regarding the vibrations were not sufficiently robust to convince him that they were more fruitful as an explanatory mechanism. Student 18 had included the concept of vibrations in his final theory but his theory also included two other ideas. These tandem ideas were that the collision itself and rubbing surfaces were also responsible for the production of the sound and the heat energy. When he was asked for the source of his ideas, he indicated that the analogies had influenced his thinking along with other things.

I: Has that idea come to you because of this [the analogy sequence] or have you not changed your views on it at all?

S18: The vibration came but because of the contact, no. I have always known about contact.

I: So where did you get the idea of the vibration causing it?

S18: From the tuning fork and the ball.

This suggests that he had experienced a degree of conceptual change as a result of his exposure to the analogical sequence.

Twenty three students identified the lack of vibrations as the reason for the conservation of kinetic energy in the magnet to magnet elastic collision. Each of these students had postulated that internal vibrations were the mechanism by which sound and/or heat was lost in the target scenario by the end of the sequence of analogies. Four of the students had stated the idea of vibrations from the beginning. As discussed above, this suggests that they had probably not experienced conceptual change during the sequence but simply had their pre-existing mental constructs confirmed. Eleven of this group of students had changed their theory at the end of the first analogy to include the idea of vibrations. The reasons for this were analysed above in the findings for analogy one. Their ability to answer the extension question in a manner that was consistent with their new theory also suggests that they had in fact changed their thinking. It could therefore be inferred that they experienced conceptual change at that early stage and maintained their new position throughout the rest of the interview.

The other eight students had settled on the idea that vibrations had occurred in the carts later in the sequence. The fact that they also managed to answer the extension question accurately also suggests that they had experienced conceptual change by the end of the sequence. Although he had only decided at the end of the third analogy that he thought that vibrations were causing the release of heat and sound in the target, student 15 gave himself a belief-rating of four for the idea that the magnet to magnet collision did not convert kinetic energy to heat and sound because there were no vibrations, since the two surfaces did not come into actual contact. As discussed earlier, student 50 had struggled to understand what he thought was happening earlier in the sequence. By the end, his ‘loss theory’ entailed compressions rather than vibrations. However, he had a clear picture in his mind of what was going on and he was able to defend it when he was challenged which also suggests that he had experienced genuine conceptual change.

I: So, why does that one create sound energy and heat energy, whereas magnet to magnet doesn't?

S50: There's no physical touch, the molecules and stuff never actually touch each other, it's just the magnets repelling each other.

I: So, why doesn't that matter, because there's still forces there you were saying?

S50: Because there's not an actual impact between two physical objects, there's an impact between forces but not objects.

I: Why does the impact matter?

S50: 'Cause the impact's what creates the sound when the molecules and stuff are compressed. If the magnet was moveable, when the magnet pushed in to the trolley there would be sound created in the trolley, but the magnet doesn't because the magnet's fixed.

I: So, are you saying there are no compressions going on here?

S50: Uh, huh.

In a similar manner, student 24 (who had been discussing tandem theories during analogies two and three) clearly stated that the elastic collision lost no kinetic energy because no vibrations occurred in the carts as a result of the lack of contact between them. In addition to the reasons given by the others, student 59 also stated that the second cart moved off with the same velocity as the first cart had before it stuck the second. He used this as a further justification for his theory that the lack of vibrations meant the kinetic energy was conserved.

7.8 The effectiveness of the elastic / inelastic sequence

Figure 7.10 below, illustrates the shifts that occurred in the theoretical stances of the thirty students throughout the sequence. It is evident from the chart that the students' theories had changed during the sequence. Increasing numbers of students decided that kinetic energy was being transformed to sound (theory E) or heat and sound (theory G) as a consequence of the vibrations that occurred in the carts as a consequence of the collision between them. This shift coincided with a decrease in the number of students who thought that kinetic energy was transformed into sound but were unclear about how this could be explained (theory C) and those who thought that kinetic energy was transformed into sound and heat but were unclear about how this could be explained (theory D).

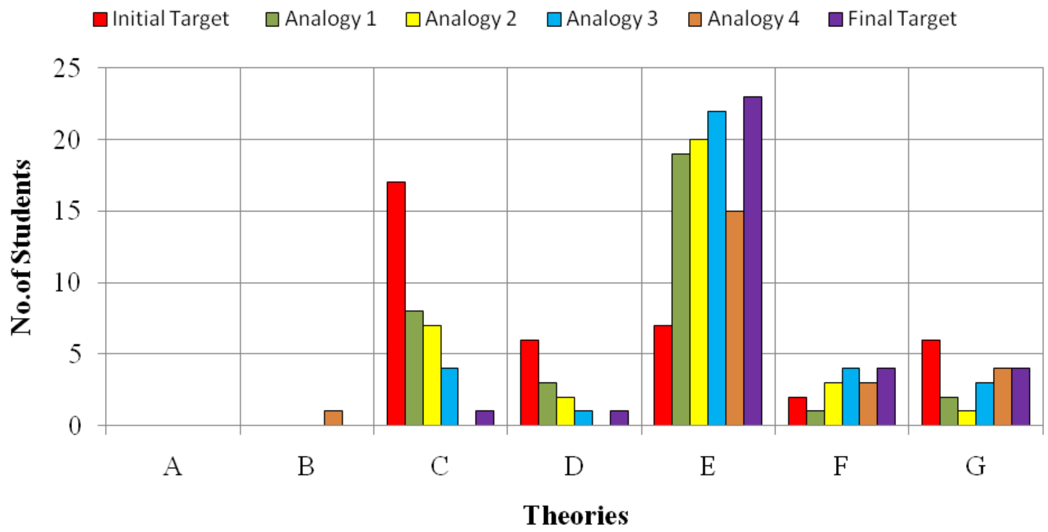

Figure 7.10: Number of students stating each kinetic energy loss theory at each stage of the inelastic collision analogical sequence.

It is perhaps not surprising, given the number of students who made significant progress at the beginning of the sequence, that the first analogy was mentioned by a total of seventeen students as being one of the most useful in the sequence. The reason most often given for this was that it made it obvious to many of the students that vibrations were causing the sound because they could see, hear and feel the vibrations. This multi-sensory stimulus seemed to be particularly helpful in engaging the students' thought processes and helped them to make a connection between the sound and vibrations. Student 26 went further than the others when he commented that analogy one might have been effective on its own, but he also said that the other analogies helped to confirm his thinking.

The second analogy was positively commented on by eight students and negatively by three. In common with analogy one, students 23 and 49 felt that this analogy had helped them to reason out that the vibrations caused sound to be released. Student 31 singled out this analogy because she had “felt the momentum going into her”. Students 24 and 32 said that they found this analogy particularly hard because they could not really see or feel the vibrations in the rubber ball. Student 50 preferred this analogy in conjunction with analogy four because he felt that he was unable to make links between the vibrations and the sound in the other two situations. This answer was consistent with the way in which he made progress throughout the sequence.

The third analogy was mentioned as being particularly useful by ten students and was commented on negatively by one student. The vibrations in the balloon were perceived as being particularly easy to see by those who commented favourably on it. These students consequently found it useful for making connections with their prior thinking. Student 49 found the third analogy harder to link with the target scenario and so he found it less helpful than the others in the sequence. Student 60 particularly liked this analogy. He stated that the first analogy had given him the idea that the vibrations caused the sound but that the third analogy had convinced him that his theory was correct.

Analogy four was mentioned as being helpful by a total of five students, while one student commented negatively. Student 49 said that he felt that this analogy was good for linking his thinking back in with the trolleys, while student 60 commented that this analogy bore the most similarity to the trolleys, which had been the intention in including it in the sequence. Student 14 was the one who commented negatively on this analogy. He said that the analogies got harder as he progressed through them and that he had difficulty with the final analogy as he could not “see much” happening, unlike the other analogies. This was another reason why it had been deliberately placed at the end of the sequence.

Several students (S10, 16, 27, 36, 54, 61, 65) stated that they thought that all of the analogies in the sequence were needed as they all gave similar ideas, while using different surfaces, which helped them to make connections and hence progress their thinking. Student 37 gave a particularly clear explanation of this when she was asked about which analogies she found to be particularly helpful.

S37: The tuning fork and hammer was quite useful because the whole purpose of the tuning fork is to vibrate and produce sound.

I: Were any more helpful in coming up with your idea, or convincing you of your idea? Because you were saying the same thing all the way through really.

S37: No, I think the tuning fork and the hammer made it slightly more clear but all of them were probably much the same.

I: What about the sequence? Did you think the sequence was helpful or would that one on its own, since you mentioned that one, would that have worked on its own completely?

S37: No.

I: Why not?

S37: It was helped by the fact that I noticed other things were banging into each other and making noises and other things were vibrating.

I: So you thought the reason must therefore be similar?

S37: Yeah.

Despite changing his thinking at the end of analogy one, and then not changing his loss theory thereafter, student 65 said that he felt the last three analogies had been particularly good for making him think more. He also made the following comment about the need for all of the analogues in the sequence.

I: Do you think you needed the whole sequence to come up with your idea or did you think three and four would have done it for you on their own?

S65: I'm not sure. There seems to be a pattern with all four but if you had only done two it might have just been coincidence.

I: So, did the pattern help you to think it through?

S65: Yeah, definitely.

Student 11 decided that the sequence was very helpful because it helped him to make links and to derive a logical explanation for what happened in the target scenario.

Three students commented less favourably on the sequence. Despite getting the accepted answer, student 32 stated that she found the sequence confusing. However she then went on to comment very favourably on this as a learning technique. Student 9, who had argued from the start that vibrations were the cause of the loss of kinetic energy in the target scenario, was of the opinion that he knew this idea prior to engaging with the sequence. He therefore concluded that the analogies had made little difference to his thinking. In contrast with this, student 45 had made no noticeable progress throughout the sequence. He said that he found the vibrations in each situation confusing. This coincides with the argument given above, that he had been unable to connect the knowledge of vibrations and the knowledge of sound production because they were too 'cognitively distant' in his mind.

The evidence that a total of twenty six out of the thirty students were stating kinetic energy was lost in the inelastic target scenario, as a result of sound and/or heat being produced as a consequence of vibrations, shows that this analogical sequence was successful in causing conceptual change. The concept behind this sequence is almost certainly less abstract than the underlying idea in the 'immoveable object' sequence. It is also true that a greater proportion of the cohort of students in this sequence made progress earlier in the sequence. However, the above detailed analysis of the students' thinking, as they worked through the sequence, shows that the analogies were influential in altering the mental schemas of many of the students. The students' perceptions of the sequence as a whole, as discussed above, show that it was well received by the vast majority of the students, and they felt that it had influenced their thinking. In answer to the second research question, it is therefore reasonable to conclude that this analogical sequence was very effective in causing conceptual change in the thinking of students from the full ability range of those who were sufficiently successful in a previous examination to be permitted to study Higher Physics.

Chapter 8

Findings 5: Bridging analogies in learning and teaching

At the end of the think-aloud interviews, the students were asked for their opinion on the use of the analogical sequence as a way of learning. In particular, they were asked whether or not they had found the analogies useful in coming up with their ideas and then to explain why they did, or did not, find them useful. The vast majority of the students thought that the analogies were helpful and commented favourably on them as a way of learning. Many of these students were also able to articulate reasons why they thought that the sequences were particularly helpful when used in conjunction with the open-ended questions that they had encountered during their interview. The comments made by the students also showed that they had been realistic in their assessment of the process as several of them described not only advantages, but also mentioned some drawbacks as well. Due to a lack of time in their interview, as a result of constraints on available time, six students did not discuss this aspect of the use of the analogies. The opinions of the fifty four students who did comment on the effectiveness of bridging analogies as a learning strategy and its potential value as a pedagogical technique will now be examined in some detail.

8.1 Criticisms

There were three main criticisms pertaining to the use of the analogical sequences as a teaching and learning tool and one less critical observation. The first was that it took a more time to work though the sequence than a teacher might ordinarily devote to the topic. The second negative comment was that several of the students stated that they did not like the lack of feedback about whether or not they were 'correct' during the sequence. The third aspect was related to the desire of some students to be told what the 'correct' answer is by a teacher. This problem arose from a concern that they might get the answer 'wrong' if they tried to work it out for themselves. The less critical observation was that a small number of students expressed the opinion that there were perhaps too many analogies in the 'immoveable' object sequence and that it could have been as effective with one or more of the constituent analogies being dropped from the sequence. Each of these observations will be exemplified and commented upon using statements made by some of the students.

8.1.1 Length of time required

One criticism of the analogical sequences was that they took quite a long time to work through, which was undoubtedly true. A significant proportion of each think-aloud interview was devoted to investigating the thinking and reasoning that the student engaged in. The primary reason for doing this was to enable the research questions to be answered, but it was also a consequence of the students being given the freedom to think for themselves during the interview with a minimal amount of interference by the researcher. This meant that the direction in which each interview went within the various analogy sections was at least partially controlled by the student. This in turn entailed many supplementary questions having to be asked to enable the student's thinking to be understood clearly.

The students who discussed this draw-back did so as part of an overall positive impression of the bridging analogies, but did mention this aspect as a potential problem in their use as a teaching and learning tool. One such example was student 34 who stated that he thought that using the analogies was a good way of learning.

However, he thought that some students might take advantage of the self-directed nature of the process and waste time by “messing about” if they were using the sequence as a group exercise. This suggests that he thought that the process could take a long time and not be very productive unless the teacher gave clear direction to a class about what they were to do. One way around this potential difficulty would be to use the analogical sequence as part of a whole class discussion which would be led by the teacher. In this study, the sequences were only used with individuals and so further research would be required to ascertain whether or not they were effective when used with a group of students.

Another potential hazard associated with the length of time taken to work through the sequence was pointed out by student 40 who felt that the time required to complete the full sequence could result in some students losing concentration part-way through the process. However, as discussed later in this chapter, he also stated that in his opinion, completion of the analogies could result in real benefits being gained by the learner.

8.1.2 Lack of feedback during the sequence

As can be seen from the extracts from several students throughout this chapter, several of them discussed (as part of their mostly positive comments) that they found not being told whether or not they were ‘correct’ at each stage in the process hard to cope with. As a consequence, they reported feeling rather uneasy about their final answer. This reticence is understandable as the vast majority of students are accustomed to being told by their teachers whether or not they are correct. However, as discussed previously in the methodology chapter, there was a deliberate decision taken in this study not to tell the students whether or not their answer agreed with the Physicists’ view of the situation until the very end. This meant that the thinking of the students could be tracked as they interacted with the different analogies in the sequence. Had they been told whether or not their thinking was moving in the ‘correct’ direction, it would almost certainly have influenced their thinking and reasoning more than the analogies themselves. Ordinarily, feedback would be given more often in a classroom setting as part of a teaching process. However, the first two research questions in this study, which sought to find out the extent to which the bridging analogy sequences were effective in encouraging conceptual change, necessitated the use of the non-interventionist approach which was employed. The other advantage of this methodology was that it enabled the students' thinking processes to be tracked much more readily as the views that they expressed were almost entirely influenced by the students themselves as external influences were minimised by only prompting the students to elaborate on their answers in order to elicit more information, and the careful use of questioning.

The comments made by student 32, which are discussed below, show that she found the lack of feedback to be somewhat off-putting despite the fact that her final theory had changed to one that was very similar to the accepted view. Student 52 also voiced this criticism when he said that "it would be useful to be pulled in the right direction", but his overall impression was that the bridging analogies were useful as a learning tool.

8.1.3 Preference to be told

Student 45, who did not experience conceptual change throughout the inelastic sequence, was the only student, out of the entire cohort of sixty, who decided that she was unsure about the usefulness of the sequence as a learning tool.

I: If you were asked to use this as a way of learning more in class, with a bit more guidance, I mean I've deliberately not given you answers here, would you think it would be a good way to learn, or not?

S45: Don't know.

I: Not so sure?

S45: I'm more a person who just kind of looks at the sheets and diagrams and that.

I: So do you prefer just being told what the answers are?

S45: Not quite what the answers are, but em, how things should be done, like just using a diagram.

I: So you'd rather just get told than work it through?

S45: Yeah.

It is clear from her comments that she had found the sequence difficult to follow and felt that it would have been better if she had just been told what the answer was as she lacked confidence in working things out for herself. She failed the Higher exam in the end, which suggests that she had difficulty in understanding parts of the course content and was not confident in applying her knowledge in problem solving situations.

Student 54 (a very able student, who got a grade A in the final exam) felt that the sequence would have been more useful if the answer had been explained to her first, followed by the opportunity to work through the bridging analogies. She had also found the lack of feedback, which she was used to getting about whether or not she was correct, to be frustrating, along with the deliberate omission of numerical values.

I: How would you rate that in a way of learning something? The other option would be for your teacher, to say here is why 'boom, boom, boom'. Would you prefer just to be told, or would you prefer a sequence, a way of doing this?

S54: I think probably a mixture of the two would have been good so you were actually told what it was first then, either you are able to do this, or the teacher does it, and like, proves it, but with these you would probably have to prove it, for me to be happy, we would probable need the measurements to taken as well, rather than just, …

I: But I have deliberately not taken measurements. So how would you rate that as a way of learning, is a good way to learn things or not, in your opinion? And why?

S54: Yeah, I think it's good, but you would also need to combine it with facts rather than, …., just working it out, say, …

I: So, normally your teacher would say you're thinking the right way, or whatever, that would help, would it?

S54: Yeah, and if you were told what it is, or whatever, and then justify it or try and work it out first and then you are told what it is.

I: Has it been frustrating not being told that you are right or not?

S54: Eh, yeah.

Her comments could be viewed as being a direct consequence of her being uncertain about the 'correctness' of her answer, which she clearly found unsettling. They also suggest that she was more accustomed to following an explanation given by her teacher, or working out the answers to numerical questions rather than trying to work ideas out for herself. Her desire to be 'correct' meant that she had found using the analogies in the manner employed in this methodology to be a rather uncomfortable, but useful, experience.

8.1.4 Fewer analogies required in the sequence

Although he thought that the use of analogies had helped his learning, student 46 expressed the opinion that it would possibly have been just as effective with fewer analogies in the sequence.

I: As a way of learning though, do you think it's better, or not as good as the teacher telling you what the official line is, or whatever?

S46: I think it's quite good, but, I prefer like, this is just myself, but I prefer a more direct approach to, like, if, …

I: 'Here is what the answer is'?

S46: No, no, no, I don't want that. But like, just less steps, kinda, just, …

I: So it was just there was quite a lot of steps in it?

S46: Yeah.

I: So let's say it was the same idea, but less steps?

S46: Yeah, that's it.

I: Would you like that?

S46: Uh, huh.

Despite this criticism, he went on to explain that he found the sequence useful as he felt that it had enabled him to feel that he had "proved" his idea to himself.

8.2 Positive comments

As can be seen from the interview extracts below, the vast majority of the students had positive impressions of the analogies and think-aloud interviews as a learning strategy, including some who had experienced little or no conceptual change during the sequence. As discussed previously some of the criticism that are outlined above were mentioned as part of several students' comments about the use of the bridging analogies and think-aloud interviews as a learning and teaching strategy. The positive feedback that students gave can be sub-divided into five categories, as outlined below. In each case the students' comments are allocated to the category that they stated first, although it will be seen that many students discussed more than one of the categories of positive comment regarding the use of the analogies.

The number of students who discussed each category of positive comment are summarised in figure 9.1 below. The number of students who gave each reason as their initial response has been shown separately from those who made the same comment as part of their subsequent discussion. The total number of students who gave each response at some point in the discussion is shown by the overall height of each bar in the histogram. For example, a total of thirty two students stated that the analogies had helped them to think for themselves, which was coded as 'self-directed thinking'.

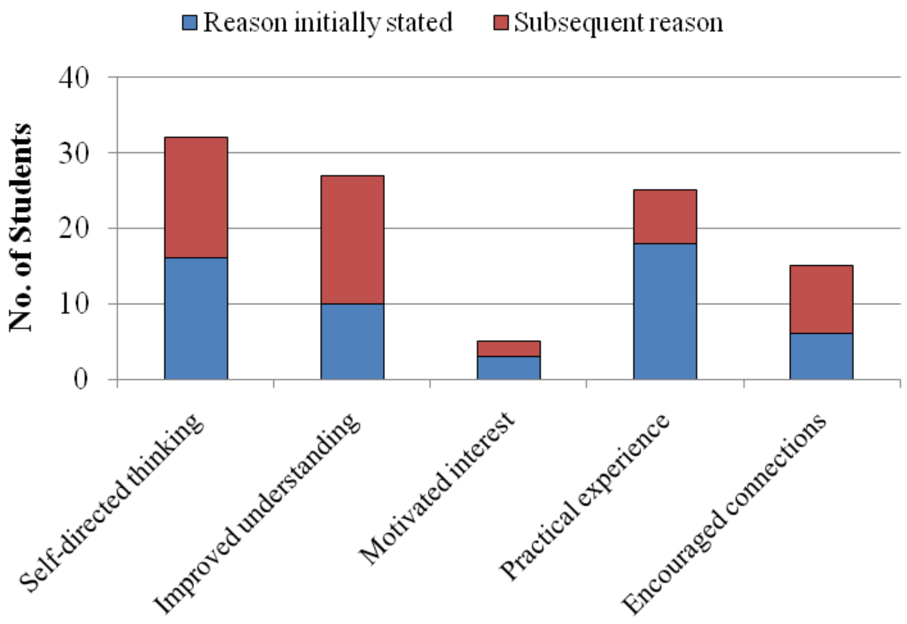

Figure 8.1: The number of students who gave each category of positive comment regarding the use of the bridging analogy sequence as a teaching and learning tool.

8.2.1 The analogies encouraged self–directed thinking

Sixteen of the students commenced their explanation, about why they thought that that the bridging analogies were a useful learning tool, with this category of justification. Essentially, their argument was that the analogies (in conjunction with the Socratic questioning that was utilised in the interviews) had encouraged them to think carefully for themselves. Several of the students went further than this and argued that the self-directed thinking process had enabled them to devise a theory that they had ownership of and some said that they felt they understood the physics better as a consequence of having thought it through without being told what to think. More than one quarter of the entire cohort of students felt that they had thought through an answer for themselves. This suggests that the researcher had been successful in meeting the original aim of not directing the students towards the 'correct' answer. The individual comments of the sixteen students are examined below.

The opportunity to think for herself during the interviews was thought to be very helpful by student 2.

I: So why do you think it's helpful?

S2: Because it sort of helps you to get to your own answer rather than being sat down and said that this is true and this is true and you just have to believe it.

I: You said near the beginning, of this, that you said momentum was conserved, because you had been taught that, is this still your reason or has this changed your thoughts at all?

S2: It's sort of still the reason but, like, this has started me thinking why it is conserved and things

I: Why do you think that this has worked for you?

S2: Because I could see it and do it myself,

I: And what about the thinking side of it, is it just because you are doing it or would it be as well as doing and experiment, where you have trolleys banging into each other and taking measurements and working out answers. Or is this better or worse than that?

S2: This is probably better because it's more general, it not just like, more like than experiments where you have to take down notes, because then you are just concentration on getting the measurements, you are not really thinking about what's going on, and what the computer is doing to get the answers, that is doing, like if you are using that to measure it.

I: So the measurements, you are saying, you get too caught up doing the numbers?

S2: You concentrate more on that rather than, …

I: So what is this doing?

S2: Sort of helping you concentrate on what is actually happening

I: So, it helps you to what, you were saying?

S2: Because, yeah, it helps you concentrate more on what is happening rather than, like, helps you understand what is going on with it

Just prior to this excerpt, she had been told that she had come up with the accepted answer regarding the momentum in the target scenario of the car hitting the building. This was divulged as she was demonstrating reticence, typical of many students. The decision was taken to let her know that her thinking was along the generally accepted line as otherwise her answer about the usefulness of the analogies and the interview as a learning technique would have been too vague and would have had more to do with her self-doubt about whether or not the answer that she had devised was merely something that she had made up, rather than about the usefulness or otherwise of the method. However, it is clear from her comments that she found the analogies helped her to think for herself and consequently she felt that her understanding of the situation improved. It is also noteworthy that she found the gathering of numerical data in most experiments to be rather distracting. She considered the non-numerical nature of the process that she had just undertaken had helped her to concentrate on understanding the physics, rather than the more common task of simply working out the relevant values.

In comparison to using textbooks to discover an explanation of the physics in a situation and then write it down, student 15 thought that he was encouraged to think much more while working through the sequence. It was also apparent that the analogy and interview approach was novel which also appealed to him.

> S15: It's better. It is different and it makes you think instead of just copying stuff down.

Student 24 also felt that he had made progress in his thinking as a consequence of having to think for himself. He singled out two of the analogies as being particularly helpful in encouraging him to think things through for himself.

> S24: Well some of the analogies here helped me. The tuning fork, if I had done that at the end I would have probably got it more but the rubber ball thing helped me as well. It just made me think a bit more about it and my answers and stuff and it helped me to grasp it. What I think it was anyway.

Student 55 displayed a little more caution when she said that analogies may not prove helpful for some topics and ideas, but she thought that the analogies in the inelastic sequence had helped her to think things through for herself, rather than simply being told what the answer was. When she was asked to expand on why she thought that using analogies was better than having the physics explained to her by a teacher, she reasoned that the analogies had involved practical experience and then re-iterated that she had been encouraged to think for herself.

> S55: Because you get to do it, like, you get to try and work it out yourself, not just someone telling you?

Although she did not acknowledge the part played by the interview technique, it can be argued that her perception that she was able to think for herself was a consequence of the combined use of the analogies with an intentionally non-directive interview process.

Two of the students who felt that the analogies had helped them to think for themselves were among the less able in the cohort. Student 29 failed the final Higher exam, while student 40 only managed to achieve a Grade C. Despite their relatively poor overall performance in the exam, both of these students had clearly experienced conceptual change as a result of working with the analogies. Student 29 ultimately decided that the car transferred momentum to the wall via each layer of brick and he also concluded that the large mass of the wall accounted for the apparent lack of movement. When asked what he thought of the analogies as a strategy for learning and teaching, it was clear that he felt he had made progress mainly because the sequence of analogies had encouraged him to think for himself.

S29: It is quite good because it gets you thinking quite deeply into all the different, …

I: And if I was to say to you if this was to be used in physics more often, would that be a good thing or a bad thing?

S29: Good thing.

I: Why? For example you might normally be told things, …

S29: Because you are actually finding it out for yourself.

I: And why does that help?

S29: Because you aren't just getting told it, you can't work it out for yourself and it gets you thinking about a lot more.

The analogies had enabled him to reason out an answer for himself which he found more beneficial than his common experience of trying to follow what he was told by a teacher. Given that he was unsuccessful in the final exam, this suggests that he was not good at understanding the explanations that he was given for many parts of the course and yet he thought that he had understood this difficult concept through the use of the analogies. Student 40 had also experienced significant conceptual change as a consequence of examining the 'immoveable' object sequence. When asked about the use of the analogies as a learning tool, he initially stated that they had caused him to "think about things in greater detail". He also said that he found the process had caused him some difficulties but, having followed it all the way through, he said "you understand it really well". A few minutes later he discussed the use of the analogies for learning science.

S40: I think it would work if you taught children like that in science, when you first really experience science in first year.

I: Mmm, hmm.

S40: And got them to do this stuff. Like say if you just took someone like me who's been told if he's right or wrong for five years.

I: Mmm, hmm.

S40: I suppose it's more likely if you're working in science, that if you find something new there isn't someone with an answer book to tell you it's right or wrong, you have to, …

I: So do you think this is how science works?

S40: Definitely.

I: What do you mean by that? Why are you saying definitely?

S40: Obviously there's not someone saying this is right or wrong, if you're using something new or finding something new.

I: So are you saying that this is a bit like you trying to work things out for yourself, is that what you're saying?

S40: Mmm, it teaches you to have confidence and pride in your own thoughts and your work.

His last comment was made despite the fact that he had not been told whether or not his answer was in agreement with the accepted answer. It is clear from his statements that student 40 had found that the use of the analogies in a think-aloud interview had encouraged him to really think for himself. He perceived the resulting thinking process as being similar to that used by scientists who were making new discoveries. This more self-directed process had resulted in him gaining increased satisfaction and confidence.

Two of the sixteen students indicated that the process of thinking through the entire sequence had been instrumental in them finding the process useful. Student 65 indicated that using the whole sequence had improved his understanding. This is noteworthy as his personal theory essentially correlated with the accepted answer by the end of the first analogy in the inelastic collision sequence. When he was asked why he thought that the entire series was helpful, he explained his reasoning as follows.

> S65: Because you are going through it bit by bit and thinking of all the things that are happening.

Clearly, he perceived that working with the sequence had helped him as a direct consequence of the level of thinking that was required to generate the ideas that he came up with. Student 58 similarly reported that she was required to think very carefully throughout the entire series. She also mentioned that she had become confused at some points, but that in the end she had been able to work out what she thought had happened.

> S58: It's a really good way of thinking.
>
> I: Why?
>
> S58: Because it gets you confused and makes you really take a good think about it and then try and work it out, and even if you end up with like, …, talking round in circles, its easier to hear yourself out loud and have physical objects to try and work it out with, than just being told.

A few seconds later she also indicated that she had found the practical element of working through the analogies very helpful as well.

> I: Ok, so if that was to be proposed as a way of learning more things, what would your thoughts on it be?
>
> S58: I actually think it would be really helpful.
>
> I: Why?
>
> S58: Eh, …, personally I find that when you get to experiment with things, and it might not be practical with time in a classroom but, having time to sit and work through all sorts of things, is really helpful.

One of the students in this group correlated the requirement to think very carefully for herself during the sequence with an increase in her perceived level of understanding. Despite having the accepted answer from the beginning, student 37 rated the use of the bridging analogies as learning technique very highly. The following excerpt shows her reasons for liking them.

I: What would you make of this as a way of learning? Let's say you were getting taught using this style in class, what would you think of that?

S37: At the moment, even though I have come up with my own reasoning, I'm not totally confident that it's right, but it really helped me come up with my own reasoning.

I: So, normally the teacher would tell you as you went along if you are right or not, I've deliberately not told you, just to see where you went because it was a free run I was giving you. But as a way of coming up with your idea?

S37: It was useful.

I: Why?

S37: Because it started off with just seeing things with the cars then you introduced the whole noise, the whole aspect of sound with the tuning fork and then you introduced the aspect of things vibrating.

I: So that got you thinking along those lines?

S37: Yeah.

I: Were you being pushed on those lines or was it what you were coming up with?

S37: No, I was pushed in those lines because that made a noise.

I: So the analogies made you think of those, not me?

S37: No. Well, probably both because, …

I: Because I was asking questions?

S37: Yeah, and making me think about it.

I: But you found the analogies helpful in coming up with the ideas?

S37: Yes.

I: The fact that this took longer than you would normally take for an explanation, do you think that is a good thing or a bad thing?

S37: I hate the fact that I'm not sure if I'm right or wrong but I don't know. Sometimes in physics you wish things would speed up because you are fed up with doing the one wee aspect of the whole big world but on the other hand, in order to get it implemented into your mind, I think it was quite good. I think it was quite good in the fact that I had to go through my own reasoning because in a way that makes you more likely to understand it and to remember it than just being told this is what happens.

She was convinced that she had come up with her answer through a process which relied on her own reasoning skills, although this had left her with the thought that she could have been 'wrong'. Despite this uncertainty, she felt that her understanding had improved which she thought had increased the likelihood of her being able to remember the underlying physics better than if she had simply been told the answer. She ultimately attributed her ability to logically reason out an answer to the combined effect of the analogies and the questions that she had been asked.

