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**Making sense of making sense: A microgenetic multiple case
study of five students' developing conceptual compounds
related to physics**

Richard Andrew Brock

Homerton College

May 2017

Supervisor: Keith S. Taber

Advisor: Sara Baker

Declaration

This dissertation is submitted for the degree of Doctor of Philosophy

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Abstract

The research reported in this thesis arose from a comment made by a student who had achieved highly in examinations yet felt that science: ‘doesn’t make sense’. Different conceptualisations of learning are analysed leading to the development of the concept of making sense as the formation or modification of a conceptual compound in which concepts are related in a coherent causal system that may be transferred to novel situations. This definition is situated within a constructivist epistemology. The research question asks how students make sense of physics concepts in dynamics and electricity. Five 17-18 year-old students, conceptualised as a multiple case study, were selected from an English secondary school using purposeful sampling. The students were interviewed once a week for 22 weeks in sessions using a range of probes such as interviews about instances, concept maps and concept inventory questions. It is assumed that data collection occurred at a frequency that was high relative to the rate of conceptual change, hence, the work is conceptualised as microgenetic. The analysis focuses on the development of the students’: a) ontologies of concepts from concrete instances towards abstractions; b) conceptual structures from temporary organisations to more stable structures; c) understanding of causality from focused on macroscopic objects to abstract concepts; d) judgments of coherence; f) conceptual change modeled as an alteration in the ‘oftenness’ of application of a concept in a given context; and e) ability to apply concepts to novel contexts. The implications of these findings for teaching and future research are discussed.

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Preface

I acknowledge that some of the argument present in this thesis has appeared in the following publications: Brock (2015), Brock & Taber, (2017a) and Brock & Taber (2017b).

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1.0 Introduction

1.1 The origins of the research

The study reported in this thesis was prompted by a comment made by a student whom I had taught physics. On results day, I had complemented her on getting the highest possible grade in an external examination. 'It's brilliant,' she replied, 'and physics doesn't even make any sense to me. I just memorised it all'. Her comment prompted my interest in what it means to 'make sense' of physics and hence this thesis seeks to develop an understanding of how it is possible to have 'memorised it all' but yet fail to experience the information as meaningful. Therefore, I sought to examine models of learning in science education to identify common features of terms such as understanding and meaningful learning and the concept of 'making sense' is defined to encompass these shared aspects. The features of 'making sense' were tracked in reports of four 16-17 year old students' thinking across twenty-two sessions over a period of approximately six months. A fifth student completed ten sessions before withdrawing from the research. The data illustrate the complex nature of 'making sense' of physics and the patterns of change that occurred in the students' application of concepts across a number of contexts and over an extended period of time. A number of recommendations for teaching and research are proposed which, it is hoped, will prevent others from experiencing my student's situation of knowing the facts but finding they don't make sense.

1.2 A taxonomy of types of learning

As learning cannot be observed directly (Taber, 2013), researchers have proposed a range of different models of learning (Agarkar & Brock, 2017). Even within communities of researchers who share similar assumptions, for example those who construct learning as a psychological process, a variety of different constructs have been used to describe learning: for example, meaningful learning (Ausubel, 2000), deep learning (Chin & Brown, 2000), understanding (Nickerson, 2000; White & Gunstone, 1992), making sense (Donaldson, 1987) and conceptual change (diSessa, 2002; Koponen & Huttunen, 2013). It has been argued that this proliferation of constructions benefits, rather than hinders researchers (Geelan, 1997), because a complex process such as learning may be best described by a range of descriptions that emphasise different facets of its nature (Taber, 2013). However, whilst the

generation of a diversity of models of learning, has illuminated a range of aspects of the phenomenon, it also presents a fragmented picture. It has been suggested that a feature of scientific explanations is that they tend to reduce the number of 'independent phenomena' (Friedman, 1974, p. 123). Therefore, a tension exists for researchers who must balance a desire to generate a unified model of learning with a requirement to represent the multiplicity of a phenomenon (Pope & Denicolo, 1986). It is hoped that the proposition of the concept of 'making sense' can unify the commonalities that underpin a number of descriptions of learning in science education without reducing the need for alternative models.

1.2.1 Commonly used descriptions of learning in science education

In this section, a number of terms that are commonly used to describe learning in science education will be compared. The commonalities between these terms are illustrated in Figure 1.1, below. My analysis of the terms began with the concept of making sense, because this is the term the student, cited above, used. However, as shown in Figure 1.0 below, a number of related concepts are used in the science education literature with related or overlapping meanings. The conceptualisations of learning were identified using 'snowball' or 'chain' sampling (Suri, 2011, p. 69), a form of purposeful sampling, in which references in one paper lead to the discovery of further concepts. Sampling continued until a subjective sense of theoretical saturation was reached, that is no further models of learning were found that could 'develop properties of the category' (Glaser & Strauss, 1967, p. 61).

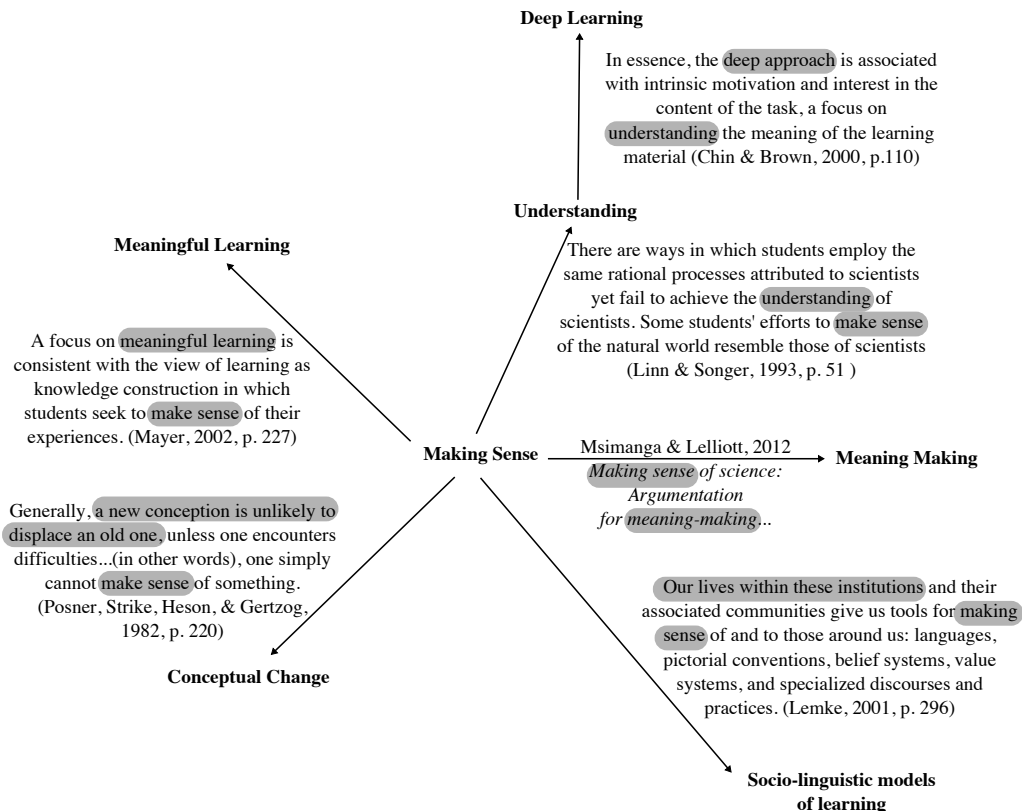


Figure 1.0: A representation of the process of purposeful sampling of models of learning related to making sense. Linked terms are highlighted in quotations.

1.2.1.1 Making sense and meaning making

Making sense is a term that has been used to describe learning in science education (e.g. Berland & Reiser, 2009; Driver, Rushworth, Squires, & Wood-Robinson, 1994; Wilensky & Resnick, 1999). Though the term is not explicitly defined in the science education literature, it tends to be used to describe the development of an understanding of the relationships between pieces of knowledge, as Murray Gell-Mann (1995, p. 89) described: 'Many facts then become more than just items to be memorized- their relationships permit us to use a compressed description, a kind of theory, a schema, to apprehend and remember them. They begin to make some sense'. Making sense has been linked with reducing novel problems to well understood contexts (Donaldson, 1987) and satisfying competing demands to reach a state of coherence (Kunda, 1999). The related term, meaning making tends to have a more social and linguistic focus (Rahm, 2004; Scott, 1998) than making sense, which is typically related to personal psychological processes. For example, meaning making is described as: 'an ongoing process of comparing and checking... understandings

with the ideas that are being rehearsed on the social plane' (Mortimer & Scott, 2003, p. 10).