Two of the students discussed the improved likelihood of them being able to remember the explanation that they had settled upon as a consequence of their self-directed thinking process. Student 34 felt that being able to see what happened in each analogy helped him as this had enabled him to think through what happened in the target scenario for himself, and he then concluded that “it sticks in your mind better”. Student 41 also thought that being able to work things out for himself was beneficial and he thought that he would be much better at remembering the ideas as a consequence.

> S41: I think that’s a good way though, ’cause it allows you to, like if you work it out for yourself you’re going to remember it longer than if someone just tells you.

Another three of the sixteen students felt that the self-directed thinking process had been a useful learning experience as it had also helped them to develop their logic abilities, problem solving skills and their exam technique. Student 42 described the analogies as helping him to think for himself as he devised his answer, which he thought was a logical explanation. He was then asked whether or not he felt that the analogies had helped him to come up with this answer.

> S42: Well yeah the analogies helped, I don’t know if I would have worked it out myself.

This suggests that the analogies had encouraged him to think through his reasoning. This enabled him to devise his answer, which was in agreement with the accepted idea. Student 60 thought that using the sequence had improved his problem solving skills be’c he had been required to work out the answer for himself rather than simply being told what it was. Student 13 felt that because of the level of thinking that had been required, the sequence had been good preparation for questions that required descriptive answers which are often asked in the exam.

When student 32 was informed that she had settled upon the accepted reason for the loss of kinetic energy in an inelastic collision, she was surprised.

I: Now if I was to tell you that you have come up with the accepted answer, would that surprise you?

S32: Yeah.

I: Why?

S32: I don't know. Because I worked it out.

I: Does that surprise you that you've got it right though?

S32: Yeah.

I: Why?

S32: Because I didn't know what I was doing.

I: And yet you were actually thinking it through as you went.

S32: Yeah.

Her surprise was based on the fact that, by her own admission, she had 'worked it out' for herself. This strongly indicates that she did not feel that she had been influenced by the researcher and that the theory that she devised had come about as a consequence of her interaction with the analogies and her own resultant thought processes. Her perception that she didn't know what she was doing is noteworthy as it also suggests that she had little or no feedback about whether or not she was correct. This had clearly worried her, despite the fact that she had been thinking along scientifically acceptable lines but, as discussed above, in a normal classroom teaching situation using the same sequence this lack of feedback would be less likely. However, the use of this technique in the present study enabled the thoughts of the students to be tracked with less interference from outside influences.

Student 63 justified his view that the analogies were a good aid for learning using several of the arguments that were used by the other sixteen students as secondary reasons. In common with the others, his initial reason was that the analogies had made him think hard for himself. But he then went on to give several other reasons why he thought that the analogies were an effective learning tool.

I: Now if it was suggested that this was used more as a way of learning rather than being told stuff, what would your thoughts be using a sequence of this sort for other things?

S63: Well you need to think a lot so it is quite a mental exercise.

I: Is that a good thing or a bad thing?

S63: It is a good thing. It is good to have your brain engaged.

I: Do you think it engages your brain more than being told stuff?

S63: For the purpose of learning, I think this helps you to understand it more, being told stuff helps you to learn it more though because this you have to think about it yourself and come to your own understanding whereas a teacher can just tell you something and you believe it because it is in the curriculum.

I: Do you just believe it straight away because when I asked earlier about conservation of momentum which you have been told, you gave it a three at the start.

S63: Yeah, because they often don't tell you the full story.

I: So, does this help you to get it better?

S63: Yeah, definitely.

I: Why?

S63: Because it is applying the theory, it is not exactly real life but it is a scaled down situation in real conditions without friction or slopes and things.

I: So the fact that it is a bit more real life is better or worse?

S63: Better as far as understanding goes.

I: Why?

S63: It means you can apply it, in your brain you can think about it more, rather than just reading something off a board where you might not really understand it, by seeing this you can see the processes that are happening and think about them.

His comments clearly demonstrate that he felt that his understanding was improved as a consequence of the degree of thinking that he had engaged in throughout the sequence. His comment that the analogies were "a scaled down situation in real conditions" also showed that he had made strong links between the analogies and the target scenario. His argument was that the combined effect of the different factors that he had sited was important in helping him to make progress. It can therefore be seen that he had learned effectively through the use of the analogies.

8.2.2 The analogies improved understanding

Ten students stated that the analogies had helped their understanding of the target situation as their initial reason for saying that they liked the use of bridging analogies as a way of learning. In common with the other sub-categories, most of these students gave other secondary reasons by way of justification of this opinion, although the first few examples below are of students who did not expand their answers much beyond their primary reason.

When he was asked to explain why he thought that the use of bridging analogies would benefit his learning if they were used more often, student 26 offered this opinion.

S26: Because it makes you think yourself instead of you just being given the information.
I: And why do you think that would make a difference?
S26: I don't know. Because then you understand what is actually going on.
I: Because you have thought it through for yourself?
S26: Yeah.
I: So, do you think that method would help you to do that, if that was used more often?
S26: Yeah.

It was evident that student 51 had come to a similar conclusion when she was asked what she thought about the use of bridging analogies for future learning.

S51: It would be quite good?
I: Why?
S51: Because you would be convinced that, …, it was true, …, that it would be proved to you.
I: So, why would you be more convinced than say, just your teacher saying this is what happens, blah, blah, blah?
S51: Because you can see it happening?

Likewise, student 43 described the sequence as giving her "evidence" for her thinking process because of the practical nature of the experiments.

Four of the ten students gave additional reasons over and above the improvement of understanding for their assertion that the bridging analogies were a useful learning aid. Student 27 gave several reasons for his positive disposition towards the analogies as a way of learning. His initial comment was that the analogies had helped him to “make more sense” of the physics although he showed a degree of caution when also stated that “for all I know I could have got them all wrong”. This statement confirms that he perceived that he had arrived at his own conclusions and had not felt pressured into giving the ‘correct’ answer that was being sought by the researcher as might happen more commonly in classroom teaching situations. After going on to state which analogies in the sequence he had found most helpful he came back to discussing the usefulness of the analogies for learning, at which point the following discussion occurred.

I: If you were to use this as a technique more in classes, how would you feel about it as a way of learning your physics?

S27: I think it would be quite useful.

I: Why?

S27: It seems simpler than just learning equations and being told what it is.

I: Simpler in what way because this is taking longer.

S27: It is easier to understand.

I: Why?

S27: Because you can test it yourself and see how one situation has one effect while another has a different one.

I: And does the fact that there were wee differences between the different analogies, did that worry you or not?

S27: Not really.

I: Why didn’t it worry you?

S27: Because you can see after you’ve done all four that they are all quite similar in ways. There are always slight vibrations and momentum and kinetic energy is either conserved or not.

I: So you could see the links between them even although maybe some of the bits were slightly different or whatever?

S27: Yeah.

I: OK. If I was to ask you to rate that as a way of learning rather than say book work or the teacher just explaining it to you without you doing it this way. How would you rate that as a way of learning on a scale of one to six?

S27: Four or five.

I: So you are quite happy with it?

S27: Yeah.

I: Because of what?

S27: Because at first it seemed quite confusing just using the two trolleys which is normally what we use in class but once you have done a couple of different experiments you can see how they link to the trolleys.

I: So that helped you to think it through did it?

S27: Yeah.

His primary reason for finding team useful was that he felt that the analogies had been easier to understand than trying to learn how to use equations and better than being told what was happening. When he was asked to explain why he thought this, he justified his answer by stating that using the analogies had encouraging him to test ideas out for himself and to assess the level of similarity between the different experiences as well as to ignore differences that seemed to be unimportant to the overall reasoning process. As he went on to fail the final Higher exam, it seems likely that he found the theory in the course, and its application in answering questions, to be generally difficult. In comparison, it is notable that he found this way of learning more accessible. He made progress as a consequence of the first analogy in the inelastic sequence and the rest had increased his belief-rating in his new theoretical stance. His comments about the use of the analogies as a learning tool were therefore consistent with his conceptual change pattern. His final comment also demonstrates that he considered the links that he perceived and constructed between the different analogies in the series and the target scenario to be the key factor in helping him to increase his understanding of relevant physics.

Student 22 liked using the analogies as he described them as being “self-explanatory”.

S22: Yeah, because diagrams, they are not very explaining what is happening really. This is self explanatory.

He went on to state that he felt that they were self-explanatory primarily as a consequence of working with them in a practical way as the personal physical experiences with his hand in particular had helped him to understand what happened when the car struck the building.

Student 56 started by saying that using the analogies had improved his understanding of inelastic collisions, but he went on to give several insights into to why he thought this and how the use of the analogies had helped him.

I: What do you make of this as a way of learning? In comparison to just been told that this is how it works, which is what you would normally be getting?

S56: Better, but in a good way, because its like, in some subjects they just tell you stuff, like in maths, they just tell you this is how you do the equation and you don't ever learn the actual understanding of the, how the numbers work, and this helps you to understand how it actually works.

I: Why, because I haven't actually told you that you are right or wrong?

S56: It would help if you had told me if I was right or wrong?

I: So, what is it that this is doing to help you understand?

S56: It helps you create your own opinion, and then you can be completely right or completely wrong, but generally in your own opinion and generally in your own understanding of it, then you can prove it right or wrong.

I: So then, you would prefer it then obviously, that the teacher would say to you that you are correct or you're not or whatever?

S56: Yeah so it allows you to come up with your own way of remembering it.

I: Ok but what about the fact that it takes quite while, does that bother you?

S56: It takes even longer doing it the other way, because you need to relearn everything, you are just sitting being told everything. I would rather sit and work it out for myself than be told it.

Despite not having been told whether or not he was 'correct' he felt that he had understood what was happening because he had been able to work it out for himself. Although his final grade of a C shows that he found physics difficult, he made it clear that he preferred to try to work things out as otherwise he had to re-learn what he had simply been told. It can therefore be deduced that using the analogies had helped him to reason out an answer for himself that was congruent with the accepted scientific idea.

Student 59 reported two ways in which the analogies had improved his understanding as shown by the quotes below, taken from the section of the interview in which he was describing his thoughts about the use of analogies as a way of learning.

> S58: Yes because, …, they show you ideas that you have never really thought about, but I suppose it's quite difficult to relate these ideas to momentum still.

He then went on to say a little more a few seconds later.

> S58: I would agree with it, because at the moment we are being taught a very simplified way of, kinetic and momentum, but never really understand what its about, at least with this we gain, …, the ability to understand it a little bit more, still I'm a little confused.

He had rated his belief in his theory as being at level five, but his statements show that he had a degree of doubt that he was correct. This was mainly because, as discussed previously, he had not been told by this that his answer was 'correct' which he was accustomed to being told in a classroom situation. Despite his understandable reticence, it is evident that he felt that his understanding had improved because the analogies had made him think about things that he had not considered previously. He is therefore suggesting that this ability to enable students to make new discoveries and new connections in their minds is a strength associated with the use of bridging analogies in particular because of the way that it affected his thought patterns.

The perception that the analogies had improved understanding was not limited to any one ability level. Student 28 (who struggled with the Higher course, and ultimately withdrew from sitting the final exam) thought that the analogies had helped him to understand what happened when the car struck the building. He had concluded by the end of the sequence that the car would have transferred momentum to the building and then to the earth. He thought that the analogies were a good way to learn partly because they examined ideas that he had not discussed in class. He felt that this resulted in him thinking more deeply about the transfer of momentum. In common with many of the other students, he subsequently stated that the hands-on nature of the process had made it more interesting. At the other end of the spectrum, student 49 (a very able student who ultimately got a grade A) had changed his theory regarding the loss of kinetic energy in the inelastic collision to one that was in sympathy with the accepted view by the end of the first analogy, although his belief rating in his new theory had steadily risen throughout the rest of the sequence. When asked for his thoughts on the use of bridging analogies as a teaching and learning tool, it was evident that he was convinced the analogies had improved his understanding of the target situation. In the extract below he articulated why he believed this to be the case.

I: What would you make of that as a way of learning things, if you had this kind of series of analogies approach?

S49: It’s good.

I: Why?

S49: ’Cause it makes things clearer.

I: In what way?

S49: Well it proves how things are actually happening, and examples of it happening make you believe it more, …., yeah.

I: So is it because you can see it happening, is that what it is? Or is it something else?

S49: Yeah, well you can see it and break it down in to different parts and see each part happening, and then you can see why things are happening in the, …

I: So, is it because you’re seeing things as similarities, it’s allowing you to think it through kind of thing?

S49: Uh, huh.

I: Ok. Now can you see any problems with using that as a teaching method?

S49: It takes a long time.

I: Yeah, but you could use it with a class potentially all at once I suppose, I’m doing it individually. But yeah you’re right, it does take a long time. Do you think it’s worth the time?

S49: Yeah.

I: Why?

S49: ’Cause I understand momentum more now than I did before.

I: The elastic / inelastic collision stuff, do you understand that more?

S49: Yeah I think so.

His assertion that the analogies had ‘proved’ what was happening in the target situation is particularly noteworthy. It suggests that he had made strong connections between the behaviour and features of the different parts of the sequence and the target. The result of these connections being made was an increase in intelligibility which then caused an increase in his belief that his ideas were correct. He agreed with the suggestion that the process took quite a bit of time, but it is evident that he considered the process to be time well spent because of the way in which he perceived it to have improved his understanding of momentum and inelastic collisions. Student 23 could be considered to be towards the lower end of the ability spectrum as she got a Grade C in the final exam. By comparing her final theory with her original idea, it is evident that she had encountered conceptual change about why kinetic energy is lost in an inelastic collision. The following extract shows that she felt that she had also increased her level of understanding about momentum in particular as a result of the process that she had followed.

S23: I didn’t know an awful lot about momentum at the beginning.

I: Do you feel you understand it better now?

S23: Yeah.

I: Why?

S23: Because I have been able to think about and stuff, instead of looking at diagrams.

I: So, you think that by doing this process it has helped you think through the whole thing?

S23: Yeah.

It also demonstrates that she was able to articulate two reasons for her improved level of understanding. The first was that she had been given the opportunity to think carefully while working through the sequence. The second reason, in common with the comments of many other students, was that she had been able to physically work with the analogies rather than just looking at a set of pictures.

8.2.3 The analogies motivated interest

Three students felt that the analogies had been useful as a learning strategy primarily as a consequence of the way in which it motivated their interest. It was evident that this was true for student 50 when he was asked what he thought of the sequence as a way of learning.

S50: No, I think it's quite good 'cause you get shown why stuff happens. You get to kind of question why you think it is. You get more involved, you're not told a law that somebody else has discovered or proved. You're not told to expect to believe why they've proved it and just blindly follow it. 'Cause that's what we do in some of our equations, you know you assume the momentum's always conserved to blindly follow that rule.

I: Ok, so what's this sequence doing to you?

S50: It's kind of challenging what I believe in, is momentum always conserved?

I: And so is the challenge the good bit about it? Is it the fact that it's challenging the good bit?

S50: Uh, huh. It's kind of treating you more as somebody who will have different opinions and who's not some, not one of the younger pupils who, …

I: And is it making you think through why you think things?

S50: Uh huh. It's not like the kind of primary maths where you're kind of learning your times tables off by heart and stuff, its more, …

I: Plug in the thing and out comes the answer?

S50: Yeah. It's more interesting and stuff as well.

I: Why?

S50: Probably because you're getting your opinions and you're getting questions, you're not just copying and writing, told something and expected to believe it, it's kind of involved learning as well.

I: It's what sorry?

S50: Involved learning.

I: What do you mean by that, that's an interesting phrase?

S50: You're involved in the experiment.

I: Oh right.

S50: What's the phrase? Tell something and you will forget, show you something and you will remember, involve you in something and you'll understand.

Just prior to this extract he had stated that he would have liked to have been told whether or not he was right or wrong at each stage in the sequence. Despite this reservation, it was clear that from his perspective, the process engaged his interest for three reasons: it challenged his existing ideas; he was actively involved in the practical activities; and he realised that part of the learning benefit was that he had to think for himself rather than being told what the ‘correct’ answer was.

Student 36 stated that the sequence had been interesting which encouraged him to think in more depth and this had increased his understanding. In addition, he liked the use of “everyday stuff” which he thought was instrumental in helping him to see what happened clearly.

Student 64 had a very similar impression of the sequence that he tackled. He found it interesting and he felt that it had been helpful in enabling him to work out his answer in conjunction with the questions that he had been asked.

I: If I was to suggest this as a way of learning rather than just being told things like you quite often are, what would your thoughts on that be? Would that be a good thing or a bad thing?

S64: I think that would be a very good thing.

I: Why?

S64: It was a very interesting sequence which helped me to form a answer, an idea of it.

I: Do you think the sequence that has got you thinking, or is it the questions that have got you thinking?

S64: Both.

8.2.4 The analogies gave practical experience

The practical nature of the analogical sequences proved to be very popular amongst the students. In total, eighteen students (S1, 4, 5, 6, 7, 8, 10, 14, 16, 18, 19, 20, 21, 25, 31, 44, 47 and 48) rated the practical nature of the analogies as their primary reason for perceiving the analogies as a useful learning strategy. Their reasons for this were not restricted to the rather predictable idea that they could ‘play’ with the equipment rather than simply read about it. Many of their answers went much further than this and included deeper insights into the educational merits associated with hands-on experience, which included several of the other positive comments that other students gave as their primary reason for finding the analogies beneficial.

Seven of the eighteen students felt that the practical nature of the analogies was instrumental in influencing their thinking throughout the sequence. Students 6 and 18 said that the practical approach, along with the visual aspects of the process, had changed the way they thought. The bridging sequence was described by student 31 as enabling her to build up a better mental picture of what happened, which she expressed as being able to see what was going on 'in her head'. In a similar manner, student 7 made a clear connection between the practical 'hands-on' nature of the analogies and her thought processes when she was asked whether or not she thought that the use of analogies was a useful way of learning ideas.

I: I'll tell you in a minute how you got on. Did you think that would be a good way to learn other things in physics or in other subjects?

S7: Yeah.

I: Any particular reason why?

S7: Because you are getting to see it and try and get what you think so it helps you to think.

I: How does it help you to think?

S7: Because you start to think about it and then you can relate to it when you are doing questions and that.

As a result of engaging with the analogies, her loss theory had changed from feeling that momentum was lost to deciding by the end that momentum was transferred to the wall, although she was unclear how this had happened. Despite experiencing this relatively modest level conceptual change, her comments above also show that that she had found the analogies useful as they had helped her to make connections between the practical examples that she had carried out and the target scenario as she considered the answers to the questions that were asked throughout the interview. Student 20 also felt that the practical experience had resulted in him changing his reasoning. He described the analogies as helping him to think and understand what happened in the target situation.

S20: See when I first looked at the picture, I couldn't really picture it, because it wasn't moving and I could actually see it happen, I couldn't think about it. But see when you actually get to use a ball and hit it and hold your hand behind it, and you can feel it hitting, it makes you think it must, …

I: So it made you think along those lines?

S20: Yeah.

The feedback given by student 19 showed that he felt similarly about the use of the analogies. He said that the hands-on experience had been "more convincing" than simply looking at diagrams and trying to work out an answer from them alone.

Student 14 said that the practical experience helped him as he was often just told to believe things that he could not see or imagine. In contrast with this, he felt that the analogies had been useful because they had enabled him to visualise what happened which increased his belief in what he had previously been told, as he could relate to the examples much more easily.

I: What would you think if you used that as a way of learning more in class?

S14: I would prefer it.

I: You would quite like it as a method of learning?

S14: Yeah. We are just told these things that you can't see. You just get told and you just learn them because you are told to learn them. It helps you to believe that these things you are being told are true by showing you more examples and showing you real life situation.

I: Why does it help you believe?

S14: Just more examples you can relate to. I can relate the tuning fork to the hammer and the cars.

His final comment about relating to the examples suggests that he found it relatively easy to make connections between the analogies and the target scenario as he made rapid progress towards the accepted mechanism for the loss of kinetic energy in the inelastic collision.

Two of the eighteen students thought that the practical nature of the analogies meant that they were better than their usual technique of memorising information. Student 1 stated directly that she usually preferred memorising things. Despite having this preference, she had found the practical nature of the analogies helpful as they allowed her to physically work with the equipment. She consequently saw things happen which allowed her to apply the relevant physics to the situation.

S1: I think it would be good, because it gets you to like, I don't know for other people but I kind of like to memorise something then apply it, but I think, this was quite good as well, which is kind of different for me.

I: Why is it good would you say?

S1: You just feel kind of, its not really theoretical situations, it's kind of stuff that you can see happening but its also good to be able to apply it, …, things like the ball and sponge to a car crash.

Student 21 (a very able student who got a grade A in the final exam) gave a similar answer. She admitted that her usual exam technique involved a great deal of memorisation, but she felt that this technique had helped her to understand what was happening for herself. Until she was told whether or not she had been thinking along the accepted lines she was also quite reticent about claiming that the answer that she had come up with was accurate, although it evidently made sense to her.

I: So, what did you make as this of a way of learning? Did you like it or not like it? Say this was to be used as a method more often, albeit with more back up to say if you are right or wrong or whatever.

S21: Yeah, I think it would probably help if it was explained when you were doing it.

I: Why?

S21: I don't know. It just makes more sense when there is something you can actually picture or feel in that case. It makes more sense because I just memorise things and that is why I don't understand. I just memorise facts.

I: But here do you feel you understand what is going on better?

S21: If I actually knew what was going on, then yeah I would understand it better.

I: Well, I can tell you you're pretty well right in what you have come up with. You have actually come up with, more or less the right answer. So given that, are you saying that that helped you to think that through?

S21: Yeah.

Two of the eighteen students expressed the opinion that the opportunity to gain practical experience had increased their understanding of the target situation. One of these was student 16 who particularly liked the practical element of the sequence as he felt that it had helped him to improve his understanding.

I: So you're saying you think it is quite a good way of learning are you?

S16: Yeah.

I: Why? What's better about it?

S16: Than?

I: Than say a textbook or getting an explanation in class.

S16: You don't understand, like it is so much easier with real life examples that are sitting in front of you rather than reading over something that someone else has done in a textbook and you can visually grasp the concept of it if you are staring right at it.

I: So the fact that you're hands on is part of it.

S16: Yeah.

I: What do you think it does to your thinking, this method?

S16: I think that if you are doing experiments and hands on stuff you are likely to want to do it and you are likely to be more open minded about it and think more rather than if you are sitting there with a textbook.

I: Or someone telling you it?

S16: Yeah.

I: Do you believe it more because you have done it yourself rather than because someone has told you?

S16: Yeah, because it is hard to screw that up with yourself, you know exactly how you have done it.

The other student (S25) felt that the ability to see what happened in each of the analogical situations had not only helped him to more effectively understand what was happening in the target scenario, but in addition, he felt that it was beneficial in terms of improving the likelihood of him being able to remember what his answer and reasoning had been

Student 48 was convinced that the practical experience of working with the analogies had been instrumental in enabling her to make progress in refining her 'loss theory' while she worked thorough the immoveable object sequence.

I: Do you think it would be a good way of learning new ideas, of using a set of analogies like that?

S48: Probably it could but, …, like especially, like I said, the last two, …, because, …, you can instantly relate it to the car problem.

I: Why would that help you to learn?

S48: Because like, you can, …, like, you see it happening, so you can't really argue with it.

I: Because it is more visual than the way you would normally be taught things maybe, is that what you are saying?

S48: Yeah. It's like you kind of get to experience it more than someone just writing it up in the board.

For her, being able to see what happened in the analogies and then link it to the target situation was highly convincing and made her consider the use of analogies to be a useful learning and teaching tool

One member of the group of eighteen students gave several reasons why she thought that the analogies were a good way to learn. Student 47 started by saying that the practical element had been useful but then went on to enunciate most of the other positive reasons that were given by other students.

I: If I was to say to you that you were going to use this as a method of learning more often, let's say I could arrange for that to happen, do you think that would be a good thing or a bad thing?

S47: I think it'd be a good thing.

I: Why?

S47: 'Cause I liked the idea that you could physically see it moving through each thing, whereas like in the class you're just told 'This is what happens, just accept it', basically. I like that you could actually see it like travelling in different situations.

I: What difference has this made to your learning, what we've been talking about, momentum getting transferred to things and so on.

S47: I think it's improved it 'cause it's actually physically been in front of you, you've not just been told 'Right learn this, this is what happens', you can see it for yourself, and if you see things for yourself then you tend to accept it a bit more.

I: Mmm, hmm. Now the fact that I've not been telling you that you're right or wrong?

S47: Yeah that's annoying [laughs].

I: How has that changed the way that you've learned this?

S47: I don't, well it's made you think for yourself I suppose.

I: And is that a good thing or not?

S47: That's a good skill 'cause you'll need that later in life.

I: And do you think this sequence has made you do that?

S47: Yeah, I think it has made you think your way through something by looking at different examples to come to a final conclusion.

I: More than you'd have done normally in class, is that what you think?

S47: More than we've done in class, yeah.

I: So what would you do in class normally?

S47: Sit and get a question and answer it.

I: And try and answer it. But this has made you think more?

S47: This has made you think through it.

This demonstrates that although she initially stated that the practical aspects had been beneficial, she was able to clearly explain why this had been important to her. She was also able to enunciate a number of other ways in which the bridging analogies, in conjunction with the interview process, had improved her learning.

8.2.5 The analogies encouraged connections to be made

A total of six students, representing participants from both sequences, commenced their comments by stating that the analogies had helped them to learn as a result of the connections that they were able to make between the constituent parts of the sequence and the target scenario. In two cases, they voiced this idea by saying that they had noticed the similarities, as well as some key differences, between various elements of the sequence in comparison with the target situation and that this factor had been instrumental in them feeling that they had successful in learning by using the analogies. It has already been noted above that several other students also mentioned this positive facet of the bridging sequence as a subsequent part of their comments. The comments made by the six students who commenced with this category of observation will now be examined.

Student 9 had given an initial answer about the target situation that essentially concurred with the accepted scientific view of why kinetic energy was lost in an inelastic collision. His views did not really change throughout the sequence. In spite of this lack of change, he thought that the analogies were a good way to learn because he felt that the identification of similarities and differences between each successive situation had helped him to think about what was happening in the real situation.

Student 61 noticed the progression of ideas between each part of the sequence and found this to be a useful learning aid as it had enabled him to make connections between the different parts of the sequence in such a way that he felt that he had made progress.

I: If I was to say, or suggest, that we use that as a method of learning in teaching more often, what would your thoughts on that be? Do you think that would be a good thing or a bad thing?

S61: I think it would be, …, I think it would be quite helpful, yeah.

I: Why?

S61: Because, …, it introduces a new idea at every step, …, by like progressing it. Sort of feeling one thing at one point, and then seeing it the next and then hearing it more in the next step.

I: So, you thought there was a kind of progression of thinking?

S61: Yeah.

I: Do you think that it would be easier or better to be just told what the answer is, because I haven't told you the answer?

S61: No, I think it was better thinking through it yourself.

I: Why?

S61: Because it made you think about it more, things more clearly, …, and if you thought that there was something that you said was wrong then you could change it by saying something else.

I: And what about the fact that it takes quite a wee while, do you think that is a bad thing or a good thing or what, or a mixture maybe?

S61: No, I think it, it helps reinforce the idea.

Despite mentioning two of the common criticisms of the analogical sequence, he was still positively disposed towards the method. He felt that there was greater benefit in thinking through answers for himself, rather than simply being told what the 'correct' answer was. Rather than being an issue, he also thought that the time that it took to work through the sequence was beneficial as it had enabled him to have the time and the opportunity to make the connections that he had discovered.

Two students stated that the analogies had helped them to see links between what they had done at each stage of the sequence and what they thought must be occurring in the target scenario. Student 35's comments are shown below.

S35: Yeah it would probably be good. I felt I understood more the more I did it.

I: Is that because of the analogies?

S35: Yeah, because this symbolises something. It made me think 'well maybe the atoms move'.

I: So, did you think the analogies themselves made you think of things you hadn't thought of before?

S35: Yeah.

I: And although that took a long time, longer than getting it explained to you, would you say that it was useful?

S35: Yeah, it was very useful. If someone was up there telling me it just gets transferred and that's it, you don't really understand how it gets transferred.

I: Whereas with this you think you understand it better?

S35: Yeah.

In effect the analogies had helped him to gradually build up a mental schema regarding the target scenario by connecting the analogical situations to the real example in an iterative process. He felt that this had allowed his understanding to improve and develop throughout the process. Student 11 expressed a very similar opinion that the analogies had helped him to learn because he had been able to connect ideas together as the sequence progressed.

I: Do you think they should, this technique would be useful in physics lessons more often?

S11: Yeah. Because in intermediate two last year we were just told momentum was just momentum. We didn't get a definition, we were just given the equation and that was it. There wasn't really any explanation around it.

I: How does this differ?

S11: It is not an actual explanation but it is logical.

I: But I have not explained anything to you at any stage, deliberately.

S11: Yeah, but the thought process and what it is.

I: So what did it do for your thought process?

S11: It just made it link on and follow through from one to the other.

His comments suggest that he felt that his thought progress throughout the sequence had entailed linking different concepts and pieces of knowledge in a logical manner. In addition he concluded that he had come to his own conclusion (which concurred with the accepted view).

Student 30 was more explicit as he discussed the way in which his understanding had improved as a result of making links between each of the analogies and the target situation. This happened as a consequence of his ability to ascertain that the similarities between each stage in the sequence had helped him to refine his ideas as he thought through each situation.

I: Now what you have come up with is the accepted answer, without me telling you whether you were right or wrong. What did you make of that as a way of learning, because I haven't told you at any stage if you are right or wrong?

S30: It's quite good.

I: Why?

S30: Because It makes you think.

I: Go on.

S30: … Just, …, seeing it and explaining it, it just looks better, but eh, …, because this, the balloon and stuff, you can see it more in a scale, but you can't really see that one vibrating so if you go to a balloon, you can see it getting hit so you can see the vibration because they are all, basically the same sort of idea and you can transfer that idea across.

I: So, you're using one thing to get the idea and use it there?

S30: Yeah.

A few seconds later, when he was describing why he would like to use this technique as a way of learning more often, he re-stated the idea that he had made connections between the various parts of the sequence when he said the following.

S30: Because with the teacher, it is drawn on the board and showing you that this happens, and that, you can't, well you can see it, but you can’t really see it on a blackboard and you can’t really see it with the trolleys, but you can see it more as you go sort of, getting something that’s the same.

In a similar manner, student 57 said that the analogies had encouraged him to make connections between the different situations because the same rules applied in each case. As a consequence of this, he thought that it was a good way to learn.

I: Ok, so let’s say if you were asked to, well let’s say it as suggested that you were going to get taught using this technique more often, would that be a good thing or a bad thing in your opinion and why?

S57: Eh, …, I think I would be quite a good thing because you see the different situations, and that the same rules apply.

I: And has it made any difference to how you have thought about the original situation? Do you think it has changed your thinking in anyway?

S57: Yeah.

I: Why?

S57: Just because at first I couldn’t see how momentum, what else happened to momentum after the car, …

I: Whereas now, what you thinking?

S57: That it must be in the bricks, in the brick wall.

He attributed his conceptual change to the fact that he had made the connections between different parts of the sequence, as well as through a process of ruling out alternative possibilities.

8.3 Overview

It is clear from all of the data reported on above, that the vast majority of the cohort of students rated the effectiveness of the analogies highly, in terms of their ability to encourage learning to occur. It is apparent that many of them were able to articulate clear reasons for their opinions, which shows that they were not merely saying complementary things in order to not offend the researcher. This is further evidenced by the clear fact that they had been realistic and insightful in several of their assessments as they had identified some of the potential problems and hazards associated with their use in the classroom. This study has shown that the students found the 'guided analogical reasoning' process (Bryce & MacMillan, 2005) that they had engaged in through the use of the bridging analogies, along with the Socratic questioning utilised in the think-aloud interviews, to be an effective and powerful learning strategy. A number of different reasons, discussed above, were articulated by the students themselves, which back up this assertion. Future studies will be required to ascertain the effectiveness of analogical sequences (such as those used in this study) when used with groups of students in a setting more akin to a normal classroom situation. However, what has been established in this study with individual students is that there is evidence to suggest that bridging analogies are effective in encouraging conceptual change across a range of student ability levels, and in relation to the third research question on this study, the students themselves highly rate their effectiveness as a learning and teaching strategy.

Chapter 9

Discussion of findings

The preceding four chapters have outlined, in some detail, the findings from the check-up questionnaires and both sets of think-aloud interviews in which the two newly created bridging analogy sequences were used. It has been demonstrated, from the students' written and verbal statements, that they harbour a number of misconceptions about the concepts of momentum and kinetic energy, in that they often overlap with one another, or with other related concepts, in students' mental schemas. It has also been shown that many students have difficulty correctly explaining how these concepts operate and apply in real-life situations. In particular, the vector nature of momentum was often ignored when an object rebounded after a collision; the law of conservation of momentum was seen by many as being irrelevant, or in some cases invalid, when an object stopped after striking a large object; and some students found explaining why kinetic energy is lost in most collisions, while momentum is never lost, to be challenging. The use of the two bridging analogy sequences that were developed for use in this study, have been shown to be very effective in encouraging conceptual change in these areas of difficulty when they are used in the context of think-aloud interviews which utilise Socratic questioning techniques. The levels of conceptual change that the sixty students experienced are indicated by the entries in table 6.1 and the summary chart in figure 6.12 for the 'immoveable' object sequence in chapter 6, and in table 7.1 and the summary chart in figure 7.10 for the inelastic collision sequence in chapter 7. Finally, the findings have shown that the vast majority of the students who were surveyed perceived the use of bridging analogies in this context to be a useful learning tool for several reasons which have been analysed in the previous chapter.

In this chapter, the findings from the sixty interviews will be used to compare and contrast the resulting evidence for each of the conceptual change models that were outlined in the literature review in chapter 2 in order to answer the third and fourth research questions. In relation to the fifth research question, a synthesis of several of these theories will then be proposed and argued for, and some implications for the teaching and learning process from the findings of this study will then be discussed. Finally, some suggestions for related future research are outlined.

9.1 Types of conceptual change found in this study

The fourth research question sought to discover whether or not evidence could be found to justify the claims of the various conceptual change theories that were examined in the literature review in chapter 2. It also sought to examine whether or not there were any common factors existed between them that could be used to unify them to some extent. Table 9.1 below, shows the number of occurrences of each type of conceptual change found in the data from the sixty interviews in this study. It is evident from the figures that several kinds of conceptual change were much more commonly exhibited than others and that some types of conceptual change share common features. For example, Posner et al's (1982) 'Accommodation' theory (ConCh a) is very similar to both Vosniadou's (1994) concept of the revision of an individual's 'framework' theory (ConCh p), and to Tiberghien's (1994) most advanced level of 'modelling' (ConCh k) in which a student's mental model and their underlying theory is modified. These similarities are in terms of the suggested final outcome, although different terminology is used in each case and Posner et al.'s theory enunciates a more detailed process through which change is thought to occur. It can be seen from the entries in table 9.1 that the number of examples of each of these categories is identical to one another. It was also noted, while devising the conceptual change criteria that were used for coding the data (see appendix 7), that another set of 'lower order' conceptual change types [ConCh e), g), h), j) and o)] had definitions that exhibited a high degree of similarity to one another. The theoretical stances that correspond to these codes and which were perceived to be very similar were: 'Meaningful Learning' by Ausubel (2000); 'Complex system building' by diSessa (1993); 'Explanatory model construction' by Brown and Clement (1989); 'Modelling' by Tiberghien (1994) where the model rather than the underlying theory was revised; and 'Theory Restructuring' by Vosniadou (1994) where only the student's specific theory was modified. Each of these share the common idea that conceptual change (at that level) involves a student in revising their 'specific' theory about the target scenario by making comparisons with either 'surface' or 'deep' similarities from the situation that they were examining (which, in this study, was one of the analogies in the sequence). As a consequence of this overlap, these categories were often coded in tandem for the same piece of interview evidence in the data set. It can be seen from the entries in table 10.1 that this group of conceptual change categories were among the most commonly found in the interview data.

Type of conceptual change (ConCh)	Immoveable sequence	Inelastic sequence	Total
a) Accommodation (Posner et al.)	10	0	10
b) Assimilation: Derivative learning (Ausubel)	24	12	36
c) Assimilation: Correlative learning (Ausubel)	12	1	13
d) Assimilation: Superordinate learning (Ausubel)	0	0	0
e) Meaningful Learning (Ausubel)	45	26	71
f) Conceptual Ecology (di Sessa) (Reorganising only within current context)	0	0	0
g) Conceptual Ecology (di Sessa) (Complex system building)	45	27	72
h) Explanatory Model Construction (Brown & Clement)	45	26	71
i) Modelling (Tiberghien) (New events added to existing model)	0	0	0
j) Modelling (Tiberghien) (Model only modified - specific level only)	43	22	65
k) Modelling (Tiberghien)] (Model & underlying theory modified)	10	0	10
l) Modelling (Tiberghien) (Social / teachers rules only)	5	3	8
m) Modelling (Tiberghien) (Use of only existing concepts)	1	0	1
n) Theory Restructuring (Vosniadou) (Existing theory enriched)	3	0	3
o) Theory Restructuring (Vosniadou) (Revision of specific theory only)	43	22	65
p) Theory Restructuring (Vosniadou) (Revision of framework theory)	10	0	10
q) Category Re-assignment (Chi et al.) Category change from matter to process	0	0	0

r) (i) Connections: new thinking & analogy	54	35	89
r)(ii) Connections: new thinking & existing mental model	32	24	56
r)(iii) Connections: new thinking & prior experience	12	4	16
r)(iv) Connections: new thinking & prior learning and knowledge (Physics)	17	16	33
r)(v) Connections: new thinking & prior learning and knowledge (other subject)	0	0	0

Table 9.1: Number of coded instances of each type of conceptual change for the immoveable object sequence; the inelastic collision sequence; and in total.

The data in table 9.1 clearly demonstrates that the most commonly found types of conceptual change were in the 'making connections' (ConCh r)) category. Two main varieties of connection were found to have occurred more often in students' minds than the other possibilities. The main connections that were observed occurring were between a student's new thinking about the target scenario and the properties of a specific analogy or its behaviour. However there were also many examples where a student connected their new thinking about the target with their existing mental schema in such a way that conceptual changes occurred. Throughout the sixty interviews, connections of this latter type were found to have occurred between the student's new thinking about the target scenario and various facets of students' existing mental schemas, including the following:

- previous teaching
- previous everyday experiences outwith the classroom
- a previous thought or statement from earlier in the interview

Other types of connection that were commonly demonstrated by students included:

- a realisation that their new theory applied to the analogy *and* to the target scenario
- connecting the common key attributes of one analogy compared with another, and then noticing a link between these thoughts and a way of explaining the behaviour of the target
- beginning to understand how the relationship between different contributory factors in a physical quantity affect one another (e.g. the relationship between the mass and velocity of an object in relation to its momentum)

In addition to analysing the number of times that particular categories of conceptual change were identified in the interview data, an analysis of the triggering factors was also carried out. Table 9.2 below shows the number of occurrences of each type of change trigger (ChTrig) that was identified.

Conceptual change triggers (ChTrig)	Immoveable sequence	Inelastic sequence	Total
a) Visual clues	57	24	81
b) Faulty logic recognition	14	25	39
c) Mis-fitting experience (cognitive conflict)	9	6	15
d) Making connections (with stated prior mental model / experience / learning	75	47	122
e) Spontaneous generation of idea	14	6	20
f) Transfer of Physics application to situation	10	10	20
g) Connection through experience with analogy	73	45	118
h) Idea making sense	5	2	7
i) Guessing	1	0	1
j) No sensible alternative	5	2	7
k) Logical thought process	3	2	5
l) Uses of numerical values	1	0	1
m) Awareness of gaps in knowledge	1	0	1
n) Realisation of relevance of an idea	0	1	1
o) Memory triggered	0	1	1
p) Seeing bigger view of situation	0	1	1

Table 9.2: Number of coded instances of each type of conceptual change trigger for the immoveable object sequence; the inelastic collision sequence; and in total.

In particular, it is noticeable that a student's ability to make connections between a particular analogy and their existing theoretical stance was crucial to the initiation of the conceptual change process. It was found that these connections often came about as a direct consequence of the visual evidence that the practical work with the analogical situations gave the students. Similarly, making connections between their current thinking and previous experiences, learning, or mental models was found to be a strong contributory factor in the change process.

It is evident that the number of instances of several types of change trigger is much higher than the number of actual conceptual changes that were recorded in table 9.1. There were two factors that influenced this. The first factor was that several students exhibited the same conceptual triggering factor on more than one occasion in their comments concerning a single analogy in the sequence. This meant that the number of change triggers that were identified for a particular individual across their entire interview could extend into double figures. The second contributory factor was that change triggers were found to occur in two different sets of circumstances. The most obvious was where conceptual change of one of the identified categories had been found. However change triggers were also identified in the transcripts when a student's thinking had changed in some noticeable way, such that they had clearly made a break-through, but the change did not correspond with any of the conceptual change categories because their theoretical stance was unaltered. For example, a student was deemed to have made progress when their belief rating in their theory increased, or when their remarks made it obvious that they had become more convinced about a particular idea or thought that they had previously discussed.

9.2 The principle of 'connectivity'

The results in tables 9.1 and 9.2 strongly suggest that making connections is a key factor in not only showing that conceptual change had *occurred*, but also in *causing* it to happen as when students perceived that there was a potential link, they then made an effort to actually make those links. An overall conclusion is that conceptual change is essentially a process which is caused and demonstrated by the connecting of various concepts in the mind of the learner. This can be argued to be a unifying principle for most, if not all, of the conceptual change theories that have been analysed in this study (see later).

The findings presented in chapters 6 and 7, along with the summative findings in tables 9.1 and 9.2, provide a body of empirical evidence from this study which suggests that the making of connections between an individual's current understanding and new pieces of knowledge or ideas is a core activity in the process of conceptual change. It has been argued throughout chapters 6 and 7, from the qualitative data presented, that conceptual change occurs when an individual is able to connect a new concept, observation or fact in some way with his or her existing mental model, prior teaching or experiences. This connection process results in their existing explanation for a given situation (or in deeper conceptual change, any generally similar situation) being altered by the newly formed links with the freshly acquired data, preferably in a way that it aligns more accurately with the accepted explanation.

Figure 9.1 below represents the process of connectivity schematically. The student initially holds to several ideas, concepts or theories. He or she is then introduced to another situation which is carefully selected by the teacher for its useful explanatory ideas or features. If the student perceives the new ideas to exhibit sufficient similarity or comparability to the student's existing ideas, he/she makes connections between the two of them which results in the formulation of a new concept that incorporates features from both of the contributory zones.

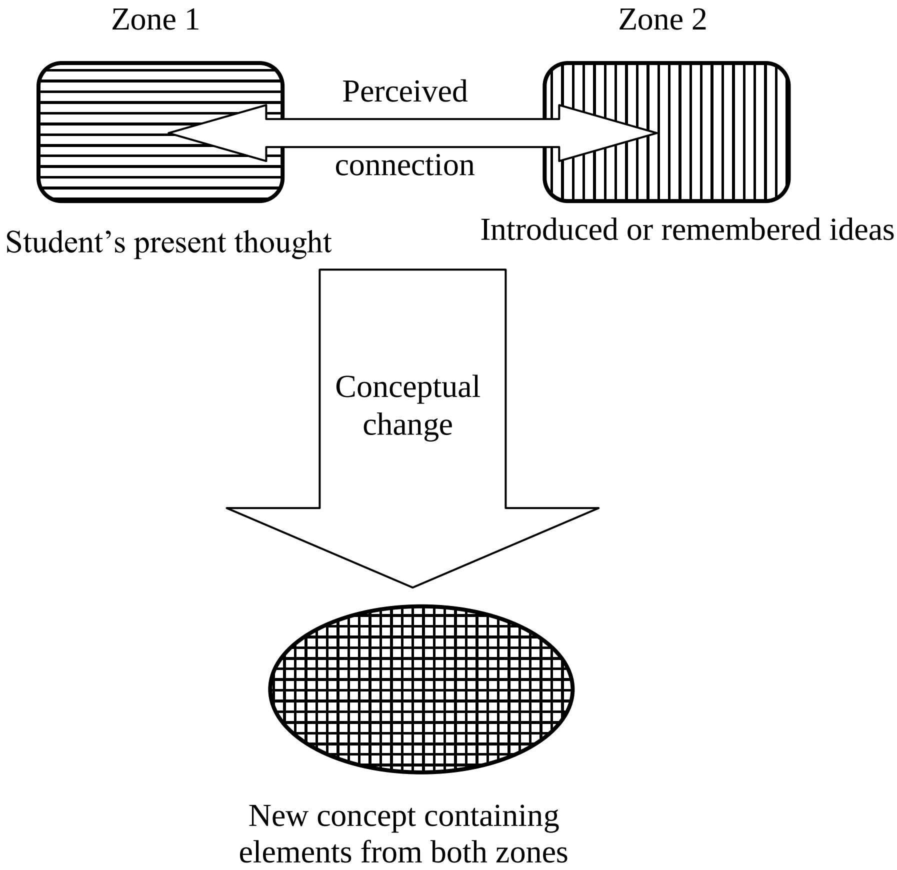

Figure 9.1: Schematic diagram of the connectivity process

In order for this connecting process to happen successfully, the new or recollected idea needs to be perceived by the learner as being sufficiently 'cognitively proximal' to the situation that he/she is trying to explain to enable worthwhile and comprehensible comparisons to be made. In other words, the two (sometimes competing) sets of knowledge need to have sufficient 'cognitive proximity' to one another. In this study, the comparisons carried out by the students were found to consist of an assessment of the relative intelligibility and then believability of the existing explanation in comparison with the new theory which was devised as a consequence of the newly made connections. If the new theory, or concept, is the more intelligible and believable one, it was found to often replace the existing version as it became more fruitful as an explanatory stance. These findings therefore concur with the widely agreed upon conditions for conceptual change suggested by

Posner et al. (1982), but the findings from this study have enabled the reasons for each stage being triggered and decided upon to be shown.

The data from this research has also highlighted why some students did not experience conceptual change, and this too can be described in terms of connectivity. Throughout chapters 6 and 7, it was argued that the reason for some students making negative progress or no progress was their inability to make strong enough connections between their existing ideas or theory and the new experience or evidence that they were getting from their interaction with an analogy. The lack of connection was found to result in cognitive conflict or confusion in several students' thinking processes. The consequence of this was that the student did not feel any need to alter their existing mental model as they considered that the newly presented evidence did not improve their ability to explain the target situation because they could not see its significance in relation to their existing, less scientifically accurate ideas. The students who made negative progress after considering a particular analogy were found to revert back to a previous explanation. It has been argued previously that this occurred as a result of the cognitive conflict that the lack of connection caused. Consequently, they withdrew to a previous mental stance since it had seemed to work as a connecting or explanatory tool for them in the past.

The concepts which underpin connectivity have links with the findings and suggestions from research on two other related topics.

9.2.1 Research on the differences between experts and novices

Bransford et al. (2000) discuss findings from extensive research on learning by the National Research Council in the United States. They suggest that there are several key differences between the way that experts and novices organise knowledge, which include the following:

1. Experts notice features and meaningful patterns of information that are not noticed by novices;

2. Experts have acquired a significant amount of content knowledge that is organised in ways that reflect deep understanding of their subject matter;

3. Experts' knowledge cannot be reduced to sets of isolated facts or propositions but their knowledge shows contexts of applicability.

Each of these findings suggest that the main difference between experts and novices, in a particular subject area, is the level of connectedness that their knowledge and concepts exhibit. The meaningful patterns in experts' mental schemas suggest that they have connected various knowledge elements or concepts together on the basis of perceived similarity so that they can be easily recalled, utilised, or added to when other similar ideas are found. Likewise, the organisation of an expert's knowledge, in ways that demonstrate a deep understanding of their subject matter, and their use of contexts of applicability, could both be argued to demonstrate the use of the connections that they have made between different facets of their subject. Analogies can therefore be argued to play a part in assisting novices to alter their mental structures to become more like those of an expert. The use of analogies can help to achieve this in two ways. Firstly, they emphasise similarities between different situations so that connections can be forged more easily; and secondly they are helpful for introducing or highlighting different contexts to which ideas can be transferred and/or applied.

9.2.2 The principle of connectivity and 'connectionism'

Connectivity, as used here in relation to the findings in this study, has several similarities to the concept of 'connectionism' that has been used to examine learning in cognitive psychology over a number of years. Connectionism is an idea developed from cognitive science which is a computational model of learning. Through suitable programming, computers are able to mimic certain traits of human learning by building up an inter-related 'network' of locations in the computer's memory that become activated when information is fed into the system. A connectionist network therefore consists of a number of elementary, linked neuron-like units, called ‘nodes’, which become connected to other nodes with variable connection strengths, so that certain outputs are triggered.

The connections between the various nodes are considered to represent the inter-connectivity between neurons in the neural network in the brain and can be used to model some cognitive behaviour such as learning. Patterns of activation (of different strengths) in specific sets of nodes link various inputs with specific outputs from the system. This enables the system to mimic responses that appear to follow an “*if-then*” rule. When the desired output for a given set of inputs occurs, the computer is considered to have ‘learned’.

Eysenck and Keane (2005) acknowledge that there are several assumptions and limitations inherent within connectionism, some of which are contested by different researchers. They suggest that the perceived correspondence between locations in a computer’s memory and human neurons is controversial as there are twelve different types of neuron in the human brain, and it is unclear which type, or types, most resemble the nodes in connectionism. Connectionism discounts the notion that human cognition involves the use of explicit rules. Instead, it presupposes that people respond to their environment in ‘rule-like’ ways in the absence of any explicit rules. Many connectionist models assume that representations of individual items of knowledge are distributed throughout the network so that the required input patterns of node activation can be produced and recognised by the network. However, Eysenck and Keane (2005) state that it is not necessary for this to be the case. They suggest (based on the work by Page, 2000 and Bowers, 2002) that a distributed representation cannot explain why individuals are capable of learning two things (like different words) at the same time, and they cite several models in which knowledge is represented locally and contend that these predict human learning more effectively than distributed models. The main limitation of connectionist network models is that they cannot adequately represent the effects of motivational and emotional factors on the learning process.

The principle of connectivity, while bearing similarity to connectionism is not the same. Connectionism is applied to the study of cognition, while connectivity is being discussed in this thesis as an idea about conceptual change. Connectivity also avoids the inevitable complications that are inherent in comparing a computer system with the human brain. The idea of connectivity has a greater degree of direct evidence since it has been elaborated from students' think-aloud experiences. While the effects of motivation and emotion on the process of conceptual change have not been directly examined in this research, their role is not discounted by connectivity. It could be plausibly suggested that more motivated students would be more likely to actively seek out potential connections and work harder to alter their existing concepts and theories in order to integrate new ideas with their existing ones. Similarly, if a student feels more interested in a task, they would arguably be more likely to seek out and make good use of newly observed connections.

9.3 Connectivity and the conceptual change theories

As discussed in the findings from the think-aloud interviews in chapters 6 and 7, clear evidence of conceptual change was found, whereby students displaced their pre-existing ideas about the target situation with another concept. The conceptual changes that were identified often demonstrated features of one or more of the conceptual change theories that were discussed in the literature review earlier in this thesis. The manner in which the different theoretical stances were exemplified in the data will now be reviewed before presenting arguments which the ways in which each of the theories can be explained in terms of connectivity which is being proposed as an over-arching idea of conceptual change.

9.3.1 'Accommodation'

Although table 9.1 shows that only ten students were judged to have demonstrated that they had fully undergone 'accommodation' as described by Posner et al. (1982), several examples were analysed in chapters 6 and 7 where conceptual change had clearly occurred through a process which was consistent with the one espoused by Posner et al. (1982) in their 'accommodation' theory. In these instances, it was argued that the change had occurred because the new concept or idea was more 'intelligible' than the pre-existing one in the mind of the student. It was also evident in several cases that the new concept had consequently become more 'believable' than the previous idea and then it became 'fruitful', in the sense that the student was able use their new idea to explain what they thought happened in the target scenario.

This conceptual change process has been shown in previous research (Posner et al., 1982; Treagust, Harrison & Venville, 1996; Bryce & MacMillan, 2005). It was noted in the literature review that Clement (2008) criticised the accommodation theory by stating that it discussed the conditions and effects of change rather than the mechanism by which a student moves from one stage to the next. What has become apparent in the transcript data from the present study is the 'micro-process' by which students appeared to make judgements that resulted in them making progress through the three stages. In particular, the various factors that trigger the change from one stage to another have become clearer. These factors included the interpretation of visual clues, faulty logic recognition by the student and the need to resolve cognitive conflict. But the most common trigger has been shown to be making connections with the analogy, prior experiences, learning, or their existing mental model. These same factors, that triggered the increasing level of intelligibility of one idea over another, also caused many students to increase their level of believability in their new idea, and they played a significant role in the new theory becoming a useful explanatory tool (i.e. in becoming 'fruitful').

The shift from 'intelligibility', to 'believability', and then to 'fruitfulness', was apparent in several students' thinking. Despite this, it could not be claimed that following this route resulted in an unequivocal change in a student's 'generalised' theory which Posner et al. had suggested should happen. More often the conceptual changes were coded as occurring at the level of the student's 'specific' theory since the individual gave little or no indication that they were thinking in terms of anything other than the target situation. Although this could be interpreted as merely demonstrating 'assimilation' in Posner et al.'s theory, it could be argued that 'accommodation' had occurred since the students clearly displayed the suggested conditions and they moved through the various stages. In addition, many of these students encountered a paradigm shift in that they changed their initial views of the target situation.

In the case of the 'immoveable' object analogy sequence, most of the students changed their views that a large building could not be perceived to have moved as a consequence of an object colliding with it, to a stance in which they could plausibly explain that the building had moved, albeit at a microscopic level. The decision to code most of the demonstrable theoretical changes as being at the level of 'specific', rather than 'generalised', could therefore be seen as having been rather cautious, based on the fact that it could not necessarily be inferred from a discussion about one particular situation that the student had changed their entire world view of 'how things are'. However, it may have been the case that they had in fact changed their 'generalised' theory without actually stating their views in such a way that this could be unequivocally judged to have occurred. As was discussed in chapter 6, some students were coded as having changed their ‘generalised’ theory by the end of the ‘immoveable’ object sequence, based on their answers to the extension scenario. In these cases, it was evident that Posner et al.’s criteria for ‘accommodation’ had been fulfilled.

In the inelastic analogy sequence, none of the students were judged to have altered their ‘generalised’ theory since their statements did not clearly demonstrate that they had changed their world view. This could also be seen as being an over-cautious view based on the fact that they did not give direct verbal evidence that their world view had changed. Nonetheless, their thinking could be judged to have involved a paradigm shift in the sense that they had altered their perception of the hard carts to include the concept that they vibrated upon impact, which resulted in the transformation of some kinetic energy into heat and/or sound energy.

As a result of the findings from this study, it can be argued from the perspective of connectivity that the connections that the students made while thinking through the sequences were not only the *triggers* that caused the shift from one stage of the accommodation process to the next. It is further posited that these connections made by the students at each stage were also actual *evidence* that conceptual change had occurred in line with Posner et al.’s theoretical stance. The analogies caused the students to become unsettled about their existing explanation as a consequence of the cognitive conflict that they encouraged to occur. Consequently, the students attempted to devise an alternative explanation which provided a better ‘fit’ for the available evidence and that would enable them to synthesise the different experiences that they had encountered. Any new explanation was perceived as more ‘intelligible’ than the pre-existing one if it made more sense because it was *connected* with their prior experience, learning or the way in which they could see things happen in the analogical situation. Thereafter, this increasing sense of ‘intelligibility’ caused an increasing level of ‘believability’ when the student felt that their new explanation had *stronger* and *more obvious links* than the explanation that it replaced, in terms of how they thought the target situation actually worked. Finally, the connections between the different facets of their experience, learning and thinking helped the students to feel that they were able to describe what they thought happened in the target situation more accurately, and often more succinctly. One example of this was student 58. Her thought process during the 'immoveable' object sequence was analysed in chapter 6. The following (previously analysed) extract from analogy two demonstrates the points made above. It can be seen from this interaction that her new theory had become intelligible and therefore more believable because of the strong connections that she had made between the analogy and the target situation. This in turn resulted in her theory becoming fruitful as she was able to use it to explain what she thought was happening in the target scenario.

I: And how would you explain that to somebody, because earlier you said that 'no way'?

S58: Eh, …, just because you can't see a physical movement doesn't mean it's not happening and to move the wall as fast as the car you would have to have a lot more momentum, and probably some wheels involved.

I: Now what has convinced you of that? Because you sound reasonably convinced?

S58: I think from actually doing the experiment with the hand and the ball.

I: And why did that help?

S58: Because you can feel, you can imagine that that [the hand] is the wall and that [the ball-bearing] is the car and you can feel, …, that even though there is still some left in the ball, you can feel that it is in your hand that you are getting something.

I: And that is making you think that the wall is getting something?

S58: Yeah.

I: How convinced are you of the story about the car giving momentum to the wall is right?

S58: A four and a half.

I: And how convinced are you that the total before and after here, is the same - which is what you seem to be saying?

S58: A four and a half maybe, a four, four and a half.

In a similar manner, student 48 also exhibited (in another previously analysed extract) the process of making connections with prior experiences as the mechanism by which she decided that her new theory was more intelligible, believable and fruitful than the one that it superseded.

I: Are you envisaging, …, you mentioned earlier something about a vibration, is that what you think?

S48: Just like, …, probably if you put a glass of water on the other side, and the water in it was still. Then if like, part of the glass was touching it, then if the water moved then it would kind of show, that there was like, …

I: Do you think that would happen if you did put a glass to the other side?

S48: Yeah.

I: How sure are you?

S48: Five.

I: You seem reasonably convinced? Why are you convinced, because before you didn't seem that sure?

S48: You see it in the movies as well, if something happens, it causes the whole house to shake.

It was also demonstrated in the findings that many students failed to experience conceptual change at various points in their consideration of the analogical sequence because they failed to see any connections, or sufficiently robust connections, between the analogy and the target situation. When this occurred, the student was often found to experience increased levels of cognitive conflict or confusion that either made them retreat back to a previous explanation or to engage in a 'twin-track' thinking process, whereby they attempted to resolve their difficulties by comparing and contrasting one possible explanation with another in order to decide which one had stronger links with their current thinking and hence was more intelligible and believable to them.

The assertion by Spiro et al. (1989), that use of a multiple component bridging analogy sequence helps students to make valid connections while at the same time filtering out unhelpful or inaccurate connections between individual analogies and the target scenario, was shown to be true for many students, as demonstrated in the interview data from this study. As was shown in chapters 6 and 7, many of the students eventually noticed the principal connecting idea that ran through each of the analogies in the sequence that they had been considering, while being able to ignore the irrelevant details or inaccuracies in each case. It can be seen from the data that the use of the analogical sequence in conjunction with relevant, judicious questioning, had encouraged this connecting process to occur.

9.3.2 Theory Transfer or Restructuring

Throughout the findings chapters, examples were discussed where students displayed traits which were consistent with Vosniadou's view of conceptual change. As outlined in the literature review chapter, Vosniadou (1994) described her idea of 'restructuring' or 'theory transfer' as an attempt to explain the nature, rather than the process, of conceptual change. However, the interview data from the present study provides empirical evidence of this model of conceptual change occurring, but in addition enables the process by which it happened to be seen.

As was the case with Posner et al.'s accommodation theory, Vosniadou's conceptual change stance can be explained in terms of the connections that students made between various pieces of knowledge, as suggested in 'connectivity'. The students were seen to make connections between their existing ideas and the thoughts or experiences that they had while working with the analogies. Vosniadou described the possibility of conceptual changes occurring at two levels: one being changes to an individual's 'specific' theory; while the other involves changes to their more deep-seated 'framework' theory. The interview data for both analogical sequences contained several examples of students altering their 'specific' theories about the target situation. This was coded as evidence of conceptual change of type (o), having occurred from the 'conceptual change criteria' list (see appendix 7). Many students were found to have adjusted their theoretical stance in this way at several points during the sequence, but the starting points were different. In some cases, the observed behaviour of the analogy encouraged the student to adjust their theory in an attempt to more accurately map what they had seen in the analogical situation with their views about the target scenario. At other times the process commenced with a student attempting to account for the observed behaviour of the analogy using their existing model. When they recognised the inability of their existing theory to adequately or accurately explain the observed behaviour, they adjusted their mental model to make it a better ‘fit’ with the observations. In either case, the learner was seen to engage in generative mental activity that consisted of recognising or making connections which resulted in a series of alterations to the student’s specific theory in order to reconcile areas of cognitive conflict. An individual’s final theoretical stance was found to have evolved via several intermediate versions, which correlate with Vosniadou’s idea of ‘synthetic’ models, and culminated in a view that was often more scientific than their initial idea.

As discussed in chapter 6, ten students answered the extension question of the ‘immoveable’ object sequence in such a way that they could be perceived as having changed what was coded as their ‘generalised’ theory, which is directly comparable with Vosniadou’s concept of a ‘framework’ theory. Vosniadou uses the term ‘revision’, rather than ‘enrichment’, to describe this deeper level of conceptual change.

This type of transformation can also be explained in relation to the connectivity principle. It was argued in chapter 6 that these changes occurred as a result of some of the students connecting the principles that they had been contemplating in the specific target scenario with the way in which they perceive all systems to operate. This enabled them to adopt a universal viewpoint of conservation, whereby momentum is considered to be transferred to increasingly massive objects, ultimately including the Earth. An explicit statement of this concept, for the first time, was considered to demonstrate that an individual had changed their ‘generalised’ or ‘framework’ theory. This newly acquired stance suggests that the required shift in thinking was sufficient to necessitate the ‘revision’ of the student’s underlying mental schema about the transfer of momentum into any ‘immoveable’ object, no matter how large it was. Their ‘framework’ theory was no longer simply being confirmed by their experience of the analogies. Instead, the changes to their theory about the target scenario, which were triggered by their interaction with the analogies, had encouraged them to adjust their ‘generalised’ theory, such that it became aligned with their new thinking. By linking their ideas about the target scenario with their view of how all things behave, they became content to suggest that the Earth (which may be perceived as the ultimate 'immoveable' object from the student's frame of reference) could be considered to have gained momentum in the opposite direction from them when they pushed their foot against the ground, despite any changes to its motion being immeasurably small.