1.2.1.2 Understanding

Understanding is a challenging concept to define (de Regt, Leonelli, & Eigner, 2009) and of all the terms discussed in this thesis, perhaps has the widest range of meanings. Even the ontology of understanding is controversial. It has been described as 'an internal seeing,' (Kvanvig, 2007, p. 198), a 'state' (Zagzebski, 2001, p. 246), a 'feeling' (Colliver, 1999, p. 189), a 'process' (Baron, 1987, p. 293; Cobern, 1994, p. 586; Rumelhart, 1991, p. 273), an 'ability' (Wittgenstein, 1953, sec. §150-§154) and as a behaviour (Perkins & Blythe, 1994; Perkins, 1998). Indeed, some authors (Entwistle & Nisbet, 2013, p. 9) argue understanding exists in multiple ontological categories: '... as mental representations within cognitive structure, as the learning processes involved in reaching it, or as the emergent property of mental operations within a neural net'.

Despite these significant disagreements, a number of commonalities are discernible in descriptions of understanding. Understanding is not an all-or-nothing concept, students may understand to varying degrees (Davidson, 2010; Newton, 2001; White & Gunstone, 1992). Understanding is often described as an appreciation of the connections between conceptual elements (Elgin, 2012; E. L. Smith, 1991). For Kvanvig (2003, p. 198), this is an '...internal seeing or appreciating of explanatory relationships in a body of information', whilst for Kosso (2006, p. 173), understanding involves '...apprehending the connections between theories and the global coherence among concepts'. Understanding is reported as conferring the ability to transfer learning to a range of contexts (de Regt, 2004; Perkins & Blythe, 1994). For example, diSessa (1993, p. 190) states: 'Understanding should evolve toward compactness, involving few principles that are as general as possible. In a sense, compactness is the essence of explanation, identifying general mechanisms beneath differences'. de Regt (2004, p. 101, *Italics in original*) argues that understanding leads to an ability to transfer learning: 'Understanding is not only knowing the formula, but in addition *being able to use* the formula in the case at hand'. Similarly, for Nickerson, understanding involves forming knowledge into a 'cohesive whole' so understanding involves 'not only having knowledge but also doing something with it'

(Nickerson, 1985, p. 234). Understanding has been linked with a range of other constructs including: knowledge of causes (Lipton, 2004; Salmon, 1984), the development of coherence (Kosso, 2006; Riggs, 2003), reducing the number of instances of a case (Chaitin, 2006; Friedman, 1974) and detecting abstract principles (Morrison, 2009).

1.2.1.3 Meaningful learning

Meaningful learning is a comparatively clearly defined term that David Ausubel (2000) described as a collection of processes which led to the integration of novel material into existing cognitive structure. Meaningful learning is contrasted with rote learning, which is defined as the possession of knowledge that cannot be transferred to novel contexts and is seen as distinct from understanding (Mayer, 2002a). Rote and meaningful learning are conceptualised as two poles of a continuum of types of learning rather than exclusive positions (Ausubel, 2000). The meaningful learning model has been critiqued in a number of ways: it has been suggested that the theory is not falsifiable (Lawton & Wanska, 1979); some reviewers have found weak or non-supportive evidence for the usefulness of advance organisers in learning, a key prediction of the theory (Barnes & Clawson, 1975; Clark & Bean, 2010), though these results are disputed (Luiten, Ames, & Ackerson, 1980; Mayer, 1979); and Ausubel's theory has been critiqued for vagueness and ambiguous terminology (Huh, Lee, & Reigeluth, 2013).

1.2.1.4 Conceptual change

Learning in science education has often been associated with the process of conceptual change (Chi, Slotta, & De Leeuw, 1994; Gorodetsky & Keiny, 2002; Hewson, 1981). Though conceptual change has been studied for over thirty years it remains a contested concept (Amin, Smith, & Wiser, 2014; Duit, Treagust, & Widodo, 2008). It has been suggested that conceptual changes is an 'umbrella' term covering a range of different but unrelated processes (Rusanen, 2014, p. 1414; Rusanen & Lappi, 2013, p. 3332) and there remains no agreement over what processes may occur during conceptual change (Rusanen & Pöyhönen, 2013, p. 1400). Different models of conceptual change emphasise different aspects of the process. For example, Chi and Roscoe's (2002) model focuses on ontological reassignment, Roschelle (1992) emphasises the construction of an abstracted model of

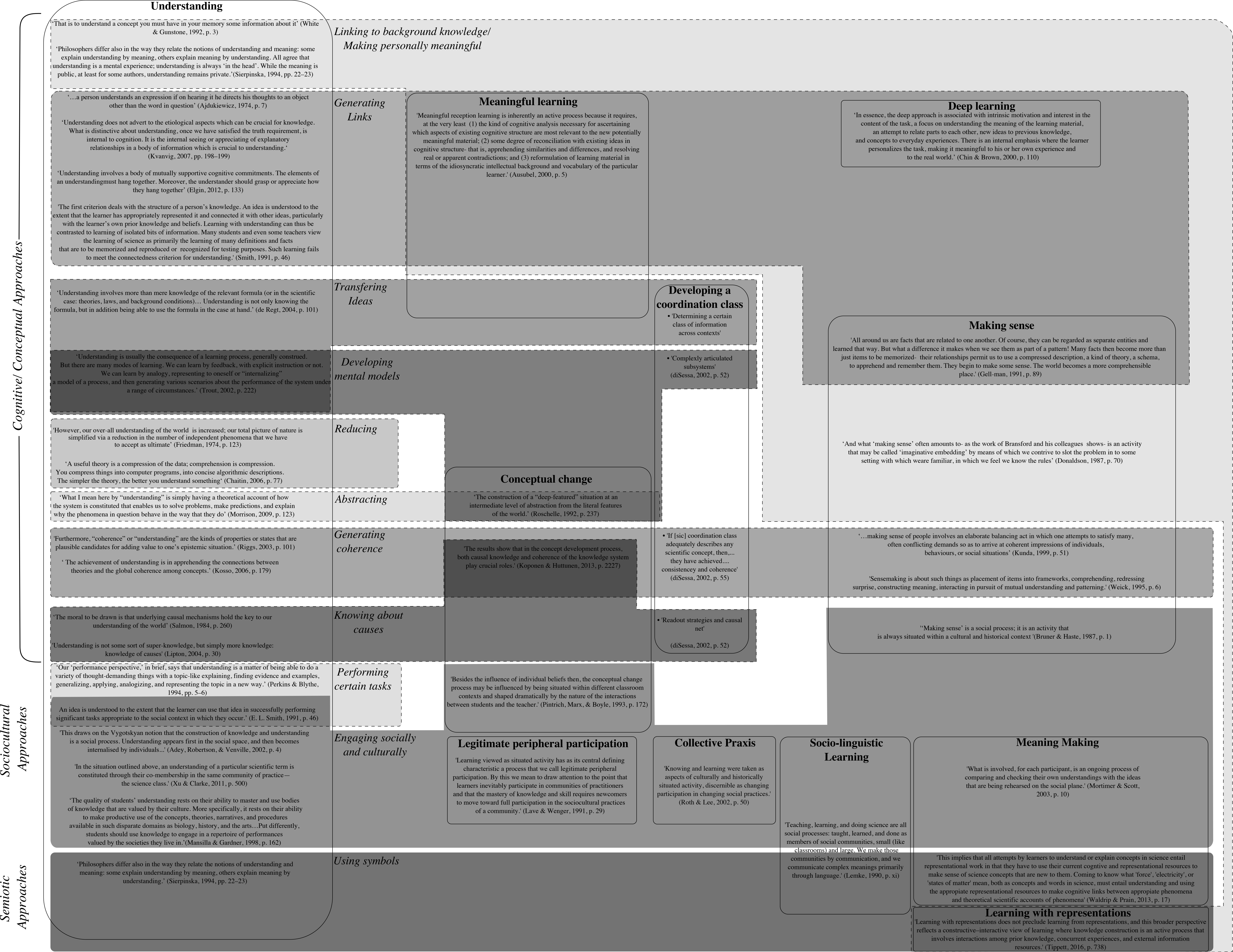
a situation, and Koponen and Huttunen (2013) propose that causal knowledge and the development of coherence play a role. Other researchers have emphasised affective and social aspects of the process of conceptual change (Pintrich, Marx, & Boyle, 1993). A particularly developed model is that proposed by diSessa and colleagues (diSessa, 2002; diSessa & Sherin, 1998; diSessa & Wagner, 2005) which describes conceptual change as the manipulation of multiple knowledge elements into structures known as coordination classes, complex systems which coordinate action across contexts leading to consistent behaviours (diSessa, 2002).

2.2.1.5 Socio-linguistic models of learning

A significant group of models of learning place an emphasis on social and linguistic aspects of learning. These constructions can be seen as arising from Vygotsky's (1962, 1978) claims that thinking and speaking are inherently connected and that functions appear first in a child's social behaviour before becoming internalised as a psychological processes. A subset of social models of learning build on the semiotic tradition founded, at least partly, on Peirce's (1902, pp. 20–21) model of the relationship between sign, object and interpretant. Typical of the claims made by this group of theories is Lemke's (1990) assertion that learning about science involves both participation in a community and the communication of meaning through language.

1.2.2 Mapping the territory

In Figure 1.1, below, a selection of terms used in science education research to describe learning have been organised to emphasise common features and areas of difference.



1.2.3 An underlying concept of learning: The elephant in the room

Researchers into learning might be likened to the blind men in the fable who examine an elephant: the one who grasps the trunk claims the object is a snake; another, feeling the leg, argues it is a tree; for a third, the tail implies the object is rope-like (Long, 2013). Researchers adopting different assumptions have developed a variety of models of learning (see Figure 1.1). Though this might seem problematic, Wittgenstein (1953, §66) pointed out that even apparently simple concepts, such as a ‘game,’ resist the development of a single definition as concepts consist of ‘...a complicated network of similarities overlapping and criss-crossing’. In this thesis, due to limited space, the focus will be on learning as constructed in the mind of the individual learner, rather than on social models. The Wittgensteinian network of similarities of the terms related to personal learning in Figure 1.1 can be seen to include the following features:

- Linking to background knowledge/ making personal meaning;
- Generating links between concepts;
- The ability to transfer ideas;
- Developing mental models;
- Abstracting and reducing;
- Generating coherence;
- Knowing about causes.

Together, these facets might go some way to describing an underlying ‘concept with blurred edges’ (Wittgenstein, 1953, §71). This is not to assume that any single cognitive process, collection of neurones or set of behaviours fully accounts for the collection of features discussed above. However, the overlap between models of learning suggests it may be useful to develop a single placeholder term to enable discussion of the inaccessible underlying processes: making sense.

As learning inherently involves change (Lachman, 1997; Marton, 1983; Mowrer & Klein, 2001), a process ontology appears to be appropriate for a model of learning. The terms understanding and meaningful learning are therefore avoided as they have an ambiguous state-process ontology. Though deep learning is situated as a process

(Marton & Säljö, 1976), it includes non-cognitive processes; for example, Biggs' (1987) use of the term includes behavioural aspects. The term sense making is commonly used in science education (Booth & Ingerman, 2002; Driver et al., 1994; Tobin, 2007; Wei, Beardsley, & Labov, 2012), and, as illustrated in Figure 1.1, has a broad range of associations. In this thesis, making sense will be taken to refer to a constructed psychological process undertaken by a learner (Danielak, Gupta, & Elby, 2010; Donaldson, 1987; Gell-Mann, 1995; Kunda, 1999). The related term sensemaking is commonly used in the context of decision-making in organisations (Weick, 1993, 1995); but, as making sense is more commonly used in science education, the latter construction will be used in this work. The concept of making sense will be defined explicitly in section 1.3.5, below.

1.3 Constraining a model of making sense

Given the plurality of models of learning discussed above, three constraining features on the concept of making sense will be discussed: a) making sense involves more than the acquisition of knowledge or following procedures (see sections 1.3.1 and 1.3.2); b) making sense is a potential for behaviour (section 1.3.3); and c) making sense does not reduce to any single process or behaviour (section 1.3.4). The discussion of these themes will draw on arguments related to the concept of understanding. However, as making sense is seen as acting as an umbrella term for various models of learning, including understanding, arguments related to subsumed terms will be taken to apply to making sense.

1.3.1 Acquiring more knowledge is not sufficient for making sense

One approach to simplifying the problem of understanding science is to argue that what differentiates understanding from rote learning is simply additional knowledge. Lipton (2004, p. 30) has argued, '[u]nderstanding is not some sort of super-knowledge, but simply more knowledge'. He (Lipton, 2004) narrows his claim for the association of understanding with knowledge, by arguing that the extra knowledge required is knowledge of causes, echoing Salmon's (1984, p. 260) assertion that '...underlying causal mechanisms hold the key to our understanding of the world'. Critics of the causal-knowledge-as-understanding model have pointed out that not all explanations in science are based on causal relationships (de Regt & Dieks, 2005), for example, laws of coexistence (Van Fraassen, 1980), such as Boyle's law, do not

invoke causes and effects. Moreover, Pritchard (2014) agrees that understanding is possible without knowledge of causes, and he points out that, even if causal knowledge were acquired, understanding does not necessarily follow (for example, causal relationships may be rote learned). A more general type of knowledge that has been linked with understanding is knowledge of explanations (de Regt, 2009; Hempel, 1965). However, it has been argued that students may rote learn explanations (Khalifa, 2012), and thought experiments or physical models, may provide understanding without explicit explanation (Lipton, 2009). Therefore, knowledge of an explanations is not a sufficient condition for understanding.

Even if understanding were a form of knowledge, it is reported that most epistemologists would argue it is not a form of propositional knowledge (Hazlett, 2014). For example, Elgin (2007, 2009) argues that understanding is not factive, but rather a ‘cognitive success term’ which arises from a grasp of how a body of information ‘hangs together’ (Elgin, 2012, p. 133). Kvanvig (2003, p. 196) points out that understanding can be present to differing degrees, whereas knowledge cannot, and so concludes that ‘...understanding is not a species of knowledge’. Similarly, for Grimm (2006, p. 532), understanding requires an additional kind of ‘achievement’ to knowing, which he links to an awareness of counterfactual situations. Wheeldon and colleagues argue that it is possible to have knowledge of a scientific principle, and achieve highly in formal assessments yet lack ‘holistic understanding’ (Wheeldon, Atkinson, Dawes, & Levinson, 2012, p. 115). If students are not lacking propositional knowledge, the gap between knowing and understanding may be explained by the lack of certain kinds of tacit knowledge (Brock, 2015).

Though it has been claimed (Pritchard, Millar, & Haddock, 2010, p. 82) that understanding may not be ‘opaque,’ that is, the understander must have explicit justifications for understanding, Polanyi (1974, p. 94) noted that, in some cases, for example an anatomist carrying out a dissection, people possess understanding ‘...which we cannot put into words’. Lipton (2009) suggested a number of other cases in which understanding might be inexpressible: a thought experiment might provide understanding without explicit explanation; understanding of the rules that bind a category together may be implicit; and a visual model may provide understanding that

is not expressible in words. For example, it is argued that observing an orrery may lead to an understanding of retrograde motion that is impossible to describe in words (Lipton, 2009). Indeed, it has been suggested that conscious thinking is ‘only comprehensible against the background provided by... inarticulate understanding’ (Taylor, 1993, p. 50). To some extent teachers are limited as they cannot completely voice their personal understanding, but must illustrate it by providing examples from which a student develops their own interpretation (Wittgenstein, 1953, p. §210) .

An alternative argument against a link between making sense and the possession of certain kinds of knowledge is the observation that novice and expert scientists may possess similar sets of conceptual resources but combine and apply them in different ways (diSessa, 1993; Sabella & Redish, 2007). In that case, the learning deficit doesn’t arise from a lack of conceptual resources but from the manner in which conceptual resources are structured and applied, a fragmentation learning impediment (Taber, 2001b). Rather than simple acquisition, learning can be seen as the ‘tuning’ of conceptual elements towards expert understanding (diSessa, 1993).