9.3.3 Modelling

Tiberghien (1994) suggested that conceptual change involves the construction or revision of a learner's mental model, but that the greatest conceptual change occurs when a person changes their thinking at the level of their theories about the world around them to become more in line with the 'scientific model' which she describes as a set of relationships between physical quantities that is used to enable predictions and interpretations to be constructed, often through the use of mathematical formulae. She therefore differentiates between a person's mental model and their theories, as she considers an individual's mental model to be an intermediary between their deep-seated theoretical ideas and the real world observations. According to her stance, a 'theory' is more abstract or general and is concerned with issues of causality, principles and laws about a situation. Tiberghien's concept of mental models and theories can therefore be seen to share much in common with the mental structures which are discussed and are thought to be altered in several of the other conceptual change stances, including the 'abstract transfer' or 'explanatory model construction' concept proposed by Brown and Clement (1989) and Vosniadou's 'Theory Transfer' or 'Restructuring'.

In this research study, many students were found to refine their mental models about the target scenario, as they encountered successive analogies. Those who made the quickest progress altered their mental model in ways that suggested they utilised a logical thought process and assessed the intelligibility of any new idea that occurred to them as a result of their interaction with a particular analogy. Changes to their theoretical stance were therefore found to have been influenced by both their existing theory and the visual evidence from each analogical situation. When the behaviour of the analogy was not concordant with their theoretical stance about the target situation, the students attempted to resolve their cognitive conflict by seeking ways to improve the connection between the observed behaviour and their mental model in order to improve the intelligibility of the observed behaviour. This sometimes triggered changes to their explanatory model which were subsequently related to the target situation by many students.

As discussed previously, ten students were judged to have undergone the deepest level of conceptual change in Tiberghien's theory. Their answer to the extension question for the 'immoveable' object sequence showed that they had altered both their mental model (which corresponds to their 'specific' theory about only the target scenario) and their underlying theory (which is essentially the same as their 'generalised' theory about the way in which all similar things work and can be explained).

Tiberghien's modelling theory can also be explained in terms of connectivity. As previously discussed in the literature review, Tiberghien (1994) stated that "learning difficulties appear as a 'gap' between the meaning constructed by the learner and certain aspects of physics knowledge, particularly concerning physical quantities, their relationships and their meaning in the framework of physics" (p. 71). From the perspective of connectivity, this 'gap' can be argued to arise as a result of the 'cognitive separation' between the behaviour of the analogy and the predictions arising from the student's current theory. Consequently, the learner tries to reduce the separation by seeking a way to improve the cognitive connection between the observed behaviour and their current explanatory theory.

There were however examples in the interview data which demonstrated that some students produced and refined their explanatory models in a more ad hoc manner, as suggested by Tiberghien (1994). These students were often the ones who were prone to exhibiting 'twin-tracking' thought processes, where they were comparing two (or more) different ideas and switched between them several times as they progressed through the analogical sequence. Tiberghien argued that the ad hoc progress happens because students very closely associate their model with their perception of specific objects and events, while the scientist relates their model more to the underlying physical quantities. Students who were more inclined to switch their theories between different alternatives did appear to be more directly influenced by the surface features of an analogy, rather than thinking in terms of how the analogy was related to the underlying physics. As Tiberghien suggested, those who developed a theory that was more in line with the 'accepted' scientific stance were found to be more proficient at filtering out unimportant details (based on the degree of similarity or difference with the previous scenario or the target itself) in order to refine their explanatory theory about momentum or kinetic energy, so that it more accurately predicted and explained the behaviour of *all* of the analogies *and* the target scenario. This can therefore be argued to be fundamentally a connecting process.

Each of Tiberghien's four types of learning can be related to connectivity. In the use of social rules (which was coded as Con Ch (l)), the student can be perceived to be trying to make connections between what they have observed with the rules that they have previously been taught, without properly comprehending what is happening or being able to predict outcomes. This type of learning was found and commented on in chapters 6 and 7.

Tiberghien (1994) calls the second type of learning an 'extension of the field of applicability' (which was coded as Con Ch (i) when it occurred in the data). In these situations, the student simply added a newly observed event or phenomena to their existing model without altering it or their more deep-seated theory. Examples of this were observed in the interview data from this study. This can also be related to 'connectivity' as the addition of a new piece of knowledge or observation to the existing model or theory was only found to occur in situations where the student was able to perceive that the two were connected in some way.

In the case of 'semantic' conceptual change (ConCh (j)), only the mental model gets modified. This means that a student's interpretation of objects and events and the associated metal model can be significantly altered, but the underlying theoretical assumptions are unaffected. This process can be explained through the formation of new connections between the model and real world events as similarities are noticed for the first time. These similarities enable the learner to re-interpret what they thought happened in a given situation or in the target scenario. Failure, by the student, to identify these connections was found to be a major factor in situations where a student failed to make conceptual progress.

Finally, Tiberghien suggests that the highest level of change, which she calls, 'theoretical' conceptual change, occurs when a student alters their model and underpinning theory – their view of the causality of a situation is restructured. This, she argues, has gone beyond looking purely at objects and events, to consider the actual physical quantities that are inherent within the situation. As a consequence of this, their personal theory changes to become better aligned with the accepted scientific theory. As with the other types of learning that Tiberghien proposed, this kind of conceptual change can be demonstrated and explained from the perspective of connectivity. The model and theory are modified when a student perceives new explanatory links between them and the behaviour of the relevant physical quantities in any situation. For example, in this study, two specific types of collisions were investigated: those involving 'immoveable' objects, and collisions in which kinetic energy was not conserved. The students' views on the transfer of momentum or the transformation of kinetic energy, in these types of collision, were found to have been altered as they made connections between the behaviour of each analogy and their existing explanation for the behaviour of the target scenario. In order to demonstrate that they had undergone 'theoretical' conceptual change, they had to be capable of making the connection not only between the analogies and the target situation, but also connect their new theoretical stance with any other generalised situation. As discussed above, ten students were considered to have demonstrated this process when they were able to correctly answer the extension question in the 'immoveable' object interview.

9.3.4 'Category re-assignment'

Chi, et al. (1994) suggested that all entities belong to one of three ontological categories: matter, process and mental states. According to Chi et al., conceptual change is a process whereby a particular idea or concept is transferred from one ontologically distinct category to another as a result of evidence and teaching that is presented to the learner. This was one of the few categories of conceptual change that was not found in the interview data at all. There was no clear evidence of any students changing the ontological category for either momentum or kinetic energy in their thinking, although it could be seen that some students did consider both of these concepts to belong to the '*matter*' category, rather than the '*process*' category as Chi et al. (1994) would argue. As previously discussed in the literature review, this lack of evidence calls the validity of their theory into question as it is clear from the data in this study that many of the students experienced conceptual change which was able to be explained and categorised using the ideas espoused by the other theoretical stances, but not this one.

It is however possible to relate this theory to the connectivity idea which is being used in this thesis. In order for a student to decide that an entity is in the wrong category, they would need to decide that its properties did not fit with the properties or behaviour of other entities in that category. This lack of connection may then result in sufficient cognitive conflict to encourage them to consider moving the entity to one of Chi et al.'s other categories. The ontological category to which they would re-assign the entity could be argued to be decided on the basis of perceived connections with other entities in that category.

9.3.5 'Abstract transfer' or 'explanatory model construction'

As was noted previously, Clement (2008) defines a model as "a mental representation of a system that focuses the user on certain features in the system and can predict or account for its structure or behaviour" (p. 418). Its usefulness in knowledge representation therefore comes from its ability to represent useful interrelationships in a system rather than just being a collection of isolated facts.

This idea is similar to the concept of 'mental models' or 'theories' espoused by several of the conceptual change theories, which have been discussed. It also links closely with the idea of connectivity as a conceptual change principle which is the core proposition used in this thesis.

The central idea in this conceptual change theory, which was first suggested by Brown and Clement (1989), is 'model evolution'. However, rather than simply *presenting* information using multiple teaching strategies recommended by Brown and Clement (1989) (such as seeking information, the use of discrepant events, analogies and presenting explanatory models to learners), this study sought to enable students to carry out these tasks *for themselves* by simply guiding them as they interacted with the sequence of analogies. For many of the students in this study, the bridging analogy sequences proved to be an effective '*dissonance strategy*' (Clement, 2008) because they helped each student to discover conflicts in their current model and preconceptions.

Clement (2008) suggested that having helped the students to discover these conflicts, the repeated use of various teaching methods would enable a student's level of understanding to be ascertained and then moved gradually towards the accepted scientific model. In particular, he considered the use of analogies to be helpful as they assist students to refine their cognitive model by enriching certain features of the model or help them to build a more abstract relational structure to their evolving model. As with several of the other conceptual change theories analysed in this thesis, the mechanism by which this would happen was not specified in any detail. Connectivity does however allow this to be explained. In the research reported in this thesis, the use of a series of linked bridging analogies has been shown to be effective in altering students' cognitive models as they self-selected the common features of each scenario. Many students were found to connect these similarities with the behaviour of the target scenario in such a way that their understanding of the situation and the underlying physics was adapted. In some cases, this adaptation appeared to have been extended to all collisions, including those which involved the Earth.

9.3.6 'Assimilation'

As suggested by Ausubel (2000), it was clear from the interview data in this study that the students engaged in an active thinking and reasoning process in order to learn. As discussed in the literature review, his term for conceptual change is 'meaningful learning' (which was coded as Con Ch (e) when it was found in the transcript data). In addition, he described various types of learning that involved lesser degrees of change to an individual's mental schema. He outlined two types of 'subordinate' learning; 'derivative' learning (coded as Con Ch (b)) and 'correlative' learning (Con Ch (c)), as well as 'superordinate' learning (ConCh (d)) and 'combinatorial' learning. Each of Ausubel's ideas can be explained from the perspective of the connectivity principle of conceptual change which is being espoused in this thesis.

Both types of 'subordinate' learning were found in the interview data from this study. Examples of Ausubel's 'derivative' learning were observed in two scenarios. The first was where a student had not changed his/her personal theory about how the target situation worked, as it already seemed to provide a good predictive fit with reality. The second was where a student had changed his or her theory to one that was more closely aligned with the accepted answer. Students who maintained their theoretical stance at a particular point in the sequence were found to consider that there were strong similarities between features of the analogy that they were examining at that point and the target scenario. These similarities were either at the 'surface' level, whereby the two situations exhibited common behaviour; or at a 'deep' theoretical level, which meant that the student felt that the analogy and the target shared the same underlying physics explanation. Particularly when the similarity was at the 'deep' level, the connectivity between the two scenarios encouraged students to feel that that their idea was correct as it enabled them to perceive the new situation as "supporting or exemplifying" the existing ideas in their cognitive structure. This is the main criterion for 'derivative' learning given by Ausubel (2000). In a similar manner, students who had 'improved' their theory, through conceptual change at an earlier stage of the analogical sequence, realised that their subsequent experiences backed up, or exemplified, the predictions that their newly adapted cognitive structure enabled them to make. Several instances of this were observed in the data. These students felt that a subsequent analogical situation confirmed the validity of their newly formed theory as a more accurate and plausible explanation for the behaviour of the target scenario. It was argued, throughout chapters 6 and 7, that this perception was a direct consequence of the connections that the students had made between the analogies, the target scenario and their theory. In common with instances where students had not altered their theoretical stance, these links were shown to have reinforced the feeling that their recently changed theoretical stance was correct because it provided a good degree of predictive or explanatory 'fit' for the behaviour of the target scenario. Some examples of 'correlative' learning were also found in the interview data. According to Ausubel, this form of conceptual change occurs when new material extends, elaborates, modifies or qualifies previously learned propositions. This process can easily be explained in terms of students making connections between different facets of their experience of the target and the analogies. In order for an idea to be extended or qualified in some way, the new experience (provided by an analogy in this study) must be compared with the target situation and the learner's existing explanatory theory for the target situation. This process requires similarities and / or differences to be identified. In situations where the degree of connection between the analogy and the target was deemed (by the student) to be sufficiently close, but minor differences caused some cognitive conflict, they often appeared to feel compelled to slightly extend or qualify the fine detail of their current theory, in some way, in order to make it explain both situations more accurately.

Ausubel (2000) considers 'superordinate' learning to have occurred when a new concept is perceived as being related to either individual, or groups of lower level ideas which become subsumed under the new proposition in the student's cognitive structure. This process can also be explained in terms of 'connectivity'. If a newly formed over-arching idea is perceived as being related to a set of existing ideas, then it is implicit that a student sees their features or principles as being connected to one another in some way. If sufficient overlap is evident to the individual, this endorses the idea that the concepts are related to one another. Having decided that a reasonable degree of overlap exists, the student then deliberately connects the idea with their new theory in their mental schema. Likewise, 'combinatorial' learning can be thought to involve students in a process whereby they actively connect relevant existing content in their mental structure with a new, potentially meaningful proposition. In this case, however, the new and existing ideas are perceived as being of equal hierarchical status, rather than the new knowledge being seen as either an over-arching principle of existing mental elements, or an example which supports an existing theory.

The process of conceptual change, which is defined as 'meaningful learning' by Ausubel (2000), can also be rationalised in terms of the connections that students made in their minds as they interacted with the analogical sequences. He states that this process is demonstrated when changes occur to both an acquired idea and an aspect of existing cognitive structure with which it becomes associated. When these changes were seen to happen, students started by comparing a 'surface' or 'deep' feature of the analogy and / or the target with their existing theoretical stance, as predicted by Ausubel. Students' thinking about the observed behaviour of the analogy was often found to alter their observations and understanding of the target scenario, as a result of attempts to make connections between them. As a consequence of making these connections, students often altered their explanatory theory for the target scenario, in order to improve its ability to intelligibly explain and inter-connect the behaviour of both the analogical and the target scenarios. From this it can be seen that the process of making connections between the different situations and the underlying reasoning for the observed behaviour, is fundamental to the changes that are inherent in Ausubel's concept of meaningful learning.

9.3.7 Conceptual ecology

The theory of conceptual ecology suggests that an individual's mind contains unstructured pieces of knowledge or information which become more structured and coherent through the learning process. The preceding analysis of the students' think-aloud interviews suggested that some of diSessa's ideas about conceptual change were justified while others were not. There were many instances in the data where students were judged to have been undergoing a process of 'complex system building', but there was no evidence of them reorganising pieces of knowledge only within their current context.

It was noted in the literature review chapter that diSessa argues that, instead of replacing existing theories, the process of learning involves the development and refining of a systematic arrangement of knowledge and ideas from a starting point which involves numerous, small unconnected knowledge structures which he calls phenomenological primitives, or 'p-prims'. This position was not backed up by the empirical evidence from this study. All of the students were found to have a pre-existing theoretical stance for explaining each of the situations that were examined in the check-up questionnaires, and for explaining the way that the target scenario associated with each of the analogical sequences functioned. While working though each stage of the bridging analogy sequences, the students' personal theories about the target scenarios were either *confirmed* or *adapted* because evidence from the analogies either corroborated, or conflicted with, their explanation of the target scenario. This progression, which concurs with the findings of developmental research by Blown and Bryce (2006), suggests that the students had a high degree of coherence in their thought processes. It also indicates that they were not simply using features from the analogies and existing knowledge elements as simple building blocks to *generate* a theory. It was pointed out in the literature review that diSessa (2008) counter-argues that an individual may be able to demonstrate a coherent line of reasoning in a particular situation and yet have different and incoherent lines on other occasions. He contends that this demonstrates fragmentation of knowledge. While some students undoubtedly displayed incoherent thought processes at various points during their interview, the general trend was towards the gradual refinement of a pre-existing theory, rather than devising one from several components. Rather than proving that their knowledge was fragmented, it simply shows that they sometimes made progress by trial and error which made some of their thought processes appear to be somewhat incoherent. Throughout the findings chapters, it was shown that the students made significant progress when they discovered new ideas or information from their interactions with the analogies. This also suggests that the process of conceptual change does not simply involve the reorganisation or re-prioritisation of pieces of unstructured knowledge from the analogies or other previous experiences.

According to the theory of conceptual ecology, an individual's explanations are thought to be highly context dependent. This leads diSessa to reason that learners find it difficult to transfer ideas or knowledge from one domain, or subject, to another. This assertion was found to be untrue for most of the students who participated in this study. The thought processes which were evident in the transcribed interviews clearly demonstrated the transfer of ideas between different analogies and the target scenario.

There was however significant evidence in the data to suggest that diSessa's idea of complex system building was occurring. This can be readily linked with the connectivity principle of conceptual change. It was found that a learner successfully integrated a new idea into their existing cognitive system when it connected with it in some way that was obvious to the individual. When the student perceived a potential link to be weak or new to them, they held the new concept or knowledge in tension with their existing mental schema. This was found to be prevalent where a student 'twin tracked' two ideas and switched between them. It was observed that many students experienced cognitive conflict when they observed the behaviour of an analogy and found it to be at odds with their existing theory. They attempted to resolve this by seeking out a way to connect the two competing cognitive zones (one containing the new idea, and the other containing their prior ideas). It was noted at several points in the earlier findings chapters that in cases where these attempts were unsuccessful, the difficulty was often caused by a high level of perceived dissimilarity between the two zones; they were too 'cognitively distant' from one another. In contrast, successful students devised a way of connecting the two sets of knowledge by seeking out a link between them that they felt was justified. This process usually required the student to adapt their theoretical stance for explaining and justifying what happened in the target scenario. When this happened successfully, the end result was that the two sets of knowledge overlapped more so that they became increasingly integrated with one another in the students' minds (i.e. they became more 'cognitively proximal' to one another). Both bridging analogy sequences fulfilled the role of cognitive 'scaffolding' (see Wood, Bruner and Ross, 1976) in this process as they supported and encouraged the discovery or strengthening of these links in the system building operation.

9.4 Potential objections to the principle of connectivity

There are two main sources of possible objections to the process of trying to unify several of the theoretical positions. The first is that at least one previous attempt to achieve similar outcomes in a similar psychological area have been criticised as having been inadequately justified on several counts. The second potential objection relates to the use of analogies as a fair and unbiased tool for demonstrating connectivity. Both of these issues will now be addressed.

9.4.1 Shortcomings in a previous attempt at unification

Cooper and Shallice (1995) discuss a previous attempt to unify several cognition theories using the 'Soar' computer program. They suggest that this attempted unification had several shortcomings, including: its methodological foundations being insecure; being ill specified as a computational/psychological theory; and its inability to stand up to close scrutiny as a unified theory under empirical testing.

In contrast, the connectivity stance that has been argued for here is based on research which has a clearly defined methodological basis. This unifying principle also has a body of corroborating empirical evidence from this research study (discussed throughout the chapters 6 and 7, as well as in the summative findings in this chapter) to justify its claims and to back it up. Another difference is that several other pieces of research, as discussed above at some length, can be seen to enable similar lines of argument to be developed.

9.4.2 The use of analogies as a fair tool to demonstrate connectivity?

It could be argued that using analogies almost inevitably leads to the idea that conceptual change is a consequence of making connections between different ideas. This argument is based on the idea that analogies are often used by teachers as a way of demonstrating similarities between one situation and another as way of improving their students' understanding of the topic. There are, however, several counter-arguments.

Although the students were 'guided' in the sense that they were asked questions about the series of analogies in a sequence, the students in this study were left to draw their own conclusions from the analogies rather than being told how to interpret them. This was done in an attempt to discover how *they* were thinking, rather than a particular way of thinking being imposed upon them. It also meant that they were able to demonstrate conceptual change in the way that worked for them as the Socratic questioning merely sought to elicit their own thinking processes, regardless of the direction that took. Although they were regularly asked to talk about similarities or differences that they perceived as being valid, students were never told what use to make of this information. This meant that care was taken to ensure that they were not pushed into making connections so that any explanatory use of the similarities or differences that they observed was left entirely up to them. Many of the students displayed somewhat erratic levels of conceptual change at various stages during their interview, ranging from significant breakthroughs, to negative changes. This also shows that students felt able to progress through the interview using their preferred thought processes and drawing their own conclusions, rather than being pushed along any particular process that favoured one outcome, or conceptual change strategy, over any other.

Other pedagogical strategies, which are perceived as being effective in encouraging learning, also rely on traits that can be described in ways which suggest that connectivity is a key process in bringing about conceptual change in any teaching and learning situation, irrespective of the subject matter. For example, teaching a subject from the perspective of a particular everyday context, the technique of mind-mapping, encouraging pupils to transfer skills between different subjects in their curriculum, looking for patterns in information, and overt cross-curricular work, all seek to make effective use of similarities between various aspects of an individual topic, or between different subjects in a student's curriculum.

Connectivity can also be related to Bloom's taxonomy of cognitive skills (Bloom, 1956). All of the tasks in the hierarchy, above the basic ability to recall information, require an increasing ability, on the part of the learner, to link different ideas together. According to Bloom, an individual demonstrates *comprehension* by their ability to demonstrate several skills. These skills include: understanding an idea; defending a position; distinguishing between different ideas or facts; explaining concepts; generalising; giving examples that demonstrate a principle; making correct inferences from given information; interpreting information; paraphrasing; predicting outcomes; rewrites; and summarising ideas or conclusions. In order to successfully achieve all of these, a student would need to connect various items of knowledge or different ideas together. The next level in the taxonomy requires the ability to *apply* knowledge. This is demonstrated through skills such as constructing new ideas or objects; demonstrating how things work; manipulating or modifying concepts or information; predicting the outcomes of new situations; and relating sets of information or ideas to one another. The next level of *analysis* also involves several skills that require a student to connect ideas together. These skills include: comparing and contrasting different ideas; deconstructing concepts into their component parts in order to discover how all the ideas fit together; differentiating or discriminating between different facts and concepts; making inferences in order to relate different concepts to one another or to make new ways of working possible; outlining the basic sub-concepts that constitute an argument or position on something; or outlining similarities or differences between different ideas. The most complex process of *synthesis*, which enables a person to explain a theory or concept in more detail or with greater accuracy, also involves several connective skills. These include combining, categorising, organizing or modifying ideas and rearranging, reconstructing, rewriting and summarising information. Finally, *evaluation* requires a person to be able to appraise, compare, contrast, criticise, interpret, summarise, justify, support or critique different concepts or theories as well as being able to discriminate between them and explain them to others. Yet again each of these skills can be seen to include a connective element.

9.5 Implications of the findings from this study in relation to pedagogy

This study has highlighted a number of pedagogical issues which suggest answers to the third and fifth research questions.

9.5.1 Bridging analogies as a teaching and learning strategy

It has been clearly demonstrated, through the findings of this study, that bridging analogies are useful learning tools for a significant percentage of learners, regardless of their ability as measured by their final performance in a national examination. In particular, the bridging analogies were found to be effective in encouraging conceptual change, especially when used in conjunction with Socratic questioning. An additional benefit was that the majority of the sixty students who used the analogies in this study felt that they had been helped to gain a better understanding of the examined topics for a variety of reasons.

Teachers should therefore be encouraged to make more use of analogies as a teaching and learning tool in the classroom. As has already been discussed, their use as part of an interview sequence undoubtedly takes up more time than merely telling a student the ‘correct’ answer. However, this study has shown that the students are generally adept at deducing the accepted answer for themselves and that they find the process of engaging with the sequence to deduce their own answer to be highly beneficial. Bridging analogy sequences should therefore be developed for other topics within the Physics curriculum. There are also potential benefits to be gained from their development and use in other scientific, and non-scientific, subject areas.

9.5.2 Momentum and kinetic energy

It has been demonstrated that many students have difficulty in understanding these concepts and in separating them from one another in their thinking. Several recommendations regarding the teaching of momentum and kinetic energy can be made as a result of the findings from this study.

It is important to help students to distinguish between kinetic energy and momentum as this difficulty had a significant influence on several students' thinking as they often confused the two concepts and used the terms interchangeably in their deliberations. It should be acknowledged that the two concepts are difficult to distinguish between, other than quantitatively, when an object is moving at a constant velocity but differences become apparent when the motion of an object is changed. The change in the kinetic energy of a single object is related to the magnitude of the force that is applied to the object and the *distance* over which it is applied. In contrast with this, the change in momentum of a single object is related to the force that is applied to it and the *time* for which the force is applied. It has been argued previously that by discussing this carefully in relation to Newton's Third Law, it is more likely that students will be better able to understand conservation of momentum in all collisions. It needs to be emphasised that because the forces on each object in a collision are equal and opposite, and that the contact time is identical for both objects, the gain in momentum for one object is the same as the reduction of momentum in the other. This means that momentum is transferred from one to the other and consequently the total amount of momentum is always conserved. Many students were found to be unable to explain this adequately.

Several students were found to have a tendency to view momentum purely from the perspective of the object that moved prior to a collision, rather than thinking in terms of momentum being conserved across a system of interacting objects. It was found that some students consequently had difficulty in understanding or believing that momentum could be conserved in a situation where the initial object clearly slowed down after colliding with another object. This observed behaviour resulted in some students stating that they thought momentum was being lost because the incoming object slowed down after colliding with a second object.

It was seen that students who thought in terms of momentum being '*transferred'* (rather than being 'shared') between one object and another often had, or gained, a better grasp of the law of conservation of momentum. It is therefore recommended that momentum conservation is discussed in terms of the transfer of momentum between objects.

Several students were found to have a velocity-centred view of momentum. This also manifested itself in a belief that momentum was lost when an object of smaller mass collided with another of greater mass. These students were found to be less adept at deducing the influence that a large mass would have on the relative velocity of an object that had the same amount of momentum. Giving the students the tactile experience of running an object into their more massive hand, helped many of them to actually experience the transfer of momentum into a reasonably immoveable object, as well as helping them to gain a better understanding of the connection between the mass and the velocity of an object in relation to its momentum. This finding suggests that there are real benefits in giving students the opportunity to physically experience momentum being transferred to parts of their own body, rather than simply engaging in experiments where pairs of dynamics carts are collided and the relevant measurements and calculations are carried out.

Students who had a more ‘universal’ perspective on momentum transfer (see Bryce and MacMillan, 2009) were found to be more able to explain why momentum could be considered to be conserved in collisions that involved apparently ‘immoveable’ objects. This suggests that it would be advantageous to help students to realise that momentum can be transferred to increasingly large objects, including the Earth, meaning that it is not destroyed in any collision.

In relation to inelastic collisions, it was found that many students were initially unclear about how and why kinetic energy is not conserved. This study has shown that when students were able to deduce, or remember, the link between vibrations in an object and the production of sound and heat energy, they were better at explaining the reduction in kinetic energy in a collision that involved contact between objects. Consequently, strenuous efforts should be made by teachers to ensure that students are helped to make this connection when inelastic collisions are introduced and discussed.

9.5.3 Students' thinking processes

In this research study the use of think-aloud interviews has been shown to be a productive technique for exposing and interrogating students' thinking processes. Many of these processes have important implications for the way in which teaching can be made more effective in enabling conceptual change to occur in the classroom.

As discussed above, the main finding of this study, in relation to students' thinking processes, was that the making of connections is a key factor in the success or otherwise of the conceptual change process. All sixty students exhibited connective thinking. Some did so only once, while others did so on multiple occasions throughout their interview. This strongly suggests that students should be given as many opportunities as possible to make connections during the learning process. Every opportunity should be taken to highlight and emphasise useful and informative links with other concepts, examples or principles when students are trying to learn. These connections can be from within the same subject are or can also be cross-curricular. This finding suggests that making these links as explicit as possible, and encouraging students to think of them for themselves, has the potential to be highly beneficial in optimising students' ability to successfully learn new concepts.

A total of thirty seven of the sixty students were found to engage in 'twin-tracking' between different ideas while they worked with the analogies, many of them exhibited this type of thinking several times during their interview This mental process, which would not normally be evident in everyday classroom interactions, meant that the student engaged in an ongoing comparison between two (or more) competing ideas in order to resolve cognitive conflict that they experienced when they were exposed to new information that they could not easily reconcile with their existing mental schema. The 'twin-tracking' often came to light when a student suddenly reverted back to a previous answer having appeared to move on at a previous stage in the interview and were then asked to explain why they had gone back to a previous idea. Returning to a previous answer could have been interpreted as the student not really understanding their new idea and therefore concluding that no real changes had occurred in their thinking. However, careful questioning revealed that the student was actually trying to ascertain whether or not their previous thinking gave a better explanation than their new idea. The twin-tracking was therefore an important part of the conceptual change process for many students. Teachers should therefore take care to investigate why a student has reverted back to a previous explanation rather than perhaps assuming that the student has failed to understand an idea beyond a particular point. It would also be potentially beneficial to acknowledge that students might be comparing one or more ideas in their heads. This could assist the students to resolve their struggle by acknowledging them and making them more explicit to the learner, as it was found that they were often not consciously aware of this mental process until they were explicitly asked to express what they were thinking.

The vast majority of students in this study employed a mental 'test' process whereby they assessed the relative 'logic' and 'intelligibility' of a new idea or theory in relation their existing mental structure. They applied this 'test' as a means of deciding whether or not they should or would alter their existing explanation or ideas about a given situation. This finding implies that it is very important for teachers to discuss *how* and *why* an idea has been decided upon and accepted by experts in any particular field of study if conceptual change is to be achieved in students' minds. These findings also emphasise the importance of encouraging students to think through these issues for themselves. It has been shown that, under guidance of careful questioning, many students are capable of arriving at the 'accepted' answer for themselves and exhibit a significant level of understanding which means that they are more likely to remember and be able to correctly apply the material that they have learned. This emphasises that simple rote learning of facts and ideas is usually an ineffective learning strategy.

9.5.4 Conceptual change

Evidence has been found to show that students encounter conceptual change in ways that correspond to several of the conceptual change theories. However, the data from this study has been used to argue that the fundamental conceptual change process involves students in making connections between different zones of knowledge in order to make progress. Each of the existing conceptual change theories that were examined in this study can be described in terms of connectivity to greater or lesser extents. As discussed above, it would therefore appear to be advisable for teachers to teach their students with connectivity in mind. They should therefore take every opportunity to connect the topic under discussion at any given time with other topics within the subject, or other subjects. It would also be important for them to contextualise teaching so that students are assisted to link what they are learning with everyday experiences. These findings also suggest that the judicious use of techniques such as mind-mapping could also be beneficial in learning and understanding a topic in a particular subject.

9.6 Potential future research resulting from this study

This research project has not examined the use of bridging analogies with groups of students, which would be more typical in a classroom setting. It would therefore be helpful if research could be undertaken to investigate the effectiveness of this mode of delivery. As indicated in the methodology chapter, research should be conducted on how to improve students' understanding of the differences between momentum and kinetic energy. This could involve an evaluation of the effectiveness of lessons such as the one outlined in appendix 8 of this thesis. It is recommended that future research in these areas (and in others concerned with students' grasp of scientific concepts) should be qualitative in nature. This study has produced a rich data set and findings which have not been accessible to previous studies which examined momentum and kinetic energy because of their predominant use of quantitative techniques like pre- and post-testing. It is acknowledged that the use of think-aloud interviews presents any researcher with a number of challenges. These include:

- expending time and effort prior to conducting interviews to persuade schools to participate in the study, and individual students (as well as their parents) to volunteer to be interviewed, which some may perceive as rather threatening as it has the potential to expose their possible lack of understanding of the topic under investigation;
- being prepared to arrange each interview at a time and a place that is suitable for the individual students so that it does not disrupt their ongoing educational programme, which places considerable time demands on the researcher;
- taking care not to introduce any bias to the students' thinking processes while conducting the in-depth interviews;
- the necessity to fully transcribe each interview in order to analyse the large amount of data that is produced in detail.