1.3.2 There is more to making sense than following procedures

An alternative to ‘knowledge-that’ is ‘knowledge-how’ (Fantl, 2008, p. 451). Ryle (1945, p. 46) argued that a scientist ‘...is primarily a knower-how and only secondarily a knower-that,’ because they must know *how* to make new discoveries. Knowledge-that has been labelled propositional knowledge and has been described as factual and declarative, whereas knowledge of how to carry out a task is categorised as procedural knowledge (Greene, Sandoval, & Bråten, 2016). The Chinese Room thought experiment, posed by John Searle to make a case about the nature of artificial intelligence, suggests procedural knowledge alone may not confer understanding. Searle (1980) imagined a room containing a person who has no knowledge of the Chinese language. The person is given a set of written rules that link one set of Chinese characters to another. A set of characters, forming a question in Chinese, is passed into the room and the person uses the rules to create a sequence of characters, which they pass out of the room. Given a suitable set of rules, it is possible that, to an observer outside the room, it appears that the person inside has an understanding of Chinese. However, the person inside the room may experience the symbols as ‘meaningless squiggles’ (Searle, 1980, p. 418), and could be considered as lacking an

understanding of Chinese. The same process may occur in the science classroom, students may carry out the steps they have been taught, solving accelerated motion problems or balancing chemical equations, but experience their actions as a meaningless performance they enact without understanding (White & Gunstone, 1992). In a sociolinguistic model of learning, this phenomenon has been described as ‘discourse imitation’ (Airey & Linder, 2008, p. 38), the process in which students are capable of using the language of a discipline without experiencing the associated ways of knowing. A research programme in cognitive science sought to develop computer programmes that replicated the strategies used by experts (Simon, 1989). However, the observation that researchers have, as yet, failed to develop a sufficient set of procedures that will lead to expert-like understanding suggests the position is more complicated than was initially imagined. It has since been reported that ‘[t]he general consensus seems to be that no set of rules can ever capture every possible situation and that interaction of rules may lead to unforeseen circumstances’ (Yampolskiy, 2013, p. 407).

1.3.3 Making sense is a potential for behaviour

A significant feature of forms of learning such as making sense and understanding, which distinguishes them from rote-learning, is they act as a potential for behaviour (Watson, 2006). Increasing understanding confers a greater ability to perform in an appropriate manner when encountering novel situations that tends to be limited with rote-learned knowledge (de Regt, 2004; Perkins & Blythe, 1994; Trout, 2002). A characteristic of understanding is going beyond the knowledge and procedures that have been taught (Bruner, 1973). As Marton, Wen and Wong (2005, p. 308) describe: ‘While memorization takes place through repetition, understanding takes place through variation’. Therefore, making sense requires not only the acquisition of facts but an ‘adaptive expertise’ (Redish, 2010, p. 1) that allows students to go beyond the information given.

1.3.4 Making sense is emergent

Understanding might be considered to be an ‘emergent’ phenomenon (Martin, Towers, & Pirie, 2006, p. 150), that is one which possesses properties that are not conferred by any of its components processes (Bunge, 1977), is not reducible to its elements and therefore is a property of system as a whole (Georgiou, 2007). This

classification seems to fit well with the notion that understanding is a relationship between elements and irreducible to any particular skill or element of knowledge. Non-decomposability is seen as an intrinsic property of complex systems like the brain (Schierwagen, 2012) and it may be that it will never be possible to describe the processes that underlie the phenomenon of making sense, either at the neuronal level or through the systems representations of cognitive science. The definition of making sense as an emergent potential acknowledges that the abilities and knowledge elements outlined in Figure 1.1, such as knowledge of causes, or the ability to make connections, are practically useful indicators for educators but that replicating those behaviours will not necessarily lead a student to make sense.

1.3.5 Defining making sense

The key facets of learning arising from Figure 1.1 can be combined to develop a general term, making sense, which combines the common features of each (see Figure 1.2, below). The model is constructed with the epistemological assumptions of constructivism (see Section 3), in particular the axiom that learning can be modelled as changes to conceptual structure (Taber, 2009).

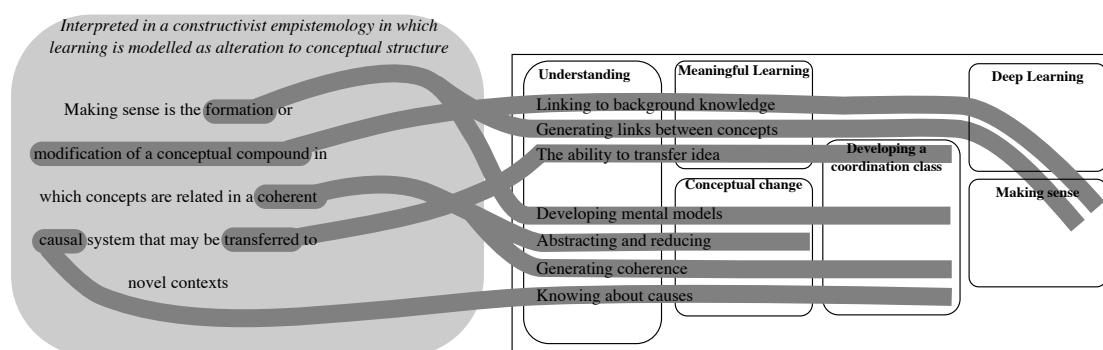


Figure 1.2: A representation of the manner in which the definition of making sense arises from an analysis of models of learning.

Making sense will be defined as *the formation or modification of a conceptual compound in which concepts are related in a coherent causal system that may be transferred to novel contexts*. A discussion of the meaning of the terms used in this definition follows in the literature review, however, as the term is not widely used, it should be noted that a conceptual compound is a representation of a system of two or more concepts that are activated and related together in a particular context.

1.4 The epiconceptual analogy

The prevailing model of learning in science education, constructivism (Taber, 2009), conceptualises the process of developing understanding as the construction of richly integrated, well differentiated and coherent networks of concepts (Chi, Glaser, & Farr, 1988; Reif, 2008; Tsai & Huang, 2001). Whilst historically there was a focus on cataloguing alternative conceptions, the constructivist description of the learning process would suggest focus should progress from examining individual concepts to a study of the dynamics of developing conceptual structure (Amin et al., 2014; Smith, diSessa, & Roschelle, 1993; Taber, 2009). The definition of making sense given above argues for this kind of an approach. Several researchers (Brown & Hammer, 2013; diSessa & Sherin, 1998; diSessa & Wagner, 2005; Koponen & Kokkonen, 2014; Roth, 2014) have modelled learning as the interaction of multiple contextually-triggered conceptual resources, but have typically not made use of a high density of sampling or tracked progress over an extended period, as was done in this research.

To draw an analogy, geneticists have moved from a view of genes as the sole determinants of inheritance (Spector, 2012, pp. 23–24) to a more nuanced view, in which the influence of genes may be mediated by their environment - a change that has been labelled the ‘epigenetic revolution’ (Spector, 2012, p. 8). The term epigenetics is derived from the Greek for ‘around the gene’ (Spector, 2012, p. 8). Research in science education may be entering a new phase, epiconceptual change research, which advances from considering individual, isolated concepts and instead seeks to understand the complex patterns of activation of concepts due to their relationships with other concepts, contexts encountered, affective states and other factors (see Table 1.0).

Table 1.0: An illustration of some areas of difference between a conceptual and epiconceptual model of change.

Conceptual Model	Epiconceptual model
Focuses on single concepts.	Focuses on the relationships between concepts.
Focuses only on concepts.	Focuses on multiple elements of conceptual ecology such as tacit knowledge and epistemological beliefs.
Describes conceptual relationships at a number of points in time with relatively long intervals between observations.	Describes the development of conceptual relationships with an interest in development over relatively short time scales.
Models conceptual change as replacement.	Models conceptual change as alteration in activation of several co-existing concepts. Change is not sudden and discrete.
Focuses on cataloguing concepts.	Focuses on the contingencies of use of concepts and the nature of conceptual relationships.

Research into conceptual change in science education has been described as passing through three overlapping phases (Amin et al., 2014). The first phase focused largely on describing students' ideas, and on the proposition of interventions to support change to concepts. The second phase progressed beyond a focus on alternative conceptions to an examination of students' interpretations of ontology, their epistemological beliefs, their use of models and an investigation of the role of social interactions. The third phase, which is described as 'emerging,' is labelled the 'systemic perspective', in which conceptual change is modelled as the interaction of multiple elements (Amin et al., 2014, p. 68). Amin and colleagues argue that future research needs to rise to the challenge of modelling learning as the interaction of diverse conceptual resources. This research, which is situated within the third wave of conceptual change research, seeks to examine the manner in which students make sense; that is, how they develop coherent conceptual compounds that can be applied across a range of contexts.

1.5 The structure of this thesis

The structure of the thesis is represented in Figure 1.3, below. Following the development of a model of making sense (above), six themes related to the concept are considered: a) the development of ontological categories; b) the development of organisations of concepts; c) the development of understandings of causality; d) the development of coherence; e) the rate of conceptual change; f) the relationship between conceptual change and the contextual triggering of concepts. These themes lead to the proposition of a set of research questions. Section 3 examines the assumptions that are made in this work, including those relating to the nature of knowledge, and emphasises their fit with the proposed model of making sense. These assumptions and the research question lead to the choice of methods discussed in section 4. The analysis is structured around the six themes related to making sense (section 5) and the final section considers the implications of the work for both research and teaching.

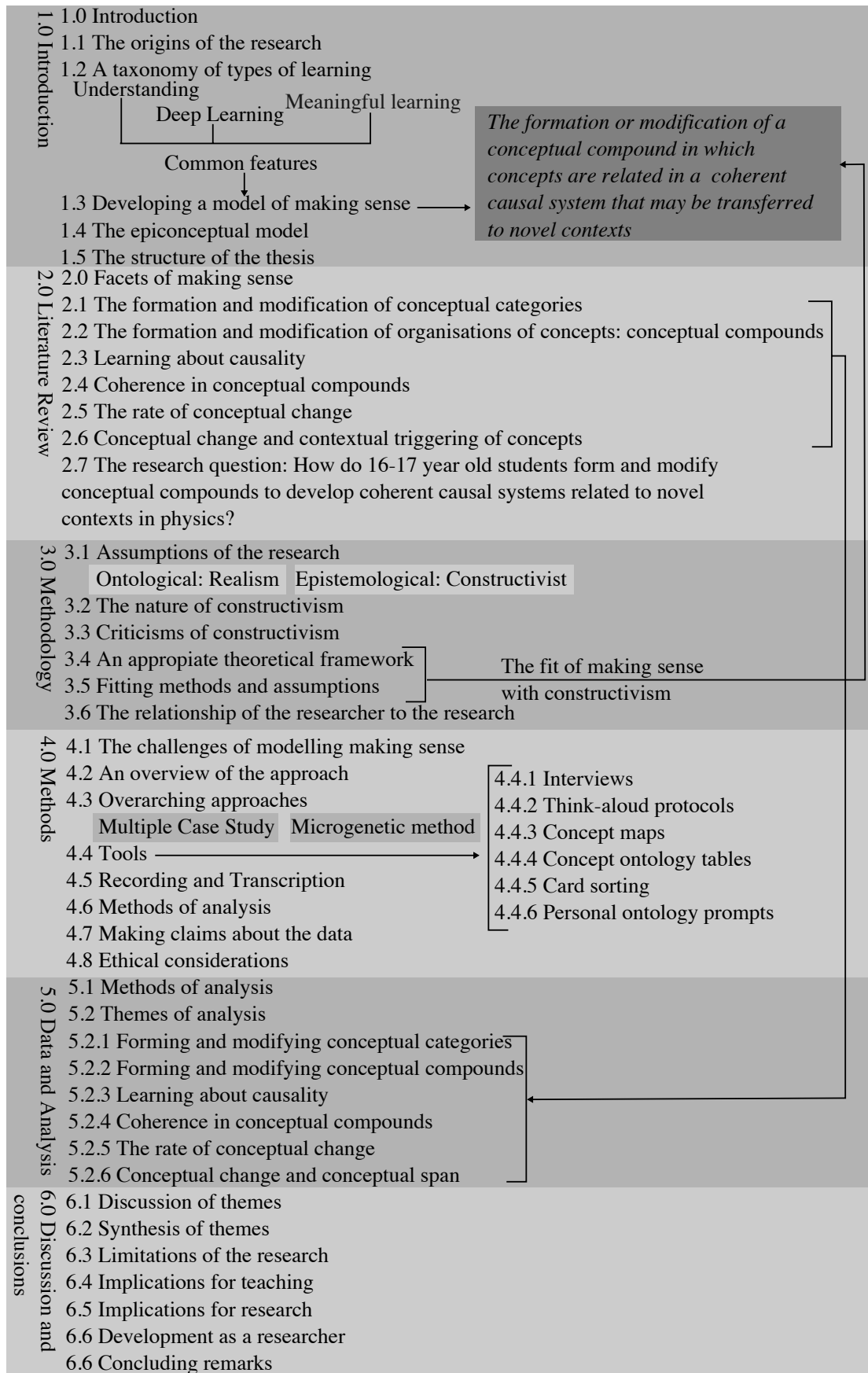


Figure 1.3: An illustration of the structure of the thesis. Note that the numbers refer to section labels.

2.0 Literature Review

The literature review is constructed in a number of sections, building on the definition of making sense in the introduction, leading to development of research questions (see Figure 2.0).

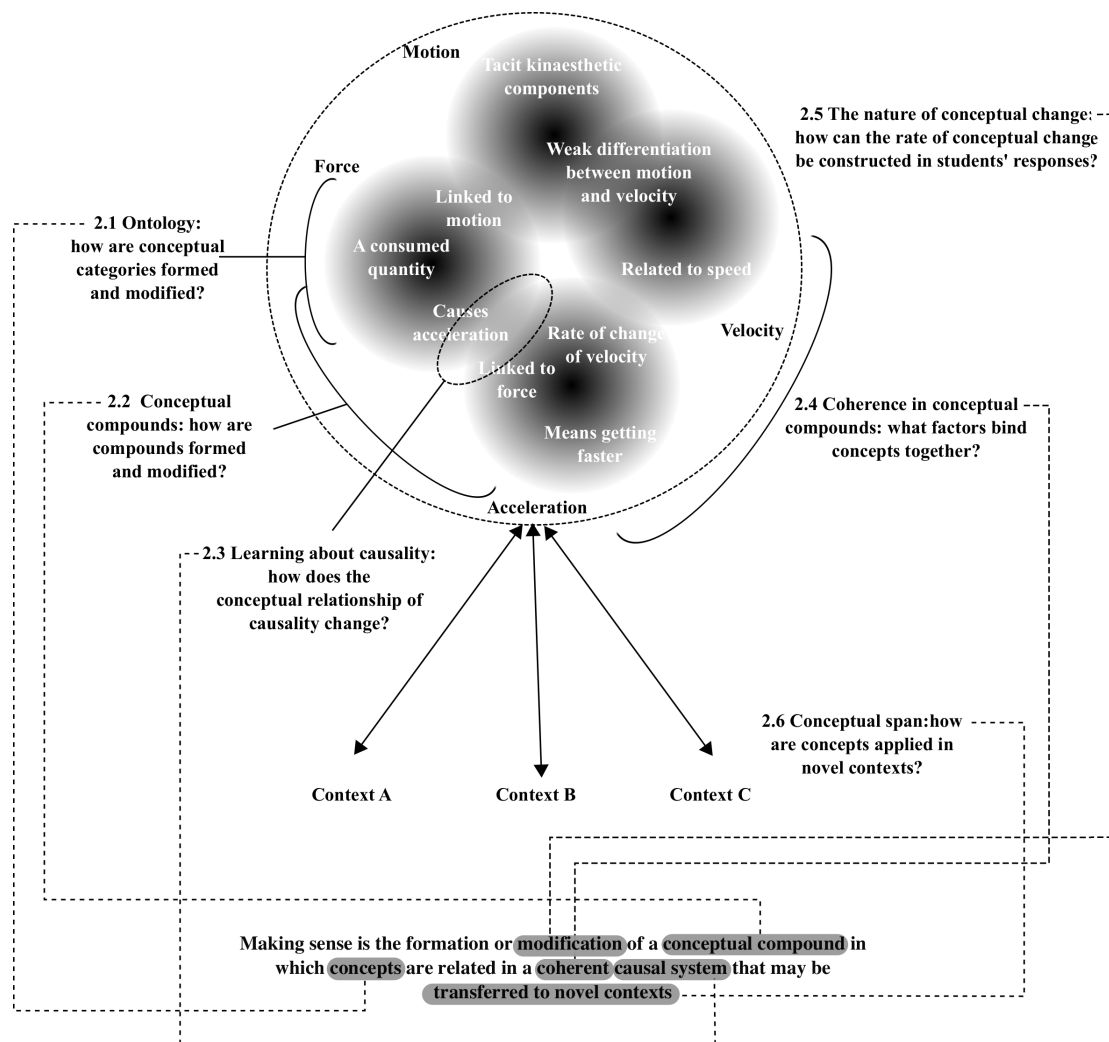


Figure 2.0: Research questions arising from the definition of making sense. The numbers indicate the section of the literature review in which each theme is addressed. Some example conceptual relationships are shown as an illustration.