However, the rewards for being willing to undertake these challenges are the potential to gain significant insights into the thinking processes of individual students (and the ability to track both the difficulties and successes encountered by each student) as they seek to gain a better understanding of the concepts concerned.

9.7 Conclusions from the study

This research study has sought to find answers to the five research questions that were posed. The initial phase of the project confirmed the findings from several previous studies by demonstrating that many students harbour misconceptions about the nature and application of momentum and kinetic energy in different situations. The two bridging analogy sequences that were developed sought to assist students to improve their understanding of two such situations. In relation to the first two research questions, it has been demonstrated that, for many students, the use of bridging analogies was effective in causing conceptual change. In particular it has been shown that many students became more adept at understanding and explaining the two situations that were addressed. The first was about why and how momentum is conserved when an object collides with an apparently 'immoveable' object. The second problem involved explaining why kinetic energy is not conserved in an inelastic collision while momentum is conserved.

The third and fourth research questions were answered by examining the ways in which the sixty students answered Socratic questions during the think-aloud, semi-structured interviews during which they worked with one of the two specifically designed analogy sequences. An analysis of the interview transcripts found that students exhibited features from several conceptual change theories which have been proposed by a number of people. Only one of the examined theories (category re-assignment) had no evidence to back it up in the data. In terms of how and why bridging analogies result in conceptual change, it has been argued that the primary mechanism is the making of connections between the experience gained by working with the analogies and other aspects of a student's existing mental structure. It was found that making these connections enabled students to refine their 'specific' theory about the target scenario or, in the case of ten of the sixty students, go as far as refining their 'generalised' theory about conservation of momentum in any situation through a process of repeated transfer. This connecting process has been argued to be a powerful way of describing how students make decisions about whether or not a new idea is more intelligible, then more believable, and finally more fruitful than alternative or pre-existing explanations.

It has been argued from the results of this study that connectivity is an overarching idea for conceptual change. All of the theories that have been examined can be described and explained from such a perspective. This relates to the final research question as it suggests that the learning process (in which conceptual change occurs) primarily consists of making connections between different concepts or bits of knowledge in such a way that new ideas are developed or existing, inaccurate ideas are revised. Although this explanation for learning has been developed in relation to the study of momentum and kinetic energy in physics, it has been argued that it can be applied to the learning of other concepts both in and out-with the sciences.

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Appendix 1a: Local Authority Letter

Dear (Director of Education),

My name is Kenneth MacMillan and I am currently a seconded lecturer in the Department of Educational & Professional Studies at Strathclyde University, having been a Physics teacher for 16 years. As part of my studies towards a PhD, I am examining a new strategy for teaching the conceptually difficult topics of momentum and kinetic energy during collisions. I am seeking your permission to include Higher Physics candidates from a few of the schools in your local authority as part of the sample for this work. I have already sought and gained the approval of the Strathclyde University ethics committee for this project.

The research involves two elements. The first consists of a check-up questionnaire which I hope all of the Higher Physics candidates would be willing to complete. The written task would require the pupils to answer a short set of questions about the physics involved in some everyday examples of collisions. This would take up less than one period of class time and would be carried in conjunction with the staff in the Physics department at a time which was deemed appropriate by them.

The second part seeks to assess the use of bridging analogies (a sequence of progressive, inter-connected analogies that take a learner from an easily understood everyday 'base' analogy through a series of intermediate steps to the 'target' concept) as a teaching and learning strategy for pupils. I am proposing to carry out individual, semi-structured interviews which will be audio taped for later transcription and analysis. The interview would involve pupils carrying out a set of simple experiments about colliding objects and discussing the physics involved in each situation. None of the pupils who volunteer to participate in this phase of the project will be able to be identified in the resulting thesis as their identities will only be known to me. The interviews would be scheduled during lunchtimes or immediately after school in order to avoid disrupting the pupils' ongoing work. The actual times for each pupil's interview would be negotiated with the pupil, their parents and the staff of the physics department (in order to ensure that at least one other adult was around while the interview was being conducted). I have enclosed a copy of both parental permission letters, for each phase of the project, for your approval.

I have successfully carried out research of this nature in my own school as part of a previous project for my Master of Education studies. I believe that participation in this project will be beneficial to both the Physics staff and the pupils who take part. Through the feedback that I will provide at the end of the study, staff will gain a greater insight into the difficulties that pupils experience in trying to understand the complex concepts associated with this part of the curriculum. They will also have been given the opportunity to see, and assess for themselves, a new strategy for teaching and learning in operation. It is hoped that the pupils will improve their understanding of the topic and gain an appreciation of the ways in which their own future learning can be enhanced through the use of 'guided analogical reasoning'.

If you would like to discuss this matter further, or if you have any questions, then please get in touch with me by email at kenneth.macmillan@strath.ac.uk, or by telephone on 0141 950 3332. If you prefer, you can also contact my supervisor, Professor Tom Bryce, whose email address is t.g.k.bryce@strath.ac.uk and his telephone number is 0141 950 3536.

Thank you for your assistance in this matter.

Yours sincerely,

Kenneth MacMillan

Appendix 1b: Letter to Head Teachers

Dear (Head Teacher),

My name is Kenneth MacMillan and I am currently a seconded lecturer in the Department of Educational & Professional Studies at Strathclyde University, having been a Physics teacher for 16 years. As part of my studies towards a PhD, I am examining a new strategy for teaching the conceptually difficult topics of momentum and kinetic energy during collisions. I am seeking your permission to include your Higher Physics candidates as part of the sample for this work. I have already sought and gained the approval of the Strathclyde University ethics committee and the approval of your local education authority for this project.

The research involves two elements. The first consists of a check-up questionnaire which I hope all of your Higher Physics candidates would be willing to complete anonymously. The written task would require the pupils to answer a short set of questions about the physics involved in some everyday examples of collisions. This would take up less than one period of class time and would be carried out in conjunction with the staff in the Physics department at a time which was deemed appropriate by them.

The second part seeks to assess the use of bridging analogies (a sequence of progressive, inter-connected analogies that take a learner from an easily understood everyday 'base' analogy through a series of intermediate steps to the 'target' concept) as a teaching and learning strategy for pupils. I am proposing to carry out individual, semi-structured interviews which will be audio taped for later transcription and analysis. The interview would involve pupils carrying out a set of simple experiments about colliding objects and discussing the physics involved in each situation. None of the pupils who volunteer to participate in this phase of the project will be able to be identified in the resulting thesis as their identities will only be known to me. The interviews would be scheduled during lunchtimes or immediately after school in order to avoid disrupting the pupils' ongoing work. The actual times for each pupil's interview would be negotiated with the pupil, their parents and the staff of the physics department, in order to ensure that at least one other adult was around while the interview was being conducted. I have enclosed a copy of both parental permission letters and pupil consent letters, for each phase of the project, for your approval.

I have successfully carried out research of this nature in my own school as part of a previous project for my Master of Education studies. I believe that participation in this project will be beneficial to both the Physics staff and the pupils who take part. Through the feedback that I will provide at the end of the study, staff will gain a greater insight into the difficulties that pupils experience in trying to understand the complex concepts associated with this part of the curriculum. They will also have been given the opportunity to see, and assess for themselves, a new strategy for teaching and learning in operation. It is hoped that the pupils will improve their understanding of the topic and gain an appreciation of the ways in which their own future learning can be enhanced through the use of ‘guided analogical reasoning’.

If you would like to discuss this matter further, or if you have any questions, then please get in touch with me by email at kenneth.macmillan@strath.ac.uk, or by telephone on 0141 950 3332. If you prefer, you can also contact my supervisor, Professor Tom Bryce, whose email address is t.g.k.bryce@strath.ac.uk and his telephone number is 0141 950 3536.

Thank you for your assistance in this matter.

Yours sincerely,

Kenneth MacMillan

Appendix 1c: Parents Letter 1

Dear Parent / Guardian,

Request for permission for your son / daughter to answer a set of written questions.

My name is Kenneth MacMillan and I am a lecturer in the Department of Educational & Professional Studies at Strathclyde University, having previously been a Physics teacher in a Glasgow school for 16 years. As part of my research, I am examining a new strategy for teaching and learning of two related topics in Higher Physics. I would like your permission to involve your son / daughter as part of the sample for this work. I have already sought and gained the approval of your child's head teacher and Strathclyde University for this project.

The written task would require your son / daughter to answer a short set of questions about the physics involved in some everyday examples of collisions. This would take up less than one period of class time and would be carried out at a time which was deemed appropriate by the staff in the Physics department of the school. Each pupil's answers to the questions will be completely anonymous.

If you are happy for your son / daughter to participate in this exercise, please complete the attached permission slip and return it to your child's Physics teacher as soon as possible. However, if you would like to discuss this matter further, or if you have any questions, then please don't hesitate to get in touch with me. My contact address is shown below. Alternatively, you can contact me directly by telephone on 0141 950 3332, or email me at kenneth.macmillan@strath.ac.uk .

Thank you for your assistance in this matter.

Yours faithfully,

Kenneth MacMillan

Permission Form

Pupil's Name: ___________________________________

I herby give my permission for my son / daughter to complete the set of questions which form part of the research outlined in the attached letter.

Signature of parent / guardian: ____________________ **Date:** ______________

Appendix 1d: Parents Letter 2

Dear Parent / Guardian,

Request for permission to conduct an interview.

In addition to the set of questions that most pupils have completed in relation to my research project which I wrote to you about recently, your son / daughter has volunteered to participate in a second part of the study, for which I have also gained the approval of your child's school and the University. I am seeking your permission for his/her involvement.

This second part seeks to assess the use of a new learning strategy for pupils. I am proposing to carry out individual interviews which will be audio taped for later analysis. The interview involves pupils carrying out a set of simple experiments about colliding objects and discussing the Physics involved in each situation. None of the pupils who participate in an interview will be able to be identified in the resulting thesis as their identities will only be known to me.

The interviews would be scheduled during lunchtimes, or immediately after school, in order to avoid disrupting your son's / daughter's ongoing work. Each interview is likely to take around 40 minutes to complete, so I would advise him / her to bring a packed lunch to eat during the interview if they select a lunchtime slot. The actual time for your son's / daughter's interview would be negotiated with him / her, along with the staff of the Physics department, in order to ensure that at least one other adult is around while the interview is being conducted. Members of the Physics department may choose to observe the interviews.

I have successfully carried out research of this nature in my own school as part of a previous project. I believe that participation in this project will be beneficial to your son / daughter as it will improve their understanding of the topic which is being examined and allow them to gain a greater understanding of the ways in which their own future learning can be improved through the use of analogies.

If you would like to discuss this matter further, or if you have any questions, then please don't hesitate to get in touch with me at the address shown at the bottom of this letter. Alternatively, you can contact me directly by telephone on 0141 950 3332, or email me at kenneth.macmillan@strath.ac.uk . If you are happy for your son / daughter to participate in an interview, then please complete the attached permission slip and return it to your child's Physics teacher as soon as possible.

Thank you for your assistance in this matter.

Yours faithfully,

Kenneth MacMillan

Permission Form

Pupil's Name: ______________________________

I herby give my permission for my son / daughter to participate in an individual, audio taped interview as outlined in the attached letter.

Signature of parent / guardian: ____________________ **Date:** ______________

Appendix 1e: Student Letter 1

Dear Pupil,

Request for agreement to answer a set of written questions.

My name is Kenneth MacMillan and I am a lecturer in the Department of Educational & Professional Studies at Strathclyde University, having previously been a Physics teacher in a Glasgow school for 16 years. As part of my research, I am examining a new strategy for teaching and learning of two related topics in Higher Physics. I would like your agreement to involve you as part of the sample for this work.

The written task would require you to answer a short set of questions about the physics involved in some everyday examples of collisions. This would take up less than one period of class time and would be carried out at a time which your Physics teacher will decide upon. Your answers to the questions will be completely anonymous.

If you are happy to participate in this exercise, please complete the attached permission slip and return it to your Physics teacher as soon as possible. However, if you would like to discuss this matter further, or if you have any questions, then please don't hesitate to get in touch with me. My contact address is shown below. Alternatively, you can contact me directly by telephone on 0141 950 3332, or email me at kenneth.macmillan@strath.ac.uk .

Thank you for your assistance in this matter.

Yours faithfully,

Kenneth MacMillan

Permission Form

Pupil's Name: ____

I herby agree to complete the set of questions which form part of the research outlined in the attached letter.

Signature of pupil: ____________________________ **Date:** ________________

Appendix 1f: Student Letter 2

Dear Pupil,

Request for permission to conduct an interview.

In addition to the set of questions that most pupils will complete, I am seeking your agreement to take part in a second part of the study.

This second part seeks to assess the use of a new learning strategy. I am proposing to carry out individual interviews which will be audio taped for later analysis. The interview involves you in carrying out a set of simple experiments about colliding objects and discussing the Physics involved in each situation. You will not be able to be identified in the report which I will be writing about the findings as your identity will only be known to me.

Your interview would be scheduled during lunchtimes, or immediately after school, in order to avoid disrupting your ongoing work. Each interview is likely to take around 40 minutes to complete, so I would advise you to bring a packed lunch to eat during the interview if you select a lunchtime slot. The actual time for your interview would be negotiated with you, along with the staff of the Physics department. Members of the school's Physics department may choose to observe the interviews.

I have successfully carried out research of this nature in my own school as part of a previous project. I believe that participation in this project will be beneficial to you as it will improve your understanding of the topic which is being examined and allow you to gain a greater understanding of the ways in which your own future learning can be improved.

If you would like to discuss this matter further, or if you have any questions, then please don't hesitate to get in touch with me at the address shown at the bottom of this letter. Alternatively, you can contact me directly by telephone on 0141 950 3332, or email me at kenneth.macmillan@strath.ac.uk . If you are happy to participate in an interview, then please complete the attached permission slip and return it to your Physics teacher as soon as possible.

Thank you for your assistance in this matter.

Yours faithfully,

Kenneth MacMillan

Permission Form

Pupil's Name: ____

I herby agree to participate in an individual, audio taped interview as outlined in the attached letter.

Signature of pupil: _______________________ **Date:** ____________

Appendix 2

Momentum and kinetic energy check-up.

This questionnaire consists of a few questions to find out what you understand about momentum and kinetic energy followed by a series of six situations in which momentum and kinetic energy play a part.

Your answers are not going to be marked in order to give you a grade in any way. However, it is very important that you **answer all of the questions,** and that you give **full answers** with **as much detail about your thinking and reasoning as possible**. By analysing your answers, it is hoped that teachers might better understand the difficulties that pupils have with these topics.

I have asked you to fill in your name, however I will be the only person who knows this information and you will not be identified in any way in the findings. Knowing your name will simply allow me to identify what Physics grade each participant got on in the final Higher exam

Thank you for your help.

Your name: ____

What is the name of your school? ______________________________

General Questions

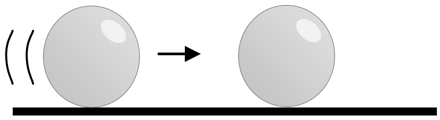
Describe what you think **momentum** is in your own words?

Describe what you think **kinetic energy** is in your own words?

Describe what you think the **difference** is between the momentum of an object and its kinetic energy.

Situations

Situation 1: Steel ball colliding with identical stationary ball.



Describe what you think will happen after the first ball hits the second.

How do you think the **momentum** of the first ball **before** the collision would compare with the momentum of the second ball **after** the collision? Please explain your reasons for thinking that.

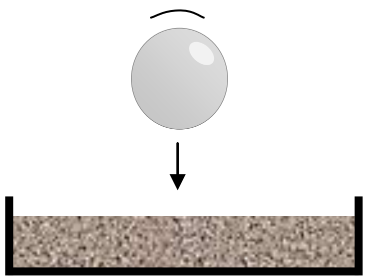
How would the total **kinetic energy** of the balls compare before and after the collision? Please explain your reasons for thinking that.

The incoming ball could be changed so that it was either bigger or smaller than the stationary one.
Explain any ways in which you think either change would alter the results that you have described above in terms of **momentum and/or kinetic energy**?

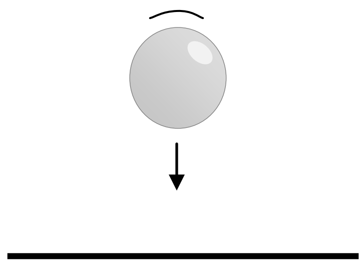
First ball bigger

First ball smaller

Situations 2a & 2b: Ball falling into sand and stopping; and ball falling on to a hard surface and bouncing.



Situation 2a: Ball landing in sand



Situation 2b: Ball hitting hard surface

For **situation 2a**, describe what you think would happen, in terms of the **momentum** of the ball and the sand as a result of the collision. Please describe your thoughts in as much detail as possible and give reasons for your answer.

For **situation 2b**, describe what you think would happen, in terms of the **momentum**, of the ball and the surface as a result of collision. Please describe your thoughts in as much detail as possible and give reasons for your answer.

In which situation (if either) do you think the ball would transfer **more** momentum to the object that it is hitting? Give a reason for your answer.

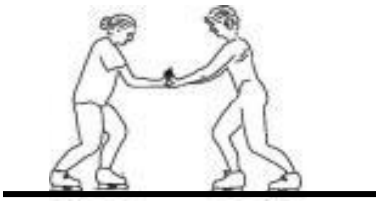
In terms of the types and amount of **energy**, what you think has happened during both of these collisions, giving reasons for each answer.

Situation 2a:

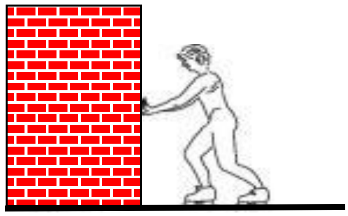
Situation 2b:

In terms of **momentum** and **kinetic energy**, what similarities or differences, if any, do you think there are between the ball landing on sand and on a hard surface?

Situations 3a & 3b: Two roller skaters pushing apart; and roller skater pushing against a wall.



Situation 3a: Two skaters pushing apart.



Situation 3b: Skater pushing against wall.

For **situation 3a**, describe what you think would happen, in terms of the **momentum** of each skater, as a result of this situation. Please describe your thoughts in as much detail as possible and give reasons for your answer.

For **situation 3b**, describe what you think would happen, in terms of the **momentum** of the skater and the wall, as a result of this situation. Please describe your thoughts in as much detail as possible and give reasons for your answer.

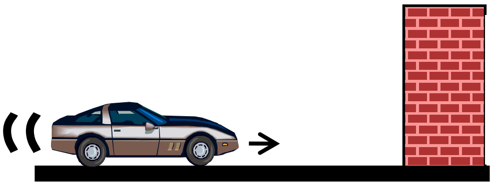
Please explain, in terms of **energy**, how you think the skaters' movement, from a stationary start, has come about in **both** situations.

Situation 3a:

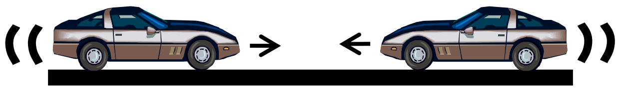
Situation 3b:

In terms of **momentum** and **kinetic energy**, what similarities or differences, if any, do you think there are between the two skaters pushing apart and one skater pushing against a wall?

Situations 4a & 4b: A car colliding with a large building at 50mph; and two identical cars, both travelling at 50mph colliding head on.



Situation 4a: Car hitting building at 50mph.



Situation 4b: Cars travelling at 50mph hitting head on.

For **situation 4a**, describe what you think would happen, in terms of the **momentum** of the car **and** the wall, as a result of this collision. Please give reasons for your answer.

For **situation 4b**, describe what you think would happen, in terms of the **momentum** of **both** cars, as a result of this collision. Please give reasons for your answer.

In terms of the types and amount of **energy**, what you think has happened during both of these collisions, giving reasons for each answer.

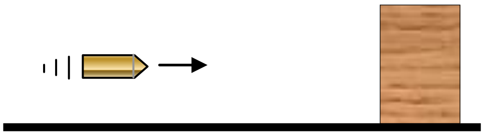
Situation 4a:

Situation 4b:

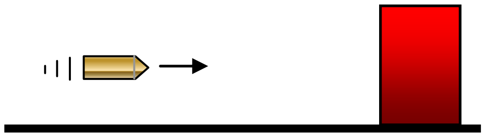
In terms of **momentum** and **kinetic energy**, what similarities or differences, if any, do you think there are between the car hitting a building at 50mph, and the two cars hitting one another at 50mph?

Which of these collisions (if either) do you think would be more likely to result in the driver(s) being badly injured? Please give a reason for your answer.

Situations 5a & 5b: Identical bullets being fired at and ***lodging*** in a wooden block; and at a rubber block and ***rebounding***.



Situation 5a: Bullet lodging in wooden block.



Situation 5b: Bullet bouncing off rubber block.

Describe what you think would happen to the **momentum** of the **bullet and each target**, as a result of these collisions. Please explain your reasoning.

Situation 5a:

Situation 5b:

In which situation (if either) do you think the bullet would transfer **more** momentum to the object that it is hitting? Give a reason for your answer.

Please describe, in terms of **energy**, what you think would happen in each situation when the bullet strikes the target.

Situation 5a:

Situation 5b:

For each situation, describe and explain how you think the total amount of **kinetic energy**, before and after the bullet hit the target, compare with one another.

Situation 5a:

Situation 5b:

This is the end of the questions. Thank you for your answers.

Appendix 3: Immoveable object sequence interview questions

Preamble

Thanks for agreeing to this interview.

Are you ok with me taping it so that I can study what's said later?

(Perform sound check while making small talk with pupil).

We're going to be talking about some Physics; about what happens when a car crashes into a large object like a building.

Scientists have an explanation concerning momentum which quite a lot of pupils say doesn't really make much sense to them. I'm going to take you through a series of analogies that might gradually help you to make sense of the scientist's explanation for yourself, with as little help from me as possible.

Do you know what an analogy is?

An analogy is where you say that one situation is like another in some way. For example, an electric current can be thought of, in some ways, as being like water flowing through a pipe so the water is the analogy for the current.
I'm sure that lots of your teachers will use analogies when they're trying to teach you facts or help you to make sense of something. They use them to help you to connect something that you already know about with the thing that you're trying to learn. However some analogies are better than others.

I want to find out whether or not each analogy, in the series that I show you, helps you to come up with an explanation about the car crashing into a large object that makes sense to you.

I'm particularly interested in what you're thinking at each stage of the process.
So **please try to think out loud** as much as possible and tell me exactly what you're thinking, because that will be very helpful.

I'll try to say very little other than to ask the questions that I have prepared, or to ask you to say a bit more, if necessary.

Preconceptions

We are going to be talking about momentum, which is a topic that you have covered as part of your Physics lessons.

What can you tell me about momentum?

(*Potential* probes to encourage the student to elaborate, depending on how they answer the first question)

Concept
What is momentum a **measure of**?

Equation
Which quantities does the amount of momentum that an object has depend on?
What's the **equation** for momentum?
What's the difference between speed and velocity?
Why is momentum related to **velocity rather than speed**?

Conservation
What do you think is meant when we say that momentum is **"conserved"?**

Under which circumstances would *you* say that momentum is conserved?

Why do things slow down if momentum is said to be conserved in a collision?

Summarise how you would describe what momentum is about to someone.

Target Situation

Look at the picture of the car about to crash into the side of a large building.

Describe, in as much detail as you can, **what you think will happen** after the car crashes into the side of the building?

How will the total amount of **momentum before and after** the collision **compare** with one another, in your opinion?

How convinced are you that you're correct on a **scale of 1 to 6**?

Could you **explain** why you think that momentum is (or isn't) conserved?

How convinced are you that you're correct on a **scale of 1 to 6**?

Look at the picture of what actually happens to the car after the collision. The car crumples and rebounds.

We are going to work through a set of analogies that you may find help you to explain what is happening, in terms of the momentum, when the car hits the building

Analogy 1 Questions

Can you explain to me **what has happened** in this collision?

How will **the total amount of momentum before and after the collision compare** with one another, in your opinion?

How convinced are you that you're correct on a **scale of 1 to 6**?

What do you think has happened to the **momentum** of the **first ball-bearing as a result of the collision**?

What do you think has happened to the **momentum** of the **second ball-bearing as a result of the collision**?

How do you think these two **changes compare with one another**?
How convinced are you that you're correct on a **scale of 1 to 6**?

What **links** can you see between this situation and the situation where the **car crashed into the wall**?

How would you **use the similarities** to **explain** what is happening in terms of momentum when the **car crashing into the wall**?

How convinced are you that your explanation is correct on a scale of 1 to 6?

Analogy Questions

What happened during the collision?

How will the **total amount of momentum before and after** the collision **compare** with one another, in your opinion?

How convinced are you that you're correct on a **scale of 1 to 6**?

What do you think has **happened to the momentum** during the collision?

How convinced are you that you're correct on a **scale of 1 to 6**?

What **similarities and differences** do you see between this situation and the **previous one**?

What **similarities and differences** can you see between this situation and the situation where the **car crashed into the wall**?

How would you **use the similarities** to **explain** what is happening **in terms of momentum** when the **car crashing into the wall**?

How convinced are you that your explanation is correct on a **scale of 1 to 6**?

Summary

Using what have been thinking about, can you **summarise** for me **why you think** the **momentum of the car is / isn't conserved** when the car hits the building?

Can you explain for me how you came to your conclusion?

How convinced are you that your answer is correct on the **scale of 1 - 6**?

Effectiveness of analogies

Which of the analogies were helpful in helping you to decide on your final answer?

How useful do you think the use of the sequence of analogies was in helping you to change your mind, or come up with your final answer?

Why were / weren't they useful?

Do you think that using a sequence of analogies like the one that you've been using would be a good way for you to learn other things in physics? Why / why not?

Extension

Using the ideas that you have been thinking about, can you **explain** to me **how momentum is conserved** when you walk along by **pushing your feet against the ground?**

Appendix 4: Inelastic collisions sequence interview questions

Preamble

Thanks for agreeing to this interview.

Are you ok with me taping it so that I can study what's said later?

(Perform sound check while making small talk with pupil).

We're going to be talking about some Physics; about what happens when objects collide with one another.

Scientists have an explanation concerning momentum and E_K which quite a lot of people say doesn't really make much sense to them. I'm going to take you through a series of analogies that might gradually help you to make sense of the scientist's explanation for yourself, with as little help from me as possible.

Do you know what an analogy is?

An analogy is where you say that one situation is like another in some way. For example, an electric current can be thought of, in some ways, as being like water flowing through a pipe so the water is the analogy for the current.

I'm sure that lots of your teachers will use analogies when they're trying to teach you facts or help you to make sense of something. They use them to help you to connect something that you already know about with the thing that you're trying to learn. However some analogies are better than others.

I want to find out whether or not each analogy, in the series that I show you, helps you to explain what happens in collisions in terms of the momentum and E_K.

I'm **particularly interested in what you're thinking at each stage** of the process. So please try to **think out loud as much as possible** and tell me exactly what you're thinking, because that will be very helpful.

I'll try to say very little other than to ask the questions that I have prepared, or to ask you to say a bit more, if necessary.

Preconceptions

We are going to be talking about momentum and kinetic energy during collisions.

Momentum

- Could you summarise for me what you **know and understand** about **momentum**?

- **How believable** do you find the idea that **momentum is conserved in any collision**, on a **scale of 1 – 6** (where 1 means 'not at all' and 6 means 'I'm totally sure'). Why have you rated yourself at that point on the scale?

- (Physicists think that **momentum is conserved in any collision**). Can you think of a **way of explaining** how or why that might happen, using any Physics that you know?

(*Potential* probes)

Concept

- **What** would you say the **'momentum'** of an object **tells us (or measures)** about it?

Equation

- Which quantities affect the amount of momentum that an object has?

- Why do you think momentum is specifically related to **velocity rather than speed**?

- What's the **equation** for momentum?

Conservation

- What do you think is **meant** when we say that momentum is **"conserved"**?

- Can you tell me of situations in real life where ***you*** think that momentum isn't conserved?
  Why do you think that momentum isn't conserved in that/those situation(s)?

Kinetic Energy

- Could you summarise for me what you **know and understand** about **kinetic energy**?

(*Potential* probes)

Concept

- What would you say the ‘kinetic energy’ of an object **tells us (or measure)** about it?

Equation

- Which quantities affect the amount of kinetic energy that an object has?
- What’s the **equation** for kinetic energy?

Momentum vs KE Differences

- How would you describe the ***difference between the momentum and the kinetic energy*** of an object?
- Do you think that they describe **and measure the same thing, or different things**, about a moving object?
- Why do you think they have different equations if they are the same?

or

- What do you think is the **difference between what they describe and measure**?

Collision Demonstrations

1. Elastic collision

Place two PASCO carts (which are identical, apart from their colours) on a track with their internal, repelling magnets facing one another. Get the student to push the first cart into the other stationary one.

Tell me, in as much detail as you can, **what has happened** after you pushed the first cart towards the second one?

How does the **velocity** of the **first cart** (that you pushed) before the collision appear to **compare** with the **velocity of the second** one after the collision?

Momentum

What does this suggest to you about **the total amount of momentum before and after** the collision has happened?

How convinced are you that you're correct on a **scale of 1 to 6**?

Use any Physics that you know to **explain** why you think that **momentum is (or isn't) conserved.**

How convinced are you that you're correct on a **scale of 1 to 6**?

(Display the equation $\mathbf{F \times t = \Delta p}$ on a piece of card if / when the student mentions it. If they don't mention it, show them the impulse equation and ask them if they can remember seeing it, or using it, in class).

Can you **use this equation** to **explain** the **changes in momentum for each cart** and how these **changes compare** with one another?

How convinced are you that you're correct on a **scale of 1 to 6**?

Kinetic Energy

How do you think the total amount of **kinetic energy before and after** the collision **compare** with one another?

How convinced are you that you're correct on a **scale of 1 to 6**?

Use any Physics that you know to **explain** why you think that the **kinetic energy is (or isn't) conserved**.

How convinced are you that you're correct on a **scale of 1 to 6**?

2. Inelastic Collision

Place the same two identical (other than their colours) PASCO carts on a track with one of their velcro pads facing the other cart, so that they will strike one another. Get the student to push the first cart into other stationary one.

Tell me, in as much detail as you can, **what has happened** after you pushed the first cart towards the second one?

Momentum

How do you think the **total amount** of **momentum** before and after the collision compare?
How convinced are you that you're correct on a **scale of 1 to 6**?

Use any Physics that you know to **explain** why you think that.
How convinced are you that you're correct on a **scale of 1 to 6**?

(Display the equation $\mathbf{F \times t = \Delta p}$ on a piece of card).

Can you use this equation to **explain the changes in momentum for each cart** and how these changes **compare with one another**?

Kinetic Energy

How do you think the **total amount** of **kinetic energy** before and after the collision compare?

How convinced are you that you're correct on a **scale of 1 to 6**?

Use any Physics that you know to **explain why you think that**.

How convinced are you that you're correct on a **scale of 1 to 6**?

3. Summary of Collisions

What differences do you think there are between these two collisions?

Analogy Questions

- Tell me, in as much detail as you can, **what has happened**?

Kinetic Energy

- **Describe what you think happened** in terms of the **type(s) and amount** of **energy** before and after the collision.

- Think about the total amount of **kinetic energy before and after** the collision. Are the values the **same or different** in your opinion?