2.1 The formation and modification of conceptual categories

It has been argued that cognition and categorisation are inseparable (Harnad, 2005), and therefore that, assessments of similarity are fundamental to cognition (Goldstone & Son, 2005; Pauen, 2002; Rosch, Simpson, & Miller, 1976). In particular, the classification of entities is an important aspect of work in science (Sokal, 1977; Van Cusem, 1994). Additionally, construction of similarities between entities is

fundamental to learning and enables predictions to be made in novel situations (Quine, 1969). Novices and experts have different approaches to dividing the world into categories (Chi, Feltovich, & Glaser, 1981; Hardiman, Dufresne, & Mestre, 1989; Rosch, Simpson, et al., 1976). It may be that some of students' difficulties with understanding science arise from the difference between their categorisations and those of experienced scientists (Chi & Slotta, 1993; Hestenes, Wells, & Swackhamer, 1992; Mortimer, 1995; Piaget & Inhelder, 1941/1997; Smith, Carey, & Wiser, 1985). Categories that students may perceive as distinct, for example, circular and linear accelerated motion, are conceptualised, by experts as ontologically equivalent (Chi et al., 1981). This section considers the nature of students' conceptual categories (2.1.1-2.1.3) and the manner in which those categories develop over time (2.1.4).

2.1.1 Defining ontology

The question of ontology can be expressed as: 'What sort of things are there?' (Sommers, 1963, p. 327). As a discipline of philosophy, ontology is the study of the things that exist (Effingham, 2013), and it aims to provide an '...exhaustive classification of entities' (Smith, 2003, p. 155). Distinctions between categories might be thought to exist either in 'intrinsic' (i.e. some external 'reality') or in the psychological 'reality' (Chi, 1992, pp. 130–131) of an individual. Given the constructivist ontology adopted in this research (see Section 3), a nominalist position, that is the notion that categories do not precisely replicate divisions that exist in 'reality' (Gabriel, 2015, p. 234), will be adopted. Therefore, in this thesis, ontology will refer to an individual's psychological categorisation (Baily & Finkelstein, 2014; Gupta, Elby, & Conlin, 2014) and no comments about the nature, or indeed existence, of intrinsic ontology are intended. Psychological ontologies can be thought of as an individual's catalogue of domains of information (Boyer & Barrett, 2005), or 'one's conception of the basic categories of existence' (Keil, 1979, p. 1). As concepts are commonly defined as categorisations (Carey, 2009; diSessa & Sherin, 1998; Murphy, 2002; Smith, 1989), they might be thought of as ontological divisions.

2.1.2 Concepts as ontological divisions

The development of ontologies occurs spontaneously during the normal course of development during infancy and childhood (De Cruz & De Smedt, 2007), and similar categories are formed, in some topics, by learners from various cultures (Atran,

1998). The nature of the concept is contested (Barsalou, Simmons, Barbary, & Wilson, 2003), and the wide range of meanings ascribed to this term has led some researchers to speculate as to whether it is a useful construct (Barsalou et al., 2003; Machery, 2010). Such ambiguity may arise as the assumptions and limitations related with its use are sometimes overlooked by researchers (Taber, 2013). Though the range of entities subsumed by the term may be broad, there are commonalities between different models, and the term remains a useful, if imperfect, construct (Couchman, Boomer, Coutinho, & Smith, 2010; Danks, 2010).

The nominalist position, which aligns with the constructivist methodology of this work, suggests concepts are not inherent division in reality but are human constructs (Babbie, 2010; Schlick, 1974). As will be argued in section 3.1.2, constructivists typically propose that access to reality is imperfect (Taber, 2009); hence, concepts are not precise representations of the external world (Lakoff, 1989). Some thinkers have argued that concepts are not psychological constructs (Clark, 2001; Frege, 1974), but have an existence as abstract entities. However, a model of concepts as abstractions fails to account for how individuals can develop personal constructs and a purely psychological categorisation of concepts is seen to have the greatest explanatory power (Margolis & Laurence, 2007) and has been adopted by many researchers (Carey, 2009; diSessa & Sherin, 1998; Murphy, 2002; E. Smith, 1989).

In many models, a concept is not seen as a unitary structure (diSessa & Sherin, 1998, p. 1170) but rather as a ‘mental representation of a class’ (Ross & Spalding, 1994, p. 120), or as a mental representation of ‘classes of things’ (Murphy, 2002, p. 5). Models of the manner in which individual elements may be clustered together in a concept have passed through a number of iterations (Murphy, 2002). In the ‘classical’ view of concepts (Smith & Medin, 1981, pp. 22–60), categorisations are defined by summary descriptions of the entire class that are often abstracted and need not refer to a specific member of the category. This model was critiqued first by Wittgenstein (1953) and then by Rosch (1973), on the basis that concepts such as colours do not have clear criteria attributes. Rosch (1973, 1975) went on to develop the prototype view which argues some members of a class can be seen as ‘clearest cases’ or ‘best examples’ though Rosch later argued for a looser description of prototypes as not necessarily

being a member of the class but rather an ‘abstract representation of a category’ (Rosch & Mervis, 1975, p. 575). This principle is seen in Rosch and Mervis’ (1975) family resemblance descriptions of categories, where individual members of a category may share some features but there is no single set of features that is shared by all members. However, the prototype theory does not explain observations of how measures of typicality combine in conceptual compounds (Osherson & Smith, 1981), and has been criticised for failing to describe clear conceptual boundaries and account for contextual variation in concept use (Croft & Cruse, 2004, pp. 87–97). An alternative account proposed that classifications are based on judgements of similarities to stored exemplars (Hintzman, 1986; Medin & Schaffer, 1978). However, the exemplar model is unsatisfactory, as a set of exemplars is, in itself, insufficient to define a concept: certain kinds of summary factual information cannot be stored in the form of an exemplar (Smith & Medin, 1999).

More recent models of categorisation emphasise the importance of theories and background knowledge for demarking ontologies (Keil, 1989; Lin & Murphy, 1997; Murphy & Medin, 1985). A different interpretation of the nature of conceptual constructs is Barsalou’s (1983, 2005) proposition of ‘ad hoc’ concepts; that is, categories are constructed pragmatically, in the moment, to interpret a given situation. In this model, concepts are not seen as static entities with a fixed structure, but rather as flexible entities that are reconstructed by the pressures and contexts of a given situation (Barsalou, 1987). Though this plurality of constructs of the concept might seem to deny the usefulness of the term, it has been argued that differing models might be conceptualised as ‘special cases’ rather than distinct kinds (Danks, 2010). Given the lack of agreement over the nature of categorisation processes, in this thesis a concept will simply be defined as a representation of a mental category. The elements that make up a concept will be labelled conceptual resources (diSessa, 1993; Hammer, 2000; Taber, 2008a).

2.1.3 Ontologies in science education

It has been reported that students, at some stages of learning, may struggle to differentiate a number of concepts including: force, momentum and kinetic energy (Brookes & Etkina, 2009), velocity and acceleration (Dykstra, Boyle, & Monarch, 1992), current and potential difference (Koponen & Huttunen, 2013; McDermott &

Shaffer, 1992; Shipstone, 1984), heat and temperature (Erickson & Tiberghien, 1985; Wiser & Amin, 2001; Wiser & Carey, 1983), and mass, weight and density (Piaget & Inhelder, 1941/1997; Smith et al., 1985). Though differences between learners' and experts' ontologies have been noted, little attention has focused on the manner in which categories develop over time.

2.1.4 The formation and modification of ontologies

diSessa and Cobb (2004) have observed that the process of developing new ontological categories is not straightforward and typically involves refinement through application, yet few descriptions of the kind of stages or features of the process of development of categories over time exist. However, some general themes can be discerned, and will be discussed in the sections below.

2.1.4.1 The nature of ontologies and their development

A central issue for ontological research is to define the nature of categories themselves. A recent debate has seen the ontological model of Chi and colleagues (Chi, 1992; Chi et al., 1994; Slotta & Chi, 2006; Slotta, Chi, & Joram, 1995) criticised by Gupta, Hammer and Redish (2010) over the nature and stability of expert and novice ontologies over time. Gupta and colleagues' critique (2010) prompted a rebuttal from Slotta (2011), to which Hammer, Gupta and Redish (2011) wrote a response. The two positions are summarised in Table 2.0 at the end of the section.

Chi (1992, p. 130) proposed the existence of a set of distinct ontological categories (originally: matter, events and abstractions (Chi, 1992, p. 130); though, in later papers: matter, processes and mental states (Chi, 2013; Chi et al., 1994)). Ontological categories were seen as distinct (Chi, 1992; Chi et al., 1994); that is, language used to talk about entities in one category would be meaningless if applied to entities in another (Chi et al., 1994; Slotta et al., 1995). Nevertheless, the model of ontology allowed entities to exist in multiple ontologies at one time (Chi, 1992; Slotta, 2011), but change between ontological categories was seen as challenging (Chi, 1992, 2013). Though there is no explicit discussion of the stability of an ontology over time, a link is made between the robustness of misconceptions to change over time and the difficulty of ontological transition, implying that the categories must, to some extent, be stable (Chi, 1992, 2013). Slotta (2011, p. 159) summarises the position held by Chi

as ‘flexible attribution of ontologies in accordance with the person’s immediate conceptual needs’.

Gupta, Hammer and Redish (2010) proposed a different version of ontologies. They suggested that experts and novices commonly reason across ontological categories and so asserted that ‘ontological blending’ is an important component of scientific thought (Gupta et al., 2010, p. 304). Therefore, they imagined learners possess ‘multiple and mutually overlapping ontological views’, which were seen as complementary and productive of a rich and complex description of the physical world (Gupta et al., 2010, p. 303) and argued against the existence of distinct, independent ontological categories (Hammer et al., 2011). They critiqued Chi’s notion that individual concepts as understood by experienced scientists, may exist in a single category (Hammer et al., 2011). Though Slotta (2011) suggested that the two perspectives agree on several issues, he suggested the major differences between the models arise from Gupta and colleagues’ greater flexibility in attribution of ontologies (see Table 2.0, below). A third model of ontology, the conceptual profiles model developed by Mortimer and colleagues (Mortimer, 1995; Mortimer & El-Hani, 2014), is classified as occupying a space between the two models described above. Though the conceptual profiles model assumes students’ utterances related to a concept can be categorised as belonging to one of a number of categories, and lacks the notion of ‘ontological blending’ found in Gupta and colleagues’ system (Gupta et al., 2010, p. 304), it does allow that a learner’s ontological classification can evolve by changing the likelihood of activation of different ontologies (Mortimer, 1995).

Table 2.0: A comparison of Chi, Slotta and colleagues' construction of ontologies with Gupta, Hammer and Redish's model.

	Chi, Slotta and colleagues' position	Gupta, Hammer and Redish's position
Can a concept exist in more than one ontology simultaneously?	Yes	Yes
Are there a finite number of pre-determined ontological categories?	Yes	No
Do the categories themselves evolve over time?	Implication that they do not	Yes; ontologies can be blended together
Do accepted scientific ideas belong in a single ontological category	Yes	No

These two models of ontology suggest different processes by which ontological development may occur. In Chi's model there is a clearly defined sequence: 1) the properties of a new ontological category are developed; 2) the meaning of individual concepts within the novel category are learned; 3) concepts may be reassigned to the new category (Chi, 1992). Hammer, Gupta and Redish (2011, p. 165) proposed that the apparent stability of ontologies arises from '...the dynamics of a complex system composed of manifold cognitive resources'. They argue that students' intuitive ontologies may be productive (Hammer et al., 2011), and dismiss Slotta's (2011) suggestion that original ontological commitments should be minimised. Their view of ontological change allows concepts to have multiple ontological categorisations; therefore, development happens through alteration in the contextual triggering of particular facets of a category. A description of such changing preferences for different ontological interpretations can be found in work by Silva, Mortimer and Coutinho, (2014) and Nicoli and Mortimer (2014), though their model carries with it the assumption of distinct ontological categories. The model of making sense described above is premised on the evolution of conceptual categories over time and hence Gupta, Hammer and Redish's blended model will be adopted for this work. The

next sections outline three areas of change that might be expected in ontologies as expertise develops: a) differentiation; b) clustering; and c) abstraction.

2.1.4.2 Ontologies become increasingly differentiated

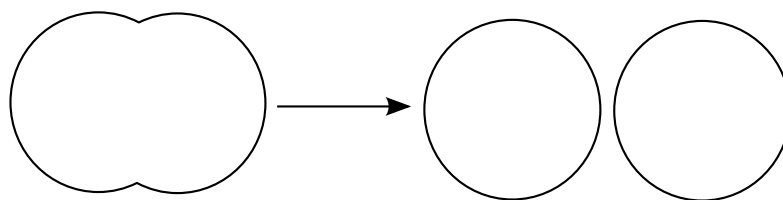


Figure 2.1: A representation of increasing ontological differentiation with expertise.

One noted path of progression in ontology is the increasing separation of concepts into distinct categories (see Figure 2.1). Conceptual differentiation has been defined as the differentiation of a single parent concept into two or more conceptual descendants (Smith et al., 1985). Piaget and Inhelder (1941/1997) reported that young children initially did not differentiate between weight and volume but, over time, became able to distinguish the concepts. As described in Section 2.1.3 a difference in differentiation of concepts by experts and novices has been reported in several topic areas in science education. In general, experienced learners may have better-differentiated categories than novices (Murphy & Wright, 1984). Experts' ability to solve problems rapidly (Chi et al., 1981) may be explained by the increased accessibility of more clearly differentiated categories (Murphy & Brownell, 1985; Murphy & Smith, 1982). Therefore, sharper distinctions between categories may lead to an advantage in learning (Murphy & Wright, 1984).

Though novice learners' concepts may seem undifferentiated when compared to those of experts, Smith, Carey and Wiser (1985) present evidence that, in the case of density, though students may in many situations not differentiate between mass and density, there may exist some contexts in which some distinctions between the concepts can be triggered. In the case of force, Dykstra, Boyle and Monarch (1992) suggested that students' initial undifferentiated concept of motion separates into velocity and acceleration before force is linked to acceleration. However, their model makes two contentious assumptions: first, the authors assume that there exists a 'stable framework of abstract ontological categories' (Dykstra et al., 1992, p. 630), an assumption that has been challenged by Gupta, Hammer and Redish (2010). Second,

it is not clear that students necessarily pass through the same series of steps in developing the concept of force: students may not necessarily differentiate velocity and acceleration before understanding that net force is linked to acceleration (see Daniel's ongoing confusion between velocity and acceleration described in section 5.2.1.2.1).

Though it might be tempting to assume that the general trend of development always involves greater distinctions between concepts, in some cases, distinctions novices possess are reduced in experts. For example, Dykstra, Boyle and Monarch (1992) describe how constant velocity and rest may initially be seen as distinct states but become collapsed into a single construct with expertise. The next section considers how development may occur through a reduction in the distinction between conceptual elements.

2.1.4.3 Ontologies become increasingly clustered

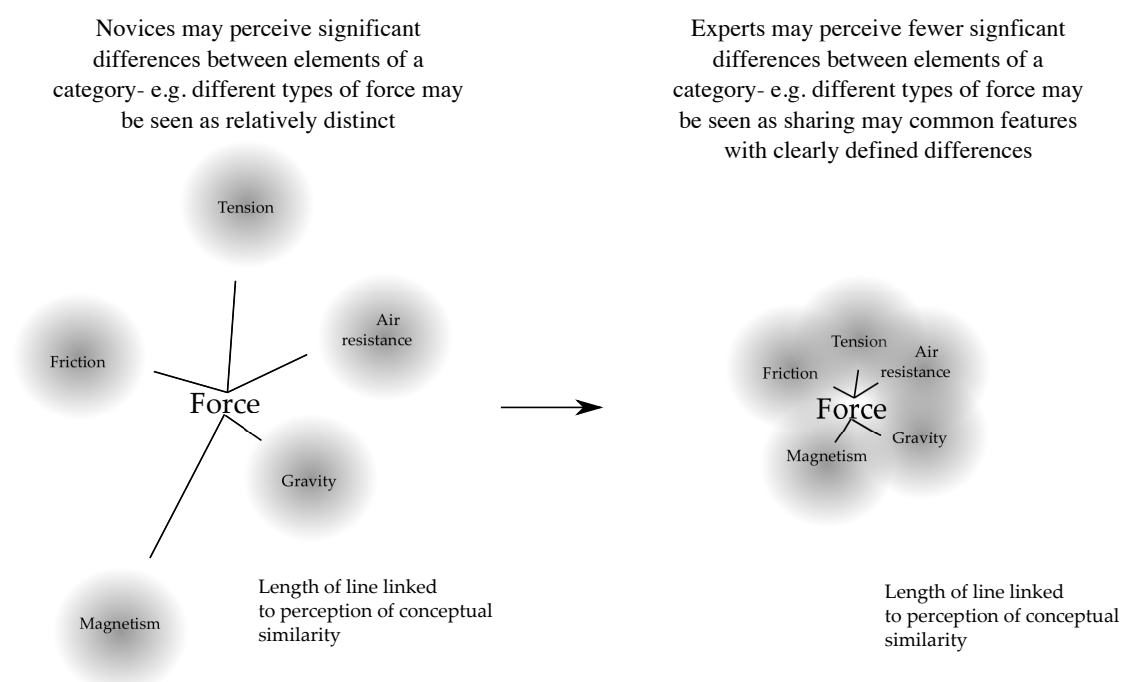


Figure 2.2: A representation of development from a novice's loosely clustered concepts to the tightly grouped ontology of an expert.