- How convinced are you that you're correct on a **scale of 1 to 6**?

- **What do you think happened** to the original kinetic energy as a result of the collision? Explain your thinking process which led you come up with your answer?

- What do you think is **causing the sound (& heat) energy** to be produced after the collision?

- How convinced are you that you're correct on a **scale of 1 to 6**?

- Why has your rating changed? (if appropriate)

Momentum

- Think about the **total amount of momentum before and after** the collision. Are these two values the **same or different** in your opinion?

- How convinced are you that you're correct on a **scale of 1 to 6**?

- How would you **explain your reasons** for thinking that the **momentum is the same (or different)**?

- How convinced are you that you're correct on a **scale of 1 to 6**?

- Can you use the **impulse equation** to **explain** how the **changes in momentum** of the **two objects compare with one another**?

Analogy Analysis

- What **similarities or differences** do you see between this situation and the previous analogy?

- What **similarities or differences** do you see between this situation and the collision between the PASCO trolleys where the **two trolleys came into contact**?

- How would you **use the similarities** to **explain** (in terms of momentum and kinetic energy) what happens when the **two trolleys come into contact**?

- How convinced are you that you're correct on a **scale of 1 to 6**?

Summary

- Think back to the original collisions involving the PASCO carts.
- Using what you have been thinking about, can you explain why the collision in which the **carts struck** resulted in **kinetic energy being lost**?

Extension Question

- In the collision in which **the two magnets repelled** one another, how would you explain **why kinetic energy was not lost**?
- (What, if any, **significance** is there to the fact that in the case of the magnets, the two trolleys never actually came into **physical contact**?)
- Can you explain for me **how** you **came to your conclusion**?
- How convinced are you that your answer is correct on the **scale of 1 - 6**?

Effectiveness of analogies

- How **useful** do you think the use of the sequence of analogies was in helping you to change your mind, or come up with your final answer?
- **Which** of the **analogies** were **helpfu**l in helping you to decide on your final answer?
- **Why** were they **useful**?
- Do you think that using a sequence of analogies like the one that you've been using would be a **good way for you to learn other things in physics**? Why / why not?

Appendix 5: Interview analysis sheet - Immoveable object

Interview Analysis Sheet: Immoveable Object

Student Number: Final Higher Grade:

1. Initial definitions & concepts	**Comments**
Momentum	
Equation correctly known /not correctly known	
Considered to be a vector / scalar	
Confused with energy	
Confused with force	
Conservation of momentum	
Yes/No	
Belief rating : 1 – 6	
Kinetic energy	
Equation correctly known /not correctly known	
Considered to be a vector / scalar	
Confused with momentum	
Confused with force	

2. Analogical Sequence (Target / Analogy / Target Final)	**T**	**1**	**2**	**3**	**4**	**5**	**TF**
Momentum conserved? [Analogy / Target]							
(i) Object level (only one object discussed) [A/T]							
(ii) System level (transfer between 2 objects) [A/T]							
(iii) Universal level (transfer between 2 objects & ground) [A/T]							
Belief rating: 1 – 6 [A/T]							
Changing direction = change in momentum [A/T]							
Immoveable wall theory	T	1	2	3	4	5	TF
Momentum lost							
Momentum stays in car							
Momentum shared between wall and car, unclear method							
Momentum transferred to wall, unclear method							
Momentum transferred to wall, vague mention of large mass, small velocity							
Momentum transferred to wall, brick to brick							
Momentum transferred to wall, brick to brick, clear statement of large mass, small velocity							
Momentum transferred to wall and then transferred to earth.							
Increase in wall's momentum = decrease in car's momentum							
Other:							
Belief rating in theory : 1 - 6							
Thought process evidenced (ThProc)	T	1	2	3	4	5	TF
a) Confusion							
b) Logic							
c) Intelligibility (idea making sense)							
d) Inconsistent (changing their mind more than once)							
e) Twin Tracking (comparing two or more ideas)							
f) Making connections							
g) Cognitive conflict							
h) Other:							

Analogical Reasoning	**T**	**1**	**2**	**3**	**4**	**5**	**TF**
Similarities / Differences	T	1	2	3	4	5	TF
No. of surface similarities with previous analogy							
No. of deep (theory) similarities with previous analogy							
No. of surface similarities with target							
No. of deep (theory) similarities with target							
No. of differences stated (Previous Analogy / Target)							
Use of analogy for explanation (Fruitfulness)	T	1	2	3	4	5	TF
Analogy understood but no transfer to target – links not seen							
Link between analogy & target stated but not explained							
Target explained using only analogy surface features							
Theoretical principles transferred from analogy to target							
Type of Conceptual Change Evidenced (ConCh)	T	1	2	3	4	5	TF
a) Replacing central concepts to deal with new phenomena							
b) New material simply supports or exemplifies existing ideas							
c) Extension, modification or qualification of existing ideas							
d) Ideas become subsumed under the new proposition							
e) Change in acquired idea & associated cognitive structure							
f) Reorganising only within current context							
g) Complex system building – from bits of knowledge							
h) Target enriched with new concrete features							
i) New events simply added to existing model							
j) Model only modified (specific objects & events level only)							
k) Model and underlying theory modified							
l) Social rules only (doing what teacher has told them to do)							
m) Use of only existing concepts to deal with new phenomena							
n) Existing theory enriched							
o) Revision of specific theory (objects & properties level only)							
p) Revision of framework theory ('how things are')							
q) Category change from matter to process							
r) Connections made between new thinking and:							
(i) Analogy							
(ii) Existing mental model							
(iii) Prior experience							
(iv) Prior learning and knowledge (Physics)							
(v) Prior learning and knowledge (other subject)							
Change Triggers (ChTrig)	T	1	2	3	4	5	TF
a) Visual cues							
b) Faulty logic recognition							
c) Mis-fitting experience (cognitive conflict)							
d) Making connections with stated prior mental model/experience/learning							
e) Spontaneous generation of idea							
f) Transfer of Physics application to situation							
g) Experience (Analogy)							
h) Other:							

3. Review of analogical sequence	Comments
Most helpful analogies	
Reasons	
Sequence usefulness	
Learning usefulness	
4. Extension situation	
Conservation of energy when foot pushes against the ground	

Appendix 6: Interview analysis sheet – Elastic/inelastic collisions

Interview Analysis Sheet: Elastic / Inelastic Collisions

Student Number: Final Higher Grade:

1. Initial definitions & concepts	Comments
Momentum	
Equation correctly known / not correctly known	
Considered to be a vector / scalar	
Confused with energy	
Confused with force	
Conservation of momentum	
Elastic Collision: Yes / No	
Belief rating : 1 – 6	
Able to use $F \times t = \Delta p$ to explain conservation?	
Inelastic collision: Yes / No	
Belief rating : 1 – 6	
Able to use $F \times t = \Delta p$ to explain conservation?	
Kinetic energy	
Equation correctly known / not correctly known	
Considered to be a vector / scalar	
Confused with momentum	
Confused with force	
Conservation of kinetic energy	
Elastic Collision: Yes / No	
Belief rating : 1 – 6	
Reasoning	
Inelastic collision: Yes / No	
Belief rating : 1 – 6	
Reasoning	

2. Analogical Sequence (Target / Analogies / Target Final)	T	1	2	3	4	TF
Momentum conserved? [Analogy / Target]						
Belief rating: 1 – 6 [Analogy / Target]						
Kinetic Energy conserved? [Analogy / Target]						
Belief rating: 1 – 6 [Analogy / Target]						

Inelastic kinetic energy (KE) loss theory	T	1	2	3	4	TF
KE not lost						
KE lost, but not sure why						
KE energy lost as sound due to collision						
KE lost as sound & heat due to collision						
KE lost as sound due to vibrations from collision						
KE lost as sound & heat due to vibrations from collision						
Other:						
Belief rating in theory : 1 - 6						

Thought process evidenced (ThProc)	T	1	2	3	4	TF
a) Confusion						
b) Logic						
c) Intelligibility (idea making sense)						
d) Inconsistent (changing their mind more than once)						
e) Twin Tracking (comparing two or more ideas)						
f) Making Connections						
g) Cognitive conflict						
h) Other:						

Analogical Reasoning						
Similarities / Differences	T	1	2	3	4	TF
No. of surface similarities with previous analogy						
No. of deep (theory) similarities with previous analogy						
No. of surface similarities with target						
No. of deep (theory) similarities with target						
No. of differences stated (Previous Analogy / Target)						
Use of analogy for explanation (Fruitfulness)	T	1	2	3	4	TF
Analogy understood but no transfer to target – links not seen						
Link between analogy & target stated but not explained						
Target explained using only analogy surface features						
Theoretical principles transferred from analogy to target						
Type of Conceptual Change Evidenced (ConCh)	T	1	2	3	4	TF
a) Replacing central concepts to deal with new phenomena						
b) New material simply supports or exemplifies existing ideas						
c) Extension, modification or qualification of existing ideas						
d) Ideas become subsumed under the new proposition						
e) Change in acquired idea & associated cognitive structure						
f) Reorganising only within current context						
g) Complex system building – from bits of knowledge						
h) Target enriched with new concrete features						
i) New events simply added to existing model						
j) Model only modified (specific objects & events level only)						
k) Model and underlying theory modified						
l) Social rules only (doing what teacher has told them to do)						
m) Use of only existing concepts to deal with new phenomena						
n) Existing theory enriched						
o) Revision of specific theory (objects & properties level only)						
p) Revision of framework theory ('how things are')						
q) Category change from matter to process						
r) Connections made between new thinking and:						
(i) Analogy						
(ii) Existing mental model						
(iii) Prior experience						
(iv) Prior learning and knowledge (Physics)						
(v) Prior learning and knowledge (other subject)						
Change Triggers (ChTrig)	T	1	2	3	4	TF
a) Visual cues						
b) Faulty logic recognition						
c) Mis-fitting experience (cognitive conflict)						
d) Making connections with stated prior mental model/experience/learning						
e) Spontaneous generation of idea						
f) Transfer of Physics application to situation						
g) Experience (Analogy)						
h) Other:						
Elastic collision - kinetic energy (KE): final conservation theory	**Comments**					
KE conserved - no reason identified						
KE conserved - no contact						
KE conserved - no contact, so no vibrations to give sound						
KE conserved - no contact, so no vibrations giving sound or heat						
Belief rating in theory : 1 - 6						

3. Review of analogical sequence	Comments
Most helpful analogies	
Reasons	
Sequence usefulness	
Learning usefulness	

Appendix 7: Conceptual change criteria

Key for terms used

- **'Surface' similarity** – similarity limited to simple, descriptive properties of the two situations.
- **'Deep' similarity** – similarity extends to less obvious properties of a situation which are at a more theoretical level, regarding the way that the two situations 'work' or 'are'.
- **'Specific' theory** - theory that attempts to explain the physics involved that is limited to a discussion in terms of features of the target situation only. No reference is made to general principles or a wider context of applicability.
- **'Generalised' theory** - theory about momentum or kinetic energy conservation that does not just refer to the target situation which is being discussed. General principles rather than features of the specific target situation are mentioned.

Type of Conceptual Change Evidenced (ConCh)	**Evidence Criteria**
a) Replacing central concepts to deal with new phenomena [Accommodation (Posner et al.)]	**Generalised** theory (about momentum or kinetic energy conservation) **replaced or clearly changed.**
b) New material simply supports or exemplifies existing idea [Assimilation: Derivative learning (Ausubel)]	**No change** to previously stated **generalised** theory or **specific** (target situation) theory. Features of analogy used along with stated prior knowledge about momentum or kinetic energy
c) Extension, modification or qualification of existing idea [Assimilation: Correlative learning (Ausubel)]	**No change** to previously stated **generalised** theory or **specific** theory. Features from analogy added to either theory without other changes.
d) Ideas become subsumed under the new proposition [Assimilation: Superordinate learning (Ausubel)]	**No change** to previously stated **generalised** theory or **specific** theory. Previous statements about momentum or kinetic energy used to exemplify deep features from analogy
e) Change in acquired idea & associated cognitive structure [Meaningful learning (Ausubel)]	Previously stated **specific** theory **or generalised** theory **replaced or clearly changed** through new linkage with ideas, **surface or deep** features from analogy
f) Reorganising only within current context [Conceptual Ecology (di Sessa)]	**No change** to previously stated **generalised** theory or **specific** (target situation) theory. Only changes between successive analogies recognised.
g) Complex system building – from bits of knowledge [Conceptual Ecology (di Sessa)]	Previously stated **specific** theory **or generalised** theory **replaced or clearly changed** using ideas, **surface or deep** features from analogy, or other situation, that are linked for the first time.
h) Target or theory enriched with new features [Explanatory Model Construct. (Brown & Clement)]	Previously stated **specific or generalised** theory is **replaced or clearly changed** by including new **surface or deep** similarities from analogy.
i) New events simply added to existing model [Modelling (Tiberghien)]	Previously stated **specific** theory **unchanged**. **Surface level feature(s)** of the analogy **only mentioned** in relation to target for the first time. No generalisation stated / evident.

j) Model only modified (specific objects & events level only) [Modelling (Tiberghien)]	Previously stated **specific** theory **replaced or clearly changed**, with **references to deep similarities** between analogy and target situation. No generalisation stated / evident.
k) Model and underlying theory modified [Modelling (Tiberghien)]	**Generalised** theory replaced or clearly changed **and specific** theory about target situation replaced or clearly changed.
l) Social rules only (doing what teacher has told them to do) [Modelling (Tiberghien)]	Direct reference to classroom **teaching** or **teacher's statement**.
m) Use of only existing concepts to deal with new phenomena [Modelling (Tiberghien)]	Previously stated **specific** theory **unchanged**. No new ideas added to theory.
n) Existing theory enriched [Theory Restructuring (Vosniadou)]	New idea or surface level analogical similarity **added** to previously stated **specific** target situation theory.
o) Revision of specific theory (objects & properties level only) [Theory Restructuring (Vosniadou)]	Previously stated **specific** theory replaced or clearly changed with references to deep analogical similarities. No generalisation stated / evident.
p) Revision of framework theory ('how things are') [Theory Restructuring (Vosniadou)]	G**eneralised** theory replaced or clearly changed. Comments suggest they refer to how most, or all things 'work'.
q) Category change from matter to process [Category Re-assignment (Chi et al.)]	Clear change from momentum and / or kinetic energy being referred to as an **object** that is transferred, to being an **interaction** between objects involving mass and velocity.
r) Connections made between new thinking and:	
(i) Analogy	Statement linking analogy and new idea.
(ii) Existing mental model	Statement linking new thinking and previously discussed model / theory.
(iii) Prior experience	Statement linking thinking with prior everyday experience.
(iv) Prior learning and knowledge (Physics)	Statement linking thinking with prior piece of Physics knowledge.
(v) Prior learning and knowledge (other subject)	Statement linking thinking with prior piece of knowledge other than Physics.

Change Triggers (ChTrig)	
a) Visual cues	Realisation that they have connected ideas that don't follow on from one another or do not match up in some way
b) Faulty logic recognition	Realisation that they have connected ideas that don't follow on from one another or do not match up in some way
c) Mis-fitting experience (cognitive conflict)	Reference is made to a prior experience or idea that is not consistent with the student's current thinking. This conflict then results in new thinking or reasoning, rather than confusion.
d) Making connections with stated prior mental model/experience/learning	Prior ideas or experiences or learning is explicitly used in (a) justifying a change in a specific or general theory, or (b) used in coming up with a new view or idea about some aspect of thinking or reasoning
e) Spontaneous generation of idea	New thought process that is not stated as being linked to any previous theory, learning or thinking when the student is asked where inspiration for the idea came from.
f) Transfer of physics application to situation	Reference is made to some aspect of learning from the physics curriculum which is used to justify thinking or reasoning.

Appendix 8: Proposed lesson regarding the difference between momentum & kinetic energy

Several pieces of the previous research literature, as well as the consultation process with the staff in the Physics Department of Strathclyde University, clearly demonstrated the problematic nature for students of all ages in concisely defining the difference between momentum and kinetic energy. At an early stage in the design of the study, a number of options for lessons which were intended to teach students about the difference between momentum and kinetic energy were therefore considered and designed. These lessons were developed to potentially precede the use of the bridging analogy sequences that were the main focus of the research study.

The lessons would have included showing a specially shot video in which students would be shown a car braking to a halt from various different known speeds. The measurements given would allow students to see that when the initial speed was doubled, the breaking time also doubled but the breaking distance quadrupled, even although the braking force was kept constant. It was thought that this might assist students to understand the difference between momentum and kinetic energy, which was considered to be extremely difficult to comprehend.

The momentum, p is the product of an object's mass and velocity ($p = mv$). The change in momentum of an object being subjected to an external force is given by the impulse - momentum equation, $F \times t = \Delta p$. If the object is initially at rest then the change in momentum will be equal to the final momentum of the object. From this it can be seen that the amount of *momentum* that an object has is related to the *time* that the force needs to be applied in order to increase or decrease its speed.

In contrast, the change in kinetic energy of the object is given by the work - energy equation, E_K = work done so $E_K = F \times s$. If the object is initially at rest then the change in kinetic energy will be equal to the final kinetic energy of the object. From this it can be seen that the amount of *kinetic energy* that an object has is directly related to the *distance* over which the force is applied in order to increase or decrease its speed. The stopping *distance* is therefore related to the amount of kinetic energy ($E_K = ½ mv^2$) that the vehicle had since the amount of work done in stopping it is the same as the kinetic energy that it started with.

A second part of the planned lesson outline involved running a large remote controlled pick-up truck, into a pillow which was placed against a wall.

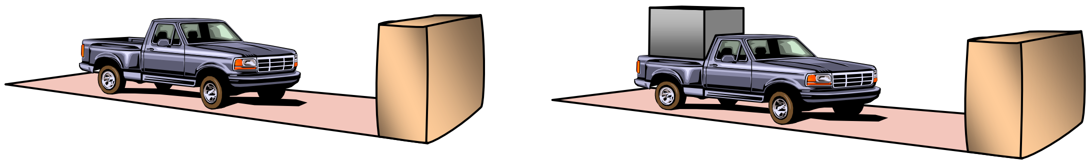


Figure A8.1: Running a remote controlled pick-up truck with different masses onboard into a pillow.

In this case the mass of the vehicle could be readily altered by placing items in its trailer section. This would allow the students to carry out some practical work rather than watching a video. The times and distances required to bring the vehicle to a halt would again be compared to see how changes to the mass affected the amount of momentum and kinetic energy that the moving vehicle had prior to the collision.

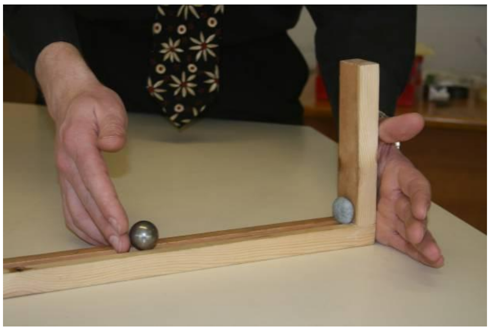
Appendix 9: Photographs of Analogy Experiments

A. Immoveable Object Analogy Sequence

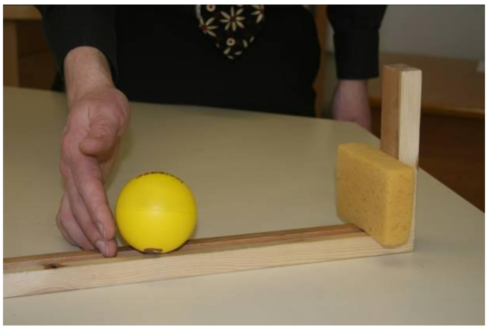
1. Ball running into identical ball.

2. Ball running into hand and stopping

3. Ball running into a set of identical balls.

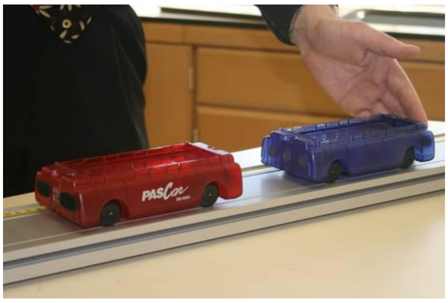


4. Ball running into blu-tac and stopping.



5. Sponge ball running into sponge and rebounding.

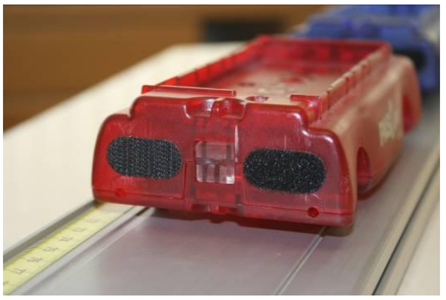
B. Elastic / Inelastic Collisions Target Situation



PASCO carts colliding elastically
(Magnet to magnet)

PASCO carts colliding inelastically
(Velcro to magnet)

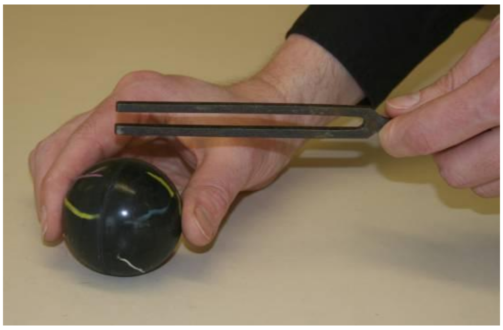
Close–up of PASCO cart - magnet end



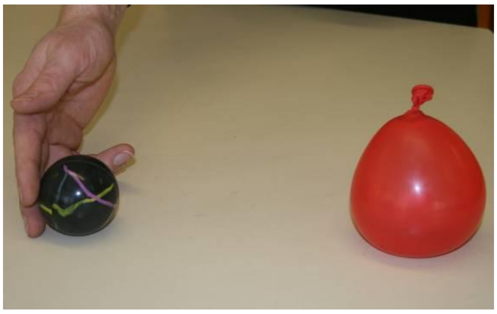
Close–up of PASCO cart - Velcro end

C. Elastic / Inelastic Analogy Sequence

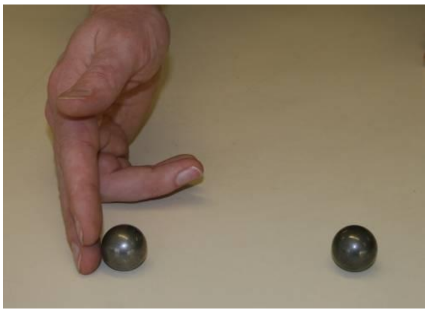
1. Tuning fork and hammer



2. Touching a rubber ball which is being struck with a tuning fork.



3. Rubber ball and water filled balloon



4. Ball bearings colliding inelastically (just)

Appendix 10: Analysis of interviews 1 and 14

Interview Analysis Sheet: Immoveable Object

Student Number: 1 Final Higher Grade: B

1. Initial definitions & concepts	Comments
Momentum	
Equation correctly known /not correctly known	Not given, but m and v known.
Considered to be a vector / scalar	Implied vector by velocity reference
Confused with energy Momentum/Ek mentioned interchangeably several times throughout.	
Confused with force	
Conservation of momentum	
Yes/No	Elastic correct, inelastic wrong.
Belief rating : 1 – 6	
Kinetic energy	
Equation correctly known /not correctly known	
Considered to be a vector / scalar	
Confused with momentum	Linked.
Confused with force	Linked [A2] Linked [A5]

2. Analogical Sequence (Target / Analogy / Target Final)	T	1	2	3	4	5	TF
Momentum conserved? [Analogy / Target]	✓	✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓
(i) Object level (only one object discussed) [A/T]							
(ii) System level (transfer between 2 objects) [A/T]		✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓
(iii) Universal level (transfer between 2 objects & ground) [A/T]							
Belief rating: 1 – 6 [A/T]	4	5	2/5	5/6	5/6	5/6 5	5
Changing direction = change in momentum [A/T]	✓		X X		X		

Immoveable wall theory	T	1	2	3	4	5	TF
Momentum lost							
Momentum stays in car							
Momentum shared between wall and car, unclear method	✓	✓	✓				
Momentum transferred to wall, unclear method (bricks involved)	✓	✓	✓		✓		
Momentum transferred to wall, brick to brick				✓		✓	✓
Momentum transferred to wall, ~~brick to brick~~, vague mention of large mass, small velocity			✓?				
Momentum transferred to wall, brick to brick, clear statement of large mass, small velocity							
Momentum transferred to wall and then transferred to earth.							
Increase in wall's momentum = decrease in car's momentum							
Other: Bricks breaking.			✓		✓	✓	✓
Belief rating in theory : 1 - 6				5/6	5/6	5	5

Thought process evidenced (ThProc)	T	1	2	3	4	5	TF
a) Confusion		✓Δmom.	✓	✓		✓	
b) Logic		✓		✓	✓	✓	
c) Intelligibility (idea making sense)		✓	✓	✓	✓	✓	
d) Inconsistent (changing their mind more than once)				✓			
e) Twin Tracking (comparing two or more ideas)		✓			✓	✓	
f) Making connections (Learning)(experience)	✓			✓			
g) Cognitive conflict Learning vs seeing.			✓		✓	✓	
h) Other: Trawling ideas / guessing.					✓	✓	

Damage idea changed to speed argument for transfer of mom.

change in mom. from 0 → moving → from fast → slow

Hard Sims — Spontaneous

Analogical Reasoning	T	1	2	3	4	5	TF
Similarities / Differences	T	1	2	3	4	5	TF
No. of surface similarities with previous analogy			1	[illegible]	1 Maybe 2		
No. of deep (theory) similarities with previous analogy				1	1		
No. of surface similarities with target		?	2	1	2	2 More?	
No. of deep (theory) similarities with target			1	1	1	1	
No. of differences stated (Previous Analogy / Target) Non opposing [illegible]		2	1	1			
Use of analogy for explanation (Fruitfulness)	T	1	2	3	4	5	TF
Analogy understood but no transfer to target – links not seen		✓					
Link between analogy & target stated but not explained							
Target explained using only analogy surface features			✓				
Theoretical principles transferred from analogy to target				✓	✓		
Type of Conceptual Change Evidenced (ConCh)	T	1	2	3	4	5	TF
a) Replacing central concepts to deal with new phenomena							
b) New material simply supports or exemplifies existing ideas						[illegible]	
c) Extension, modification or qualification of existing ideas		?✓	✓				
d) Ideas become subsumed under the new proposition				[illegible]			
e) Change in acquired idea & associated cognitive structure				✓		✓	✓
f) Reorganising only within current context							
g) Complex system building – from bits of knowledge				✓			✓
h) Target enriched with new concrete features				✓		✓	
i) New events simply added to existing model							
j) Model only modified (specific objects & events level only)				✓			
k) Model and underlying theory modified							✓
l) Social rules only (doing what teacher has told them to do)					✓		
m) Use of only existing concepts to deal with new phenomena							
n) Existing theory enriched							
o) Revision of specific theory (objects & properties level only)				✓			
p) Revision of framework theory ('how things are')							
q) Category change from matter to process							
r) Connections made between new thinking and:							
(i) Analogy		?	✓	✓	✓	✓	
(ii) Existing mental model							
(iii) Prior experience			✓	✓	✓		
(iv) Prior learning and knowledge (Physics)			✓			✓	
(v) Prior learning and knowledge (other subject)							
Change Triggers (ChTrig)	T	1	2	3	4	5	TF
a) Visual cues		✓(B)	✓	✓✓	✓✓	✓✓	✓
b) Faulty logic recognition						✓	✓
c) Mis-fitting experience (cognitive conflict)			✓				
d) Making connections with stated prior mental model/experience/learning			✓	✓	✓ from cog conflict	✓ from spontaneous idea	✓
e) Spontaneous generation of idea (after prompting a bit).				✓		✓	✓
f) Transfer of Physics application to situation			✓		✓	✓	✓
g) Other: Making sense.				✓			✓
g) Experience of analogy.					✓		

Good quote re not telling on p15

3. Review of analogical sequence	Comments
Most helpful analogies	3, 5 (linked to target) spontaneously.
Reasons Found hand analogy (2) hard to see as there was such a small impact (missed the point). although feeling it was quite helpful.	(3) "Could see the transfer of momentum" (5) See denting effect on wall. but couldn't see that with hand or bl[illegible]
Sequence usefulness	Can see it + goes with what we've been taught.
Learning usefulness "I like to memorise things"	Good as not theoretical situations Can see things happening ~~Good~~ to be able to apply situations
4. Extension situation	
Conservation of energy when foot pushes against the ground	Got idea that earth was moving small v, big m. after thinking about friction + gravel moving.

Ch Trig (d)(a). Th Proc(c)

Made good progress during review in terms of theory.

Interview 1

KM: First question: What can you tell me about momentum? You have been studying physics so what can you tell me about it?

S1: mm, momentum is a force and its mass on the move, it's when an object of a certain mass is moving and the force it creates

KM: now what would you say it's a measure of, when measuring momentum, what are you measuring?

S1: it's the …….kind of impact it has on another object

KM: ok that's fine …. And what are the quantities that are involved in it?

S1: eh….. the mass, kilograms and the velocity,

KM: why velocity?

S1: because its moving

KM: ok what's the difference between that and say speed, for example?

S1: velocity has a direction

KM: so does momentum have a direction?

S1: yes,

KM: ok now, one of the things that you have talked about before in physics would be conversation of momentum, can you tell me what you understand by that?

S1: mm, energy does not just disappear its usually used up in some way

KM: you have said energy there, is that different from momentum or the same?

S1: mmm…..I think they are linked, I'm not sure they are the same

KM: go on

S1: mmmm….. because momentum will if its moving then it has energy it is kinetic energy, and if something is fallen then it has potential energy, but

KM: how does that link to momentum?

Momentum + E_K mixed together.

1

S1: just by the fact that it's moving

KM: because you have two moving objects your saying that means there must be a link to momentum and kinetic energy

S1: yeah

KM: are you sure, or not sure, how they are linked, any thoughts?

S1: I'm sure they're linked because the fact they are both moving and … when…if.. two objects are moving or one that's moving or ones that's still then if they collide then you will have energy and then energy change.

KM: going back to conversation of momentum, would you say that's always true, or do you think there is situations where its maybe isn't true?

S1: mmm… inelastic collisions??

KM: tell me about them

S1: eh in an elastic collision the momentum is conserved and the energy is conserved but in the inelastic, the energy is conserved but the momentum is not.

KM: are you sure about that? You don't look very sure.

S1: Ah, no, because you were looking at me like I was talking rubbish, I was a bit worried, ha ha ha

KM: im trying not to tell you the answers yeah,

S1: yeah

KM: ok, deliberately trying not to give anything away. So are you thinking then that momentum isn't conserved all the time or it is?

S1: ……. I think it is, I've changed my mind, I think it is conserved

KM: why have you changed?

S1: just because of thinking of situation, about momentum in the real world, and what would happen, I think it is

KM: so you think it's always conserved or just sometimes?

S1: mmm I say it was always conserved

Elastic Inelastic Collisions

2

[T]

KM: ok, what we are going to do then is, to look at a situation where some people struggle with that idea, ok, and I would like you to tell me, what you think in this picture would happen to this car. So this car is running into a brick wall, its part of a building or it might just be a big sturdy wall and its crashing into that, tell me, in terms of momentum particularly, what you think is going to happen?

S1: mmm… … some of the momentum would go against the wall and the wall would be damaged but the car would be mostly damaged

KM: ok, now in terms of the total amount of momentum before and after, what would you think is going on?

S1: mmmm…….. total momentum before would equal the total momentum after

KM: ok now, how convinced are you that you are right, if I ask you, (I'll do this several times), to rate yourself in a scale of 1 to 6, 1 means you're not very sure at all and are really not convinced , up to 6 means you are completely positive,

S1: ok

KM: where would you put yourself?

S1: mm .. 4 [Cons B4.]

KM: why have you put yourself at a 4?

S1: because I can see it my head what would happen, and because of the stuff I know about momentum and the equations we have learned.

KM: ok so you think on that roughly a 4 for momentum concervation. Ok what's going to happen to the car after it hits the wall, what happens next, if you watched it.

S1: it could be either bounce back, kinda move in and then move back slightly and then. Or it could depending probably on how good the wall is, the wall could be damaged, it might just stop.

KM: so why would you say that momentum is being conserved here? If I was to ask you to explain how it's being conserved, how would you explain it?

S1: well, because the car has momentum, and when the car stops the momentum has to be transferred, so that probably why the momentum has to be transferred, so that probably why the wall and the car becomes damaged.

KM: so where is the momentum being transferred to?

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S1: if the car bounces back then the momentum maybe changing direction or if the wall is damaged then it would, kinda momentum, would kinda be transferred to the bricks of the wall [Change direction]

KM: right lets have a look then, and see how we get on with these, that's the picture of afterwards, is that roughly what you were describing?

S1: yeah

[A1] KM: the car being damaged, moving backwards, ok, lets move on to the first analogy then, what I'm going to get you to do is, just with 2 of these balls I want you to run one of the balls in to the other and describe to me what's happening during the collision? [Th Prz(a)]

S1: mm, the kinetic energy or the momentum of the first ball has kinda been transferred to the second and so that kinda moves of but this one still contains some of it, so that ones moves off slower than this one started [p/Ek confused.]

KM: ok in terms of the total momentum before and after, for the two balls when you take both into consideration before and after, how would the two values would compare? [May not be confusion? Ek and p both transferred. Student might be distinguishing them.]

S1: of the conservation of energy you say?

KM: no, just tell me how much energy, not energy, momentum, sorry, how much momentum would you say there is, totally before compared to total after?

S1: it would be the same just maybe shared between the two

KM: ok give me on the scale of 1 to 6 how convinced you are you are right?

S1: …..5 [Cons B5 A]

KM: why has 5 changed from the 4 before?

S1: bit more sure now, because it's kinda a visual thing you can kinda see what you think [ChTr(a) QUOTE]

KM: ok , now, why do you think it is the same as before and after can you give me the reasoning in your head?

S1: well because……this one has more velocity than the second when it moves off, but, this one still continues to move, so kinda thinking that…..

KM: the first one

4

S1: yeah, so I mean if you hit it then that ones going faster, but then that one moves off slower but this one still moves off a bit. So I'm guessing if you worked it out and add it up then it would be the same.

Th Proc (a)

KM: I'm deliberately not getting you to work it out, I'm going for gut feeling. Ok, you have answered this, but what would you say is happening to the first ball bearing when it hits the second?

S1: momentum is transferred, but not all of it that why it kept on moving

KM: ok, what's happening to the momentum of the second ball as a result of the collision?

S1: ...its...... gaining momentum

Th Proc (b)(c).

KM: from where?

S1: from the first ball, because it still doesn't have any momentum

KM: how do you think the change in momentum in the first ball, that you talked about, compares with the change the second balls got?

S1: ... well the first ball went from moving quickly to moving slowly, this one went from moving - from still to moving, so I'm guessing its probably a bigger change in momentum for the second one

KM: why you saying bigger in the second?

S1: because its going form still to moving and the second is from fast to slow

KM: so if it's a bigger change form the second than the first then where did they get that bigger change from do you think?

S1: I think most of the momentum from here was transferred to this one, the second ball. But, the first one still has some of it so...

KM: so if that still got some momentum left, what is your thinking that arrives you at you saying that this has a bigger change in momentum in that one?

S1: ...just really because its moving from fast to slow for the first one because it still moves but this one being from still and then moving away, there is a bigger change going from still to moving, than from just fast to slow.

KM: how convinced are you that you are right? On the same 1 to 6 scale?

S1: pretty sure, I'm about a 5 again.

Con B5 4.

5

KM: now, using the similarities between what you have done here and the car hitting the wall, can you have a go at explain what similarities you see and how you use it to explain this to somebody? Or differences you can describe as well?

S1: well, with the balls, this one can move, Difference (wall cant move).

KM: the second one

S1: yeah the second one is able to move, so I mean obviously the wall can't move, so, hmm, the first ball hitting it, if this one is still then that will probably move back, and because they are different mass this one could get damaged ...

KM: are these balls different mass?

S1: don't think so

KM: no they are meant, should, to be the same,

S1: yeah, that's what I meant about theses two being different and this being the same, Difference (mass)

KM: the car and the wall

S1: ok, yeah the car and wall, these are the same but ...

KM: so do you think that the physics argument that you a re giving me here is anyway related to the physics argument here? How would you explain that to somebody?

S1: well, kinda like, having a difference of mass, and one being still and one being moving, and looks the same thing that has been applied here apart from this can move, and if theses very different, the balls being a difference mass, then the ball that was moving, if the second one was still thelit would still move back off it, if it was going a certain speed and

Vague Similarity

Wall theory (vague).

KM: so do you think they are linked?

S1: yeah

KM: ok, lets move onto the second analogy, and what I want you to do this time, you can put your hand on here or you can do it on the desk, whatever you like, and basically I want you to roll one of the balls into your hand and we will concentrate particularly on your hand here, what do you think your hand is representing in the initial situation?

S1: eh the wall, Sim (Surface)

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KM: ok so think about that, and then run the ball reasonably quickly into your hand, and then trap the ball with your hand

S1: trap it?

KM: try and just hold it. Ok, lets go a wee bit faster than that, ok, so that's not all that quick. Now tell me what you notice happening during the collision, what are you noticing?

S1: you can feel it, hitting and then moving away

KM: ok, or if you caught it would not move away. So what is happening to your hand during the collision would you say

S1: … … probably using the momentum and some of the eneregy

KM: so how would you explain that?

S1: probably with the fact the ball hits it and then unless it was cracked it would move off at a sort of speed

KM: ok now, it terms of the total momentum before the ball hit your hand and the total momentum after the ball hit your hand, if you assume at the moment, that you have grabbed it, how do they compare?

S1: hmmm, if you grabbed the ball?

KM: yeah, it's the impact point I'm really interested in. grabbing is slightly artificial.

S1: I don't know, my hand sort of moved back slightly when it, I mean like,(lots of mumbling) I can feel it like dented my skin kinda!

KM: ok, and so what are you saying about the momentum before and after?

S1: hmmm ……I would say it was conserved,

KM: the total before is the same as the total after?

S1: yeah,

KM: how convinced are you on a scale form one to six.

S1: not really, hmm, about a 2

KM: why has it gone down?

S1: don't know because its kinda like what I know from like, doing physics, but its not really what you see from doing it.

KM: so, why are you giving a 2 at all? What is that to do with?

S1: like why its not a one?

KM: yeah

S1: I don't know I kinda trust what I have learned more than what I see

KM: that interesting, so tell me about, you said about your hand denting, what has that got to do with it?

S1: it shows that some of the energy has been kinda, em, exerted into my hand or some of the force

KM: so what about momentum? How does that fit in?

S1: probably means that some of the momentum has been transferred into my hand

KM: some or all would you say?

S1: well, unless I grab it, it moves back, so I'm guessing some of it,

KM: and if we assume it does move back what differences would that mean to your answers? If you haven't grabbed it?

S1: alright, then yeah, I would say that definitely some has been when its not moving back, at the same velocity because, part of my hand has gained some of the momentum.

KM: so, if I asked you, if I let you bounce of your hand, how convinced are you that the momentum is conserved? In that situation? On that one to six again

S1: with the hand thing how convinced am I that the momentum is conserved?

KM: yeah, how believable it is?

S1: …… 5

KM: so why has it gone from a 2 to a 5?

S1: it's a different question isn't it?

KM: not really, its still a ball hitting your hand is it not?

S1: yeah,

KM: the only difference is, whether you grab it or not.

S1: I know, I'm confused in a way, yeah I would say it was a 5 because emm, don't know I kinda makes more sense when I think about it, like moving away rather than me grabbing it.

KM: so it's got some thing to do with the fact that its bouncing back, that makes you feel that it more like, it feels more that momentum is being conserved there?

S1: yeah, like, it's like something like grabbing like a tennis ball in their hand, or something like that and it was going fast and you can kinda see that your hand went, (smack)

KM: but if you moved that fast enough would that happen?

S1: I'm guessing, because it's quite heavy?

KM: now, in terms of, what happening to the momentum, eh, what similarities, lets go back to that, what similarities do you see between this situation and the previous one?

S1: about the car?

KM: the previous one, where you had the one ball bearing hitting into the another one, what similarities or differences do you see?

S1: similarities are …..my hand, I can feel it moving and so the pressure in,my hand, obviously my hand has a bigger mass than the ball, so its not going move away as much, and you can still see the ball either em, well before it moved , kept going in the same direction, but this time, probably because its more sturdy its not able to move, its going back the way.

KM: what similarities or differences, do you see between the ball and the hand and the car with the brick wall or the building?

S1: oh, there are very similar.

KM: why?

S1: well because, car is lighter than the brick wall, so its kinda hitting it and then moving back, which is the same thing that happens with the hand.

KM: in terms of your hand and the wall, do you see any similarities?

S1: yeah because it's kinda bigger and more immovable

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KM: ok in terms of the physics? What's going on, do you see anything?

S1: yeah.

KM: what do you see?

S1: it's kinda the same thing, but its like conservation of the momentum,

KM: so how would use that analogy, then, to explain to someone that didn't understand what was going on with the car and the brick wall?

S1: I would say that, when an object is moving and it hits an object of greater mass, or something that is more, like it can't be moved then, some of the energy will be transferred, but it will also be kept in the object and move back the way , and change direction.

KM: so how would you explain this big building moving?

S1: bricks being crushed

KM: so, an individual brick, gets squeezed up, is that what you are saying?

S1: well like, if you drop a brick on the floor then it will break, so probably, the car hitting it, would cause the momentum to kinda go woooomphh, and the force would cause the bricks to breaks,

KM: so it's just because the bricks break, that you think that it works, or is there something else, kinda?

S1: no, because the car slows down when it moves and changes direction, so you have to lose some of the momentum somewhere, otherwise, it would go, and move back at the same speed,

KM: ok lets me jut clarify, you said there that you would lose some momentum there?

S1: no no no, you wouldn't lose it, it would be transferred.

KM: to what???

S1: the wall

KM: ok let's move on to the next analogy. Now I'm going to give you three ball bearings, which has got very very slightly separated, ok, I want you to run that ball bearing into them, reasonably quickly. And tell me what you see happening?

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KM: you can do it several times, if you want?

S1: I didn't think that would happen………………… Ok, that's what I thought would happen

KM: now, you said a second ago that isn't what you thought would happen, what was strange?

S1: like, they all slight separated, I rolled that one into all those 3, and then just one moved off,, and the others just stayed where they were,

KM: and not move at all?

S1: not really

KM: try it again.

S1: yeah, they moved a tiny bit,

KM: until what happened?

S1: until …. That one had moved off

KM: so what happened to the first ball? When it was hit by the moving one?

S1: it probably had the momentum and it kinda transferred it to that, which transferred it to that and that had nothing to stop it so that one went off.

KM: so basically, are you saying then, that the momentum is transferred from one ball to the next to the next?

S1: Yeah

KM: now, if I was to ask you before and after that interaction, the total momentum before the total momentum after, what would you be saying?

S1: eh, they're the same

KM: how convinced are you that you are right?

S1: 5/6 Con B 5/6 4.

KM: so why are you more convinced this time, because last time you where a 4 or a 5, I think?

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S1: yeah, eh, before or after this?

KM: just now, why are you more confident in this case than the previous one?

S1: you can see it more clearly, that, em don't now, visualise it CKTrig (a).

KM: when you say visualise it what do you mean?

S1: not really visualise it, you can see it right in front of you, em, I don't know its just, you can really see it happening, I mean that there is no real change, in like, the energy, or the momentum, it kinda …….. QUOTE ?

KM: why are you saying that?

S1: well, because if you move this one quickly, that one doesn't move off slowly, it moves of quickly as well.

KM: so, how does the speeds compare, is that what you are judging it by?

S1: yeah, kinda.

KM: and what are you saying about the speeds of the first ball and the final ball?

S1: roughly the same, not a lot of momentum is lost, but before it was hitting against a wall then you couldn't really

KM: now that's an interesting phrase, you say that not a lot of momentum is lost and yet you are saying 5 or 6 for conservation?

S1: hmm, sorry I'm getting really mixed up now, Th Proc. (a) (d)

KM: I'm just asking questions to clarify!

S1: yeah no, not a lot of em………….. em …. Velocity has been lost.

KM: so what you are saying is, you you think the overall the total momentums probably the same, is that what you are saying?

S1: yeah yeah, the momentum is the same.

KM: right, now, em, how convinced are you, on a scale to 1 to 6 that that's right, oh we have done that sorry, yeah"! What similarities or differences do you see between this situation and the one before with your hand?

S1: hmm,

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KM: with one ball in your hand and this is one ball hitting three balls?

S1: the differences is that they are moving off in the same direction, ~~that~~ and the similarities are that the, I suppose you are still getting a change, in the momentum.

KM: tell me more about that?

S1: well, in your hand, you can't see, that or the wall, you can't see that, you gain momentum as well, because you're kinda invisible

KM: so how did you know that you had gained momentum?

S1: because you can feel it, or visualise it, the car and the wall thing, but with these you can actually see that one moving off,

KM: now how would you use that analogy there, to explain to somebody that didn't understand what was going here? Could you use that?

S1: not really, em, it would kinda show how the momentum can be transferred but it wouldn't really show what would happen with the car and the wall

KM: what represents what here?

S1: wall, car [pointing]

KM: so the single ball represents the car, and the three balls represent the wall?

S1: yeah

KM: so can you think of any similarities or differences between the three balls and the wall that might help explain it?

S1: yeah, well, the difference is that these are, these can be moved, but you can still see the change, the transfer of the momentum from the car to the wall and this ball to the three balls.

KM: and how would you use that to explain the car hitting the brick wall? Any thoughts on that?

S1: mmm, ……

KM: any significance that the fact there is several balls here, compared to the wall for example?

S1: yeah, kinda, it kinda makes it a bit more, sturdy-ish

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KM: do you think there is any link between several balls and several bricks for example?

S1: hmm, maybe yeah, just trying to think

KM: try to the think out loud…. What are you thinking?

S1: well like, I don't know, if a car hit a thin brick wall, then like, or maybe if there was just like 2 bricks in line and a car hit it, then, both would be damaged, sort of thing, but in this kinda like, you just said the fact that, well yeah that's the same because both would be damaged, which kinda shows that, the momentum from one would transfer to the other one which is what is happening here, because if this one hits it here, then say, and that could damage it then the momentum is transferred because it moves and this one moves up.

KM: now, I'm interested in you saying damaged here, is that first ball being damaged?

S1: no

KM: is the momentum being transferred ~~form~~ from the first ball to the second? So are, tell me what your thoughts are regarding damage and transfer of momentum, does one need the other to be true?

S1: ……

KM: do you need to damage something to get momentum transferred to it?

S1: no no, but like, just like, if you think about it visually, its easier to think about it, because you can actually see damage but you can't sometimes – you can't see momentum.

KM: so taking that, lets say that there wasn't obvious damage to that wall, would that mean, it hadnt had momentum transferred to it?

S1: no, because the car, would move off slower,

KM: so how would you explain using this, how we are transferring momentum?

S1: because even though, the first ball hits the second, the first of the three, it's the third one that moves off, and that hasn't been hit.

KM: so, what do you think is going on in the wall that is maybe similar or maybe you think its totally different, tell me what you think?

S1: hmm. ..the bricks, could still feel like, kinda,, I don't know how to say that, but like, it would not just be at the front of the wall, that would feel momentum

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KM: so where would the momentum go?

S1: it depends, how hard it struck it.

KM: say it was 50 mph or something like that, it was fairly hard hit, where would the momentum go?

S1: hmm, I think into the wall

KM: it could be a whole building, it doesn't make much difference

S1: maybe, a metre, half a metre

KM: so you think the momentum is going into the wall in some way, travelling through the wall?

S1: yeah, brick by brick, kinda like ball by ball

KM: do you see that this is showing that? Is that where you got that from or? Ok how convinced are you that this theory you have come up with is right?

S1: mmm, I was pretty sure until you said theory, hahaha,

KM: I'm just using that as a word, because thats all a theory is, its your ideas, don't assume anything from that word.

S1: probably about, ……5, 5 or 6, I don't want to be completely sure,

KM: why, are you putting it as a 5, that's quite a strong ……?

S1: yeahhh, I think ……it makes sense, you can see it happening, I mean…..

KM: why does it make sense?

S1: because whenever you do something, I mean it not, just a very, the bit that you hit that becomes damaged again, I mean, it's the whole bit around it, so momentum must be being moved, kinda transferred.

KM: what are you basing, 'it makes sense' on?

S1: just kinda making me think, kinda….cos like, if you punch, put your hand through a window, then it would be just a clear cut, the whole would be spread out.

KM: so you are basing it on other experiences that you have had?

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S1: I don't really put my hand through window!!

KM: I know that, but you are thinking processes are based on what you already know from other situations, is that what you are saying?

S1: yeah, its kinda like, not really common sense but what you could see happening or what… you know. But also from the ball thing, because I think that kinda shows it well, from the fact that you know, one moves off,

KM: ok lets move on to the next analogy, this time we are going to take this ball and we are going to run it into the blue tank, I have deliberately made a slight dent in the blue tack, so it will catch the ball, ok? So run that into the blue tack and put your hand behind the, behind here, so just put the palm of your hand, or your fingers, whatever, against the wood, and then run it fairly fast into the blue tank. Now tell me what you are seeing or noticing going on during this collision?

S1: well it hits it and then it moves off again, but the whole wood thing moves

KM: how do you know that?

S1: I can fell it

KM: so you are feeling some kinda of movement?

S1: and I can see it.

KM: right, so, there is a whole movement going on there. What would you say about the total momentum before, ie of the ball, compared to the total of the system afterwards, how do they compare?

S1: they are equal

KM: how convinced are u?

S1: very, 5 …..6

KM: why is it as strong as that, explain your reasoning?

S1: because …….again because what I have studied in physics and the fact that I can see it moving and moving off again

KM: ok so, so is it from what you have been taught mainly and what you can see?

S1: yeah, mainly, if I didn't know the total momentum before these collisions and things, equals the total of momentum after. Then I might not think that, but I probably would have a guess, because I can see it happening.

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KM: ok, now, what do you think is going on here, explain to me what is going on, in this collision then?

S1: ....mmm....im guessing your using blue tac as it is stickyish, maybe.

KM: so so, in terms of the momentum, tell me what is going on?

S1: mm......I'm guessing the blue tac absorbs, or is transferred some of the momentum from the ball, and then the ball, also keeps some of the momentum, so that's why it moves off again.

KM: sow what about the fact that you could feel the thing moving with your hand. How do you explain that?

S1: it shows that, its being transferred because...

KM: to where?

S1: it shows that, it has been transferred because,

KM: to where?

S1: from the blue tack probably to this whole wooden structure thing, and to my hand.

KM: so you reckon that there is momentum being transferred from the ball thorough the blue tack through the wood, to your hand?

S1: yeah, kinda like the thing with the balls and the brick.

KM: now, go back then, as you have just rightly mentioned there, to some similarities and difference, the last one you had one ball hitting three balls, this one ball hitting blue tack and so on. What similarities or differences do you see?

S1: hmmm. The similarities that kinda like from impact,....it moves, ...but .....its not like, I don't know, its probably trying to transfer in some way, but you don't see just the transfer of it so clearly, you don't see how it hits one and then affects the very last one, at the end of the line, I don't know, (mumbling) my hand it moved.

KM: what is your hand equivalent too? In the previous analogy?

S1: it would be the third ball, but it doesn't really move,

KM: is it obviously?

S1: yeah, yeah,

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KM: your fairly sure it does move?

S1: yeah

KM: ok what about, in terms of this analogy and the original with the car, how do they compare?

S1: pretty well because you see the wall hit and head off, the ball hits and moves off, but you also see the impact that it would have on the wall.

KM: tell me more about that?

S1: well, I think that the wall would be damaged, and the kinda movement of the aparatus, it show that it wouldn't just hit and back off, it would actually have some impact and some force on it

KM: so tell me in terms of momentum, what you think is happening here? In other words try an use this to explain to me what is going on in terms of momentum in this crash?

S1: well the car has momentum, it hits the wall, some of the momentum is transferred to the wall, but the car keeps some of the momentum and moves backwards.

KM: so how would you use this to explain to someone that momentum is being transferred to the wall, because they didn't believe you?

S1: well, by the fact you can feel it by putting your hand there, or if you didn't, then you could see that it moves.

KM: so, because you can see a small amount of moment and you can feel a small amount of movement there must be a transfer?

S1: yeah, so otherwise it just wouldn't move.

KM: ok, despite the fact, in this situation you can't see the building move?

S1: yeah

KM: how convinced are you, that you are right? That the building gets some of this momentum transferred to it?

S1: mmm, 5, 6

KM: pretty strong

S1: yeah

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AS KM: ok lets move on to the last one, which is a wee bit different, this time I'm going to give you a sponge ball, and I'm going to put a sponge instead of the blue tack at the end, and I don't want you to hold it this time, as in the wooden block, I just want you to run the sponge ball into the wooden set up, and see what happens? Maybe a bit quicker if you like! Try hit it at an angle, its bouncing off, its not quite central, ok try it now. Tell me what you noticed?

S1: yeah, it moves

KM: whats 'it'?

S1: the apparatus and the sponge.

KM: the apparatus and the sponge. Anything you noticed during the collision going on?

S1: ... it bounces back off it

KM: tell me about the sponge, is there anything happening to the sponge?

S1: don't know, is it becoming dented or something? It's moving on its own

KM:. Explain what you mean by that?

S1: eh, … it contracted, kinda

KM: . so it gave a wee bit, is that what you are saying?

S1: yeah

KM: now, how, what are you saying, in terms of momentum here, before and after, total before versus total after?

S1: they're the same

KM: how convinced are you?

S1: 5 A Con B 5

KM: so why are you saying a 5? What's your thinking process that makes you say that?

S1: because, the ball runs in, causes the sponge, when it hits it, to contract and so then there has been some change, transfer there, and then … it runs back off again, back the way, changes direction.

KM: tell me about the sponge and the wood and so on?

S1: it moves, like,

KM: is it moving a lot or a little?

S1: not as much as it was before,

KM: so why are you still thinking it has conserved if its hardly, moving at all?

Th Proc (c) S1: becuse the sponge contracts which is probably using the same momentum more, then when it just kinda just straight on, so it's probably… ChTry(a).

KM: is this wood getting any of the momentum?

S1: yeah

KM: how do you know?

S1: because the whole thing is moving and..

KM: so despite the fact this is a solid object, right, you are still saying that it's getting momentum transferred to it?

S1: yeah

KM: how convinced are you about your ideas?

S1: very convinced, 5 6,

KM: 5 6 ok. What similarities and differences do you see between this one and the previous one, when you had your hand and the blue tack and so on?

S1: it doesn't kinda, it moves away faster than the other one did, um, but you can also kinda see the impact it has more on this one, than you could see on the blue tack, im guessing probably, that the blue tack did the same thing, but you just couldn't see it.

KM: and what about the wood part? Are there any similarities or differences there? A 5 cns

S1: yeah, it's the same basically, I think, they are still moving. Surface 2.

KM: now, going back to our car hitting the wall for the last time, ok, can you use what you have done here, to explain this to someone that didn't understand what you are now thinking?

S1: ok, well, .. the car is the ball and it moves with momentum and when it hits the sponge or the wall, the wall becomes, the wall gets transferred some if the momentum from the car which goes, from like, it make the sponge dent, and it also makes the (mumble) move, so you can see some of the momentum has been transferred.

KM: so there is s mall movement in the whole thing, is that hat you are saying?

S1: yeah, that wouldn't happen with the wall,

KM: would the wall not move at all?

S1: uuu… no. probably not, it's looking pretty big, so I'm guessing it wouldn't move

KM: so how do you explain then that the momentum is being transferred to the wall? If you are saying that it's not moving

S1: you can see you see that the sponge doesn't move, the whole thing moves, but the sponge still contracts.

KM: so you have said there that the whole thing moves, is there a equivalent in this situation?

S1: these would probably be, the kinda, first bricks, around where the car hits, that's what im guessing.

KM: so, you're saying that there is a little bit of movement in the wall somewhere, but you are not totally sure how, that ends up, in the fullness of time?

S1: well, I mean, I'm not really sure unless you actually drive a car into a wall, the you wouldn't really, I mean like, it would be where the car hit it probably

KM: it would be where the movement was?

S1: yeah

KM: you would still say that this is totally conserved yeah? The momentum is totally conserved when you crash your car into a big building, lets say?

S1: well, I'm really confused, when you say conserved, does that mean, that you can …

KM: the total before, if we are saying it's completely conserved then it means the total after is the same as it was before. So how would you explain then to someone, that says, this is a big building Rachel, how in earth can you say that this is conserved?

S1: em well if momentum wasn't conserved then there would be no force in the bricks and nothing would happen

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KM: and you are saying there is a bit of movement in that brick wall or that building or whatever it happens to be?

S1: yeah, like you can see that the sponge

KM: ok, lets just finish off then with a couple off of questions that, once I can find them, you have kinda given me a summery there, how convinced are you that you are right?

S1: pretty convinced, I would give it an overall 5,

KM: with you theory?

S1: yeah

KM: in terms of those analogies, which ones would you say, which ones would confirm the whole lot, which ones would you say where helpful coming to your conclusion?

S1: hmmm, that one, number 3, the ball, the ball running into the set of identical balls,

KM: why was that effective?

S1: you could see the transfer of momentum

KM: from one to another to another, is that the idea? Was there any others helpful?

S1: yeah the one about the sponge and the one about the car, I liked

KM: that's just the, we call these the target situations, so these are the analogies. How was the sponge helpful?

S1: you could kinda see what affect it would have on an actual wall and the fact that it gets dented, where you couldn't actually see that with the blue tack or when it went into your hand, but I didn't like the one about the hand

KM: why didn't you like that one?

S1: I don't know, I found it kinda difficult to see and there was such little impact

KM: did the fact that you could feel it help at all?

S1: yeah it did but it like, I don't know, if you did it with this one, it would be better as you could feel it a bit more, or maybe something like a big tennis ball

KM: well that's fairly hard, so?

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S1: yeah, but it was really tiny

KM: so it was the size more than the heaviness. Now, if you were learning something new, if you think, this is just your opinion you can say what you like here, do you think that this way of learning would be good or bad, and if so why?

S1: ummm…

KM: other things in physics lets say? If we could get this kinda of sequence going for this type of topics?

S1: I think it would be good, because it gets you to like, I don't know for other people but I kinda like to memorise thing then applying it, but I think, this was quite good as well, which is kinda different for me

KM: why is it good would you say?

S1: you just feel kinda, its not really theoretical situations, its kinda stuff that you can see happening but its also good to be able to apply it .. things like the ball and sponge to a car crash.

KM: now at no stage have I told you, that you are right or wrong, does that, are you still fairly happy that you have got a more or less right answer, Ill tell you later, but are you fairly sure that you have the right answer here, or what scientists say at least are the right answers …..

S1: hmmm.. … yeah! Yeah I would, if I wasn't then, I kinda couldn't have keep coming up with answers.

KM: what has led you to think, that you're right, why do you think now that you are right?

S1: just because I think you can see it right in front of you and it goes with what we have been taught

KM: let me ask you a quick extension question, can you use any of this to explain this situation to me, when you walk along the ground, planet earth, walking out, not in a building, just out on the ground and you are just walking along, your moving forward, can you explain to me, how momentum is being conserved in that situation?

S1: when I am just walking along the ground?

KM: yeah, because you are moving and you weren't before when you were standing still, so how come, momentum is conserved? Can you use anything that you have learned here to explain it?

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S1: between me standing still and then moving?

KM: yeah

S1: hmm… maybe my force in the ground

KM: keep going, tell me more?

S1: like, kinda, umm,, I don't know, the weight from the gravitational force field and stuff like that, to the mass on the ground and then…

KM: so you weren't moving forward and you now are, so how is momentum being conserved? Bearing in mind big objects and things here, big brick walls and stuff.

S1: maybe it's got something to do with the fact that if I was standing still, I would have two feet on the ground, so if I was walking, it would kinda be, distributed differently like, it would be one foot then the other, sort of thing, um, well I don't think that really made sense.

KM: you have gained momentum, haven't you? How have you got it overall conserved then? Are you trading it off against something?

S1: …… …… um

KM: this is a hard question; it's a deliberately difficult question.

S1: it is, are you talking about ~~gravity or is it~~ like, well if you are walking along the ground then you have friction, so maybe because of the fact the ground is getting some of the momentum

KM: the ground is getting your momentum?

S1: yeah because, when you are going over like,….

KM: when you push back?

S1: yeah

KM: so what is gaining momentum, when you, say you are going forwards, what's the trade off?

S1: the ground, and the friction of the foot and the ground

KM: so you are saying the ground is gaining momentum?

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S1: well, .. I suppose, but you will…. I mean if you are walking in gravel or grass, or something like that then you would be able to see the gravel moving, which means they are getting momentum

Ch Trig (d) (experience) ✓

KM: so lets say that its concrete, it was a street, there is no bits moving, do you still think that true?

S1: yeah, I would say so,

Th Proc (c) ? - Flimsy evidence!

KM: so what's moving? You obviously are but what else is moving because you seem to be saying that something else needs to move?

S1: it doesn't need to move, because I mean obviously, you know, the world, and then me, so that means that there is not exactly going to be, like, if you had one of those wee ball bearings and you hit it against a brick wall, its not exactly going to have a huge impact on it is it, …

Big m; small v ✓ clear.

Th Proc (f)

Ch Trig (f) ✓

Con Ch. r(i) ✓

KM: but does it move slightly? The wall?

S1: …….

KM: although you can't maybe see it.

S1: yeah you can't see it yeah, I suppose,

KM: do you think it is moving though?

S1: probably

KM: so when you are walking what is happening? In your words something about the earth, what's happening, even at a very small level maybe?

S1: so small that you couldn't even see it or calculate it or anything

(a) ? ✓

KM: what do you think is going on?

S1: the earth is gaining momentum

Con Ch. r(i). ✓

KM: in which direction?

S1: the opposite to the way I am walking

KM: ok, thanks very much.