Some models of categorisation propose that the members of a category have different degrees of perceived typicality within a concept (Rips, Shoben, & Smith, 1973; Rosch, 1973, 1975). This 'graded structure' of representativeness (Barsalou, 1985, p.

629) can be represented by a spatial distance: more similar items are drawn closer together (see Figure 2.2). Evidence suggests items that are perceived as more typical of a category are more easily learned than items that are perceived as less typical (Rosch, Simpson, et al., 1976). It has been suggested that ‘...expert physicists have their knowledge tightly organized around relatively few major principles’ (Reif, 2008, p. 139) in contrast to the conceptual structures of novices which tend to consist of a collection of unstructured facts. Greater experience with a domain leads to members of a category being rated as more similar to each other, and more different from non-members (Homa, Rhoads, & Chambliss, 1979). The drive towards tightly clustered concepts, that is, the reduction of a diverse range of facts and observations to a few underlying principles, has been called the ‘great desideratum for any science’ (Maxwell, 1890/2010, p. 59) and has been linked with developing understanding (Friedman, 1974; Kitcher, 1989) (see Figure 1.1).

2.1.4.4 Ontologies develop from instances to abstractions

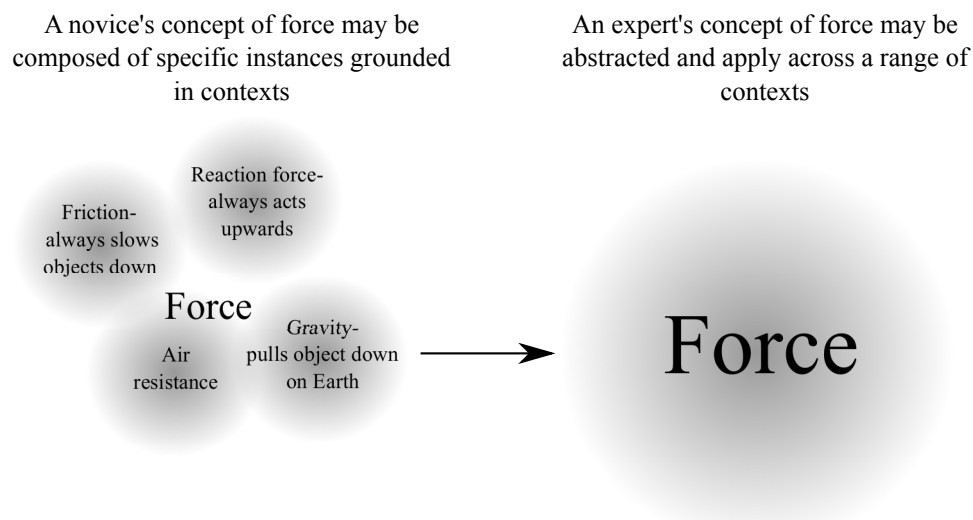


Figure 2.3: A representation of the development of classification from multiple specific examples to a single unifying abstract principle with expertise.

The third trend in ontology during the move towards expertise is a progression from categorisation via multiple concrete and specific instances towards a more unified abstract conceptualisation (see Figure 2.3). Vygotsky (1962/2012) suggested young children initially have unorganised, incoherent collections of data based on physical similarities about objects; but, as they learn, they develop increasingly coherent and

organised abstractions. Novices' intuitive beliefs may be highly context-dependent (Hestenes et al., 1992), whilst expertise can be related to the ability to transfer principles to a variety of situations with surface differences within a domain (Kimball & Holyoak, 2000; Novick, 1988). Quine (1977, p. 171) described the progression as: '...a development away from the immediate, subjective, animal sense of similarity to the remoter objectivity of a similarity determined by scientific hypotheses and posits and constructs'.

One model of concept acquisition suggests individuals begin with exemplar-based categorisations but transition to more abstracted definitions as they gain experience—the so-called 'characteristic-to-defining shift' (Keil & Batterman, 1984, p. 232): children may first acquire categories defined by perceptual characteristics and then develop an understanding of more abstract relationships (Imai, Gentner, & Uchida, 1994). Chi, Feltovich, and Glaser (1981) report that novices tended to categorise problems based on surface similarities, whilst experts used abstract laws and principles. Acquiring causal knowledge may assist this transition: category membership is initially based on observable features, but may develop to be dependent on a shared underlying cause (Rehder, 2007). This move towards abstraction may arise from a desire to maintain conceptual coherence: when novel contradictory information is encountered, increasing abstraction may allow more elements to be included in the category (Ohlsson, 2009).

It is debated as to whether the development of ontology proceeds from lower to higher levels of abstraction (Pauen, 2002). Mandler and McDonough (1993, 1996) have argued that even young children may appreciate abstract similarities between entities, and Pauen (2002) has suggested initial categorisation may be broad in scope before a global-to-basic shift in categorical thinking occurs. An intermediate position was suggested by Rosch and colleagues (1976): ontological development begins with psychologically fundamental 'basic' level categories. For example, the category of 'chairs' (basic-level) is acquired before the subordinate category of 'kitchen chairs' or the superordinate category of 'furniture', and the basic level is seen as maximising information gained (Rosch, Mervis, et al., 1976). However, this notion has been critiqued by Tanaka and Taylor (1991), who argue there is no absolute notion of a

basic category and that prior knowledge may affect judgements of the basic level of categorisation. Though the development from instances to abstractions may not be as simple as suggested in some models, the development of abstractions is a facet of several models of learning (see Figure 1.1), and the transition presents a useful working hypothesis for the development of ontology.

2.2 The formation and modification of conceptual compounds

A common facet of models of learning is the claim that students develop links between concepts to form compound organisations (see Figure 1.1). Such organisations are highly significant as concepts are defined by their relations to other concepts (Ruiz-Primo & Shavelson, 1996). The notion that cognitive entities may be arranged into some kind of structure has existed for many years (Deese, 1962; Vygotsky, 1962) and many different conceptualisations of these arrangements have been proposed some of which are analysed in the following sections. The concepts of explanation and argument have been excluded from the discussion as they are seen as linguistics structures rather than constructs of psychological entities (Osborne & Patterson, 2011).

2.2.1 Schema, and cognitive and conceptual structures

Perhaps the earliest description of a conceptual organisation is Bartlett's (1932, p. 201) schema, 'an active organization of past reactions', which became influential through its adoption by Piaget (1955, 1970). The term schema is not widely used in science education research (Taber, 2013); rather, the terms conceptual or cognitive structures are often used. The term conceptual structure has an ambiguous usage, as it may refer either to the structure of a single concept (Komatsu, 1992; Medin, 1989) or the relationship between multiple concepts (Shavelson, 1972). The terms cognitive and conceptual structure are used interchangeably; for example, the representations developed in concepts maps are referred to by some authors as describing cognitive structure (Novak & Musonda, 1991; Towbridge & Wandersee, 1998), and by others, as depicting conceptual structure (Chang, 2007; Regis, Albertazzi, & Roletto, 1996). Descriptions of conceptual structure typically define this construct as having relatively long-term stability (Shavelson, 1972), or conceptualise it as a largely stable structure with some variable elements (Ausubel, 1963; Taber, 1995). The terms conceptual and cognitive structure are often used in the plural form, implying a

learner is imagined as possessing multiple structures (Dhindsa & Anderson, 2011; Tsai & Huang, 2001); but little indication is given as to how such separate structures might be demarcated. Other researchers imply a representation of cognition as a single structure; for example, ‘the learner’s conceptual structure’ (Ausubel, 2000; Osborne, 1980; Tsai, 1998). The ambiguous usage of these commonly-used terms suggests a more clearly defined alternative may be useful.

2.2.2 Mental models

The diversity of existing constructions makes mental models hard to define (Franco & Colinviaux, 2000; Rapp, 2005; Rouse & Morris, 1986). However, mental models are described by some researchers as compound structures, formed from the organisation of a number of entities (Chi, 2008; Johnson-Laird, 1983; Nersessian, 2013; Rapp, 2005). There is broad agreement that mental models are dynamic (Greca & Moreira, 2002; Harrison & Treagust, 2000a; Rapp, 2005) and idiosyncratic (Gilbert, Boulter, & Rutherford, 1998; Greca & Moreira