Student seems to have developed (partly) a generalised theory, hence (p) more than (o). Possibly (k) applies? Also ChTrig (e)

[illegible]

Interesting discussion re Δ dir and Δp in A3

Interview Analysis Sheet: Elastic / Inelastic Collisions

Student Number: 14 Interesting critique of sequence usefulness Final Higher Grade: C

1. Initial definitions & concepts	Comments
Momentum	
Equation correctly known / not correctly known	✓
Considered to be a vector / scalar	Vector
Confused with energy	"Impact of a collision"
Confused with force	✓ "Momentum is the hitting force" but then says not linked to force.
Conservation of momentum	
Elastic Collision: Yes / No	Y4 | Clear explanation on p2. [Y4]
Belief rating : 1 – 6	
Able to use F × t = Δp to explain conservation?	Not sure about Δp. but logic works
Inelastic collision: Yes / No	Y4 | Y.
Belief rating : 1 – 6	3 | Combined speed after = speed before
Able to use F × t = Δp to explain conservation?	✓
Kinetic energy	
Equation correctly known / not correctly known	✓
Considered to be a vector / scalar	Scalar
Confused with momentum	
Confused with force	
Conservation of kinetic energy	
Elastic Collision: Yes / No	Same.
Belief rating : 1 – 6	3
Reasoning	What teacher said. Not making contact
Inelastic collision: Yes / No	No
Belief rating : 1 – 6	3
Reasoning	Can hear sound being produced

2. Analogical Sequence (Target / Analogies / Target Final)	T	1	2	3	4	TF
Momentum conserved? [Analogy / Target]	✓	✓ ✓	✓	✓ ✓	✓ ✓	✓
Belief rating: 1 – 6 [Analogy / Target]	3	5	4	5	5	
Kinetic Energy conserved? [Analogy / Target]	X	X X	X X	X X	X	X
Belief rating: 1 – 6 [Analogy / Target]	3	5 5		4 5	.	
Inelastic kinetic energy (KE) loss theory	**T**	**1**	**2**	**3**	**4**	**TF**
KE not lost						
KE lost, but not sure why						
KE energy lost as sound due to collision	✓					
KE lost as sound & heat due to collision						
KE lost as sound due to vibrations from collision		✓	✓	✓	✓	✓
KE lost as sound & heat due to vibrations from collision						
Other:						
Belief rating in theory : 1 - 6	3	4/5	5	5	4	
Thought process evidenced (ThProc)	**T**	***1***	**2**	**3**	**4**	**TF**
a) Confusion				✓		
b) Logic	✓	✓✓✓		✓✓	✓✓✓	✓
c) Intelligibility (idea making sense)		✓	✓		✓✓✓	✓
d) Inconsistent (changing their mind more than once)						
e) Twin Tracking (comparing two or more ideas)						
f) Making Connections		✓✓	✓	✓	✓	
g) Cognitive conflict		✓				
h) Other: Belief of Physics Teacher	✓✓					
i) Visual clues.	✓	✓	✓	✓		
j) use of equation (law) to justify answer.			✓	✓	✓	

Analogical Reasoning						
Similarities / Differences	T	1	2	3	4	TF
No. of surface similarities with previous analogy						
No. of deep (theory) similarities with previous analogy				1		
No. of surface similarities with target			1			
No. of deep (theory) similarities with target		2				
No. of differences stated (Previous Analogy / Target)						
Use of analogy for explanation (Fruitfulness)	T	1	2	3	4	TF
Analogy understood but no transfer to target – links not seen						
Link between analogy & target stated but not explained						
Target explained using only analogy surface features						
Theoretical principles transferred from analogy to target		✓				
Type of Conceptual Change Evidenced (ConCh)	T	1	2	3	4	TF
a) Replacing central concepts to deal with new phenomena						
b) New material simply supports or exemplifies existing ideas			✓H			
c) Extension, modification or qualification of existing ideas						
d) Ideas become subsumed under the new proposition						
e) Change in acquired idea & associated cognitive structure		✓				
f) Reorganising only within current context						
g) Complex system building – from bits of knowledge		✓				
h) Target enriched with new concrete features		✓				
i) New events simply added to existing model		✓				
j) Model only modified (specific objects & events level only)		✓				
k) Model and underlying theory modified						
l) Social rules only (doing what teacher has told them to do)		✓				
m) Use of only existing concepts to deal with new phenomena						
n) Existing theory enriched						
o) Revision of specific theory (objects & properties level only)		✓				
p) Revision of framework theory ('how things are')						
q) Category change from matter to process						
r) Connections made between new thinking and:						
(i) Analogy		✓(*)				
(ii) Existing mental model		✓				
(iii) Prior experience						
(iv) Prior learning and knowledge (Physics)		✓				
(v) Prior learning and knowledge (other subject)						
Change Triggers (ChTrig)	T	1	2	3	4	TF
a) Visual cues		✓		✓		✓
b) Faulty logic recognition						
c) Mis-fitting experience (cognitive conflict)						
d) Making connections with stated prior mental model/experience/learning		✓(*)	✓			✓
e) Spontaneous generation of idea						
f) Transfer of Physics application to situation						✓
g) Experience (Analogy)		✓(*)	✓			✓
h) Other: Relieving senses.				✓		✓

Elastic collision - kinetic energy (KE): final conservation theory	**Comments**
KE conserved - no reason identified	
KE conserved - no contact	
KE conserved - no contact, so no vibrations to give sound	✓
KE conserved - no contact, so no vibrations giving sound or heat	
Belief rating in theory : 1 - 6	

At T saying conserved because of no external net forces

3. Review of analogical sequence	Comments
Most helpful analogies	1
Reasons	Can hear sound + its really obvious.
Sequence usefulness Got confused with later ones - 1st one - understood it more - Neutral @ 3 Too many things	Yes but Didn't like the ball bearing one as couldn't see it (!) much. They were harder as they went on ⊛
Learning usefulness + got confused. Not just told to learn things but helps you to believe things told are true by showing examples + real life situations	Yes - helps to visualise what happens. In class just take it as true because told but when put it into practise, have you understood it a little better.
4. Extension situation	
Loss of kinetic energy for a pushed object experiencing friction Cons. of momentum for a pushed object experiencing friction	

[41] - Comes up with vibration by connection with analogy, then wobbles due to not being able to see it, then convinces themselves

Ⓐ Big one for analogy use, connections with previous + feels proved it Ⓐ

[A3] Acknowledges Δ direction = Δp. but then ignores in statement about if ball stopped more mom. would have been transferred.

Interview 14

KM: First question, what do you understand by momentum? What do you think that means?

S14: Momentum is when…

KM: What is it a measure of do you think?

S14: A measure of mass times velocity.

KM: OK.

S14: When two cars hit each other, the momentum is the hitting force.

KM: So you think it is linked to the force that they hit with?

S14: No. Without my sheets I can't remember what the actual definition of momentum is.

KM: Well you've given me the definition but what do you think I measures about a moving object?

S14: The impact of its collision.

KM: Now you've learned in physics that momentum is conserved. What does that mean to you?

S14: It is kept within the collision. None is lost to outer forces. The momentum before is the same before as after the collision.

KM: OK. Now on a scale of one to six, I am going to ask you to do this several times, one means you don't believe it at all and six means you are totally sure. How convinced are you that in the real world that is true?

S14: Four.

KM: Why is it a four?

S14: Because that is what I've been told by my physics teacher and I have no other proof to say otherwise so I can't really say it is wrong. I know not to believe everything I am told, just because it is that but I have no other way of knowing.

KM: So because you have been told it and you have no reason to disbelieve it, you are reasonably sure?

S14: Yeah.

KM: OK. That's a good enough reason. What about the fact that you said there momentum was mass times velocity. What does that suggest about momentum? Is it a scalor or a vector?

S14: A vector.

KM: And what does that mean?

S14: A vector is described as having a quantity as well as a direction.

KM: OK.

S14: Like a magnitude or a size as well as a direction.

KM: OK. Now you have already given me the equation. What about kinetic energy? What can you tell me about that?

S14: It's equation is $\frac{1}{2}mv^2$.

KM: Anything else?

S14: Is it movement energy?

KM: OK.

S14: I can't think if that is movement energy or the energy it has before an object moves.

KM: Now in terms of scalor or vector, what would you say?

S14: It is a scalor.

KM: Why do you think it is a scalor?

S14: It doesn't have a direction, it has just got a magnitude.

KM: And what about the difference between momentum and kinetic energy? What would you say the difference is because they are both measures in some way of a moving object so what do you think is the difference between them?

S14: I think kinetic energy is what, say if it was a car hitting another car, what the car has before, the energy it has before and the energy it has after and it can sometimes be lost to sound and all that and heat. Momentum is the actual impact but it is always equal. You can't lose it. The only difference is that you can lose kinetic energy when you shouldn't lose momentum.

T

Elastic

KM: But in terms of what they measure, what would you say the difference is?

S14: Well obviously kinetic energy measures the energy. Maybe the energy the car has before it hits and momentum is the actual measure of what it has as it is hitting.

KM: So momentum has got something to do with the collision itself?

S14: Yeah.

KM: Rather than before or after so much?

S14: Yeah.

KM: OK. What we're going to do is look at two collisions similar to the sorts of things that you would have done in class. We've got two trolleys here and I've got a magnet there and a magnet there that repel each other. The two trolleys are identical to each other apart from the fact that is blue and that is red but they are the same mass. Run the blue trolley for me into the red trolley and I want you to describe for me what you notice happening in that collision.

S14: When it hit, they didn't move off together. The blue one was coming in at speed and the other one was at rest and then they switched and the other one moved off and the blue one was at rest.

KM: Now tell me what you think is happening in terms of momentum in this collision. Is it conserved or not and how do you know?

S14: Yes I think it is conserved. My guess is that that other trolley moves off with the same speed or velocity as the blue one came at it with.

KM: So you're saying because that moves off at the same velocity, you are reckoning that momentum is conserved.

S14: Well they are exactly the same mass as well.

KM: Now how convinced are you that momentum is conserved there?

S14: Four again. For the same reason.

KM: Tell me what you think is happening in terms of kinetic energy.

S14: I think that the blue one would have more kinetic energy and that all of it wouldn't be conserved when it hits the red one.

KM: But once it is moving, just before the crash compared with just after the crash. How would they compare?

S14: The same. Conserved.

KM: How much are you convinced of that?

S14: Three.

KM: Now tell me why you think that?

S14: Because that is what my teacher said. (*) Th Auth(h) ✓

KM: Is there a logic in your head as to how that is happening? How that is working?

S14: Well maybe some is lost because two external things, there is sound when that hits that there is a sound.

KM: Is there? Try it again.

S14: Yeah it is all conserved there because the magnets repel each other. It is not actually hitting.

KM: And so?

S14: So the energy is conserved because it is not giving any energy to any external things.

KM: OK.

S14: That changes my thinking about momentum there. Did you ask me about momentum there?

KM: I did ask you about momentum there.

S14: Because they don't actually hit.

KM: So it momentum being conserved?

S14: Yes.

KM: Because?

S14: I don't know.

KM: There is a collision.

S14: Yes there is a collision. It is conserved.

KM: OK. Now you learnt that equation in physics. Can you use that equation to explain what is going on in terms of momentum?

S14: Well the force at which I pushed that and the force at which it hits the red car times the time that it took for the collision to happen equals the change in momentum.

KM: The change in momentum of what?

S14: Of the collision?

KM: But a minute ago you were saying that the momentum before and after are the same.

S14: The momentum that it had before the collision and the momentum it had after the collision.

KM: So what is changing in momentum in this collision?

S14: You mean what force or time?

KM: No I mean which object is changing in momentum?

S14: The red car.

KM: Does the blue car's momentum change?

S14: Yes because it transfers onto that.

KM: So you are saying that the blue car's momentum changes because of what?

S14: Because…actually I'm not sure.

KM: Well is there a force on the blue car during the collision?

S14: Yes.

KM: And is there a time of collision?

S14: Yes.

KM: And does its momentum change?

S14: Yes.

KM: What about the red car?

$F \times t = \Delta p$

S14: The same.

KM: The same in what sense?

S14: Well it is hit with a force so its force changes and then the time it takes when it is hit and when it moves off is changed as well.

KM: So its momentum changes. How do the two changes in momentum compare?

S14: They are equal.

KM: Are the equal in terms of everything or is there a slight difference in one way?

S14: I think there might be a slight difference, there is the same time but the force at which they hit might be different.

KM: To each other?

S14: Well are they the exact same weight?

KM: Yes.

S14: Well yeah it would be the same.

KM: So what change in momentum happens to the blue car? Does its momentum increase or decrease?

S14: Increase?

KM: What happened to it as a result of the collision?

S14: It stopped.

KM: So its momentum has been?

S14: Lost.

KM: And what about the red one?

S14: It has gained.

KM: And the loss of that one compared with the gain in that one would be what?

S14: Equal.

KM: How sure are you?

ThPrz (b)✓ Guided.

In Elastic

S14: Four.

KM: Right what we will do is we are going to turn this trolley round to the Velcro side and we're going to put the Velcro side to the magnet side of this one. Same idea, run the blue trolley into the red trolley and tell me what you think is happening this time. Tell me in terms of momentum first and if you can use that to explain it, all the better.

S14: The momentum is conserved. This time because it is not the two repelling magnets they both move off, not necessarily at the same speed. The speed that I rolled it in at equals the speed of the two as they move off together.

Th Proc(i) Visual. ✓

KM: Combined?

S14: Yeah.

KM: So although the blue one was going slower than it started, you're saying the red one makes up for that?

S14: Yeah.

KM: Now how sure are you that momentum is conserved?

S14: Three. I'm not really sure about it. Momentum was never my best topic.

KM: So you're not that sure because you are a wee bit unsure about momentum?

S14: In general, yeah.

KM: What about kinetic energy? What is happening?

S14: It is $\frac{1}{2}mv^2$, well half of that mass times it's velocity as it is moving along on the blue car I think equals the $\frac{1}{2}mv^2$ of the blue and $\frac{1}{2}mv^2$ of the red after the collision as they move off so I think it is conserved. Actually there might be some lost to sound. There was a sound wasn't there?

KM: Try it again.

S14: Yeah there is.

KM: So you're saying what is happening there?

S14: A little bit is lost.

KM: As what?

S14: As they collide.

KM: Due to what energy? What is it becoming?

S14: Sound energy.

KM: Now how sure are you that kinetic energy is not conserved here?

S14: Three.

KM: Not all that sure. How come you're not more sure? Why are you a bit wary?

S14: I am not sure. Just because I find it much easier when you can see something happening. I can't see energy of whatever so I'm a bit shaky on that.

KM: Can you hear the sound?

S14: Yeah.

KM: Does that convince you a bit?

S14: Yeah.

KM: Now can you explain why there is sound being lost here? What is actually going on that is causing sound to be lost?

S14: What do you mean?

KM: What is going on during that collision that is making the sound happen? Whereas before when we turned it round, how come there is no energy lost that time?

S14: Because they never touched each other. They were never in contact.

KM: And what difference does that make?

S14: When they are in contact there is an impact.

KM: And why does that mean that sound gets produced?

S14: Because there is a transfer of energy?

KM: But there is a transfer of energy in magnet to magnet was there not?

S14: When it hits the other one, there is a wee change in momentum when the red one has to move off.

KM: But that was true of both collisions was it not?

S14: Yeah.

KM: So why have we got kinetic energy not conserved in one and it is being conserved in the other? How would you explain that?

S14: Maybe they are conserved in both. I'm not sure if I am getting mixed up with something else.

KM: But you were fairly sure when they hit each other that there was energy getting changed into something other than kinetic whereas there you were pretty sure…

S14: Well because the energy is conserved because there was no point of contact so…

KM: And what difference does that actually make?

S14: All the energy is conserved. There is no external net forces or anything. There is nowhere for it to go.

KM: For the energy to go?

S14: Yeah because when they do that there is no hitting.

A1

KM: OK. We're going to do a couple of analogies and see if this helps you to explain it. What I want you to do is take the hammer and don't batter it off the tuning fork but just gently tap the tuning fork and tell me what you notice. And then touch the tuning fork with your finger,

S14: It is vibrating.

KM: OK. So tell me what is happening in terms of kinetic energy here, before and after.

S14: Well the kinetic energy coming from me hitting it with the hammer is making the tuning fork vibrate. Movement energy is changing into potential energy? Has kinetic energy been transferred into…missing bit…..

KM: Is there energy in the tuning fork once you have hit it?

S14: Yes.

KM: And is there any other kinds of energy around?

S14: Potential? Sound?

KM: When you say potential, what do you have in mind?

S14: Movement energy?

KM: Is that the same as kinetic?

S14: One of them is before, like if you have a wee ball at the top of a slope, I can't remember if it is potential…

KM: Would it be potential at the top?

S14: Yeah, it is potential and then kinetic is movement energy. That means that when I hit it with that, it has got kinetic energy. The tuning fork has got kinetic energy.

KM: And what else is it producing?

S14: Sound energy.

KM: Now what about the total kinetic energy of the hammer before versus the amount of kinetic energy after? How do they compare?

S14: They are not equal because sound energy has been given off.

KM: So why has sound energy been given off? What is causing that sound to be produced?

S14: The two plates on the tuning fork hitting off each other.

KM: Are they?

S14: Well I don't know how it works. It is probably too fast for me eyes to see.

KM: OK. If I tap it and then I want you to touch it immediately after and see if this helps. What do you notice when you touch it?

S14: It is vibrating a lot.

KM: And as soon as you have touched it, what happens to the sound?

S14: It stops.

KM: So why is that?

S14: Because I am stopping…

KM: What is causing the sound is what I'm getting at. If you think back to first year.

S14: Waves? Sound waves?

KM: Caused by?

S14: Travelling between each of the two…

KM: Caused by what though?

S14: The vibration.

KM: OK. So there is vibration which is making sound. Now can you link that at all with this situation when the two hit each other with the Velcro?

S14: Can you summarise what we just said about this?

KM: No you summarise what you think rather than me telling you. So when you hit it with the hammer, what happened to the kinetic energy?

S14: There was some given off to sound energy but the rest was kept within kinetic energy.

KM: And why was there sound given off there?

S14: Because of the vibrating. So when that hits off that there is a small vibration which causes sound.

KM: Vibration where?

S14: You can't see it. Maybe not a vibration but when they hit…

KM: So what do you think is vibrating?

S14: Not vibrating but like when they hit each other, the two ends of the car, I don't think it is a vibration but it is a…

KM: Why don't you think they are vibrating?

S14: I don't know, I can't see if it is. It would be so small a vibration anyway.

KM: But do you think there might be?

S14: Yeah, I think there would be some vibration. In most things you hit, if there are two bits that hit each other there would be vibrations.

KM: OK. Give me a rating on how much you are convinced that kinetic energy is not conserved now.

S14: When I did this?

KM: With the trolleys.

S14: Five.

KM: It's gone up. Why?

S14: Because I proved with the analogy that it helped me see what happens. I am convinced of the vibration.

KM: How convinced are you that there is a vibration in the trolleys?

S14: Four from your suggestive tone.

KM: I'm not trying to suggest anything deliberately. I'm trying to not suggest. I want you to tell me what you think.

S14: Yeah, five.

KM: Why are you giving it a five?

S14: Because that is what I have learnt in class and I've proved it with this so I backed it up with this.

KM: Tell me about the momentum there. Tell me what you think is going on with the momentum between the hammer and the tuning fork.

S14: It is conserved.

KM: How sure are you?

S14: Five.

KM: Why?

S14: Because there is really nowhere else that the momentum, momentum is force times time.

KM: The change in momentum?

S14: Yeah, the change in momentum is force times time so when you hit this the time you take to hit it and the force at which you hit it transfers on to the fork. There is not really any other way. There is nowhere for it to go.

A7

KM: OK. Second analogy. What I want you to do is get the same tuning fork and bounce it off this rubber ball. Just hold the rubber ball like that and gently tap it. What do you notice happening to the rubber ball?

S14: It moves slightly.

KM: In what particular way?

S14: Towards me. It jumps a wee bit.

KM: If you give me the tuning fork and let me tap it. I have not hit it as hard but do you notice anything happening to the rubber ball when I have tapped it.

S14: Nothing except for I can feel it.

KM: Feel what?

S14: I can feel with the force that you hit that I can feel it hit off, there must be something happening between the tuning fork, the ball and the ground.

KM: What are you feeling between your finger and your thumb? Are you feeling anything?

S14: Yeah like a jut and the ball is going down slightly.

KM: OK. If I did it slightly to the side then.

S14: It is going slightly towards me.

KM: Is there a vibration there?

S14: Yeah.

KM: Tell me what you think is happening in terms of momentum in that collision.

S14: When you hit it with the fork it vibrates and because it is two objects hitting off each other it is really really quick and then that is the momentum transferring from the fork to the ball. Momentum is conserved.

KM: How sure are you?

S14: Four.

KM: And how convinced are you about this transferring of momentum thing?

S14: Three.

KM: Now in terms of kinetic energy, what is going on? Before versus after.

S14: Well you are moving the fork to hit it with and then when you hit it the ball moves slightly so probably the energy is conserved. Wait, I don't know if there was a sound. Can you hit it again? There was a very small sound.

KM: So is there energy being changed into anything else?

S14: Yeah a little bit. There is a very small bit of energy transferred into sound energy.

KM: And why is it becoming sound?

S14: Because of the vibrations.

KM: In what?

S14: The vibration of the fork hitting the ball and the ball jutting off.

KM: So the tuning fork vibrates? You feel it vibrate?

S14: Yeah.

KM: And you think the ball is vibrating?

S14: Yeah because you can hear it off the ground a wee bit.

KM: Tell me how that compares with the trolley situation.

S14: I know the direction in which the momentum goes because when the blue one comes from one angle, you know how you did it from the side and it moves the other way? The movement always opposes the direction in which it came in.

KM: Explain what you mean by that.

S14: Well not quite opposes, it does go in the same direction but if the car came from the right and it hits, it is obviously going to go to the left.

KM: The car is coming from the right, moving towards the left and so that moves to the left, is that what you're saying?

S14: Yeah. (Sim (surface))

KM: Is there any link between the reasoning why you said kinetic energy was being lost here compared with here?

S14: It is the same because some of the energy is being transferred into sound energy.

KM: Because of?

S14: The vibrations.

KM: So how convinced are you that there is a vibration here?

S14: Five. I am never going to say six.

KM: Why are you saying five? Why are you so sure?

S14: I have got no reason to doubt that. I've got no way of knowing. I'm just guessing.

KM: Is it just a guess?

S14: Well from talking about it and using the tuning fork which is an indicator of vibrations.

A3 KM: OK. Next analogy. Water filled balloon. You can see the air trapped so that is just water. What I am going to do is run the same rubber ball into the balloon and see what goes on. So run the ball into the balloon. What do you think is going on in terms of momentum first?

S14: The momentum with which it hits it is the same as when it comes back except it is negative when it comes back because it has changed direction. The ball.

KM: What happens to the balloon?

S14: The balloon vibrates. It moves slightly. It rolls forwards and then it rolls back.

KM: So has the balloon got momentum?

S14: Yes.

KM: So tell me before we have got momentum going…

S14: It would only have momentum if it was a solid wall that doesn't move at all but you can't really get anything that can't move at all.

KM: If we have got that ball coming in to the left and then you are saying it goes to the right, how does the momentum of the ball compare before and after?

S14: Well the momentum in magnitude is equal except for the direction.

KM: So why does the balloon move?

S14: It does.

KM: Does that not mean we are creating momentum.

S14: Momentum is not conserved because when it hits it, when the ball hits the balloon it moves, therefore some must be lost to kinetic energy.

KM: How does that work?

S14: Well not kinetic, like movement. When I hit that, some momentum must be used to move that balloon which is why…

KM: So where is that momentum coming from?

S14: The contact of the ball and the balloon.

KM: So are you sure that there is exactly the same amount of movement in the ball after as before?

S14: No. I realised that when that moves, only if that was a solid wall would that be completely conserved.

KM: So why do you think momentum is not conserved here?

S14: Because momentum is mass times velocity. The mass isn't going to change but the velocity at which it hits it is probably different when it comes away because it has moved.

KM: Before the crash, there is only one mass moving. After the crash you have got two masses moving have you not?

S14: Oh yeah. Actually before, when it hits it, the one before will be equal to mv of the balloon and the ball after.

KM: So why have you changed your mind now?

S14: By thinking about it a little more.

KM: So tell me what you think is happening to the momentum of the ball?

S14: The momentum of the ball, before it hits the balloon is equal to the momentum of the balloon and the ball after the collision. The mass times the velocity of the balloon, the mass times the velocity of the ball, that is equal to before when only that was moving.

KM: Does the fact that that has changed direction have any influence on the momentum?

S14: No just that it becomes negative. Its magnitude is still the same.

KM: Does that mean its momentum is the same or has it changed in some way?

S14: It has changed.

KM: In what way?

S14: From positive to negative. The ball has changed direction.

KM: So how does that work then if that has got momentum? What is going on? Has this got quite a lot of momentum or very little?

S14: A lot of momentum. Well just what I said before. Mass times velocity, it has got a really big mass but the velocity will be much less than when that hits it.

KM: But overall its momentum you would say would be what? Big or small?

S14: Big?

KM: How do you justify that?

S14: Just using the equation. The mass is large.

KM: So has it got anything to do with the fact that the ball has changed direction? Does that make this momentum bigger or smaller than it had been if the ball hadn't changed direction? Or does that not matter?

S14: If that had just gone and stopped dead there would be much larger momentum in the balloon.

KM: It would have been bigger had the ball just stopped?

S14: Yeah. But the ball came and hit back off it.

KM: Tell me about the kinetic energy in this collision.

S14: The kinetic energy before is equal to the total kinetic energy after the collision.

KM: Is there any loss of kinetic energy this time?

S14: Movement energy but that is kinetic energy.

KM: But is there any loss of kinetic energy?

S14: No. No sound.

KM: Is there none at all? Try listening.

S14: Yeah actually there is a little bit of sound energy.

KM: So is there a loss of energy or not?

S14: Yes.

KM: Caused by what?

S14: Transfer to sound energy.

KM: And why is there sound energy being produced?

S14: Because there is vibrations and…

KM: How do you know that?

S14: Because you can see it and because there is a transfer of energy causing the collision.

KM: So what do you think is vibrating?

S14: Both objects.

KM: The rubber ball and the balloon?

S14: No just the balloon.

KM: How does that compare with the one before when we tapped the rubber ball with the tuning fork? What links would you make?

S14: There was vibrations.

KM: In what?

S14: In both so there were vibrations in both of these as well.

KM: How sure are you?

S14: Four.

KM: Go back to this crash here with the Velcro and the magnet hitting each other. What is your story? How would you explain this now, using what you have been doing? In terms of similarities and so on.

S14: When the blue car comes at a speed and hits the red car which is at rest, they both move off and the momentum is conserved but kinetic energy is not conserved because some kinetic energy has been transferred into sound energy from the collision.

KM: And why has it been converted?

S14: Because there is vibrations during the collision between both cars.

KM: OK. Let's do some ratings. How convinced are you that momentum is conserved here?

S14: Five.

KM: How convinced are you that kinetic energy is not conserved here?

S14: Five.

KM: And how convinced are you about your vibration idea?

S14: Five.

A4

KM: Last analogy. Two balls, they happen to be made of glass but they look like steel. I want you to run one into the other and tell me what happens. Try and keep it on the track. Tell me what you think is going on there.

S14: The momentum is conserved because the momentum before the collision is equal to the momentum after the collision. * Th Proc (j) ✓

KM: And how do you know that?

S14: Because it is a law of physics.

KM: Can you use that to explain it?

S14: The force of which the ball hit the other one and the time with which that took to happen equals the change in momentum.

KM: Of the first ball?

S14: Yes.

KM: And what about the second ball?

S14: Its momentum before is zero.

KM: After it is? Is it still zero?

S14: No.

KM: So it has changed in momentum. Why?

S14: Because before it was at rest and didn't have a velocity and then after…

KM: So what has caused it to have a velocity?

S14: The vibration.

KM: Well using that equation. Can you use that equation to tell me why it ends up with a momentum? It didn't have one before but it does now.

S14: It didn't have a momentum before. Well it did have a momentum, it was zero but after it is increased because the change in momentum before the collision is the same as after and the momentum before will be higher.

KM: So what has happened that has made the second ball move?

S14: A transfer of energy, of momentum.

KM: Has it got anything to do with a force?

S14: Yes.

KM: So tell me what it has got to do with a force.

S14: It has been hit with a force.

KM: By the?

S14: The other glass ball.

KM: And how does the force of the first ball hitting the second compare with the force that slowed the first ball down? Are they the same size or are they different?

S14: They are equal.

KM: OK. That's fine. Now go back to this. What is your final story on the trolleys hitting?

Th Proc 1(b)(c) able to argue $Ft = \Delta p$

S14: When the blue trolley hits the red trolley and they both move off, the momentum before, which is basically just the blue car because the other one was at rest, when the blue car hits the other one and they move off, the momentum of both those two cars moving off is equal to the momentum of the single blue car at the start of the experiment.

KM: And you are rating that as a?

S14: Five.

KM: Now tell me about the kinetic energy.

S14: The kinetic energy before the collision is not equal to the kinetic energy after the collision because some kinetic energy is transferred into sound energy because of the vibrations caused between the two cars in the collision.

KM: And how sure are you of this vibration, despite the fact that you can't see it?

S14: Four.

KM: Why are you so sure?

S14: Just because I can't think of any other reason. We've been discussing it for a while and I seem to be picking up the vibes that that is the correct answer.

Th Proc (b)(c) ✓✓

KM: It might be, it might not be. Explain to me why there is no loss of energy there then?

S14: What do you mean?

KM: Magnet to magnet, there is no loss of energy. How come?

S14: Because there is no collision.

KM: And what difference does that make?

S14: There is no sound energy lost.

KM: Why not?

S14: I can't hear. They don't contact.

Th Proc (b) ✓

KM: And so what doesn't happen as a result of that?

S14: There is no transfer in sound energy and there are no vibrations. There are no vibrations in this experiment.

KM: There is no vibration because there is no contact?

S14: Yes.

KM: So there is no loss of sound energy?

S14: Yes.

KM: OK. Right there is the things that you were doing, did you find that as a series was quite useful in learning? What did you think of them as a way of learning?

S14: Because I don't know if I am right or not, I can't really say if I am sure they help.

KM: If I tell you that you are right?

S14: Then I think it did help because it helped me to visualise what happens and gives different examples. In class you are not really sure, you just take it as true because you are getting told that but when you put it into practice here you understand it a little better.

KM: What did you think of it as a series? Did you think any were better than others?

S14: Yeah. I didn't like the ball bearing one.

KM: Why?

S14: You can't see as much.

KM: But that is deliberately why it is at the end.

S14: With the tuning fork one you can hear it and it is really obvious.

KM: The first one or the second one?

S14: The first one. The second one you can feel the vibrations and you can hear the vibrations. The third one was harder. They were harder as they went on. I really didn't like the fourth one. The third one was alright.

KM: They are designed to get harder.

S14: I preferred the first one.

KM: Did you think it worked better as a series or would it have worked better as just one analogy?

S14: Maybe a couple. I think by doing the four it just made you a little more confused. Like when you did the first one I understood it more and then you did the second one and

I understood it more. Then you di d one and I was back to kinda neutral again. There were just too many things, I ng confused.

KM: What would you think if you used that as a way of learning more in class?

S14: I would prefer it.

KM: You would quite like it as a method of learning?

S14: Yeah. We are just told these things that you can't see. You just get told and you just learn them because you are told to learn them. It helps you to believe that these things you are being told are true by showing you more examples and showing you real life situation.

KM: Why does it help you believe?

S14: Just more examples you can relate to. I can relate the tuning fork to the hammer and the cars.

KM: OK. Thanks very much.

Th Prac (f)

Ch Trig (a)(d)(h)(g)(f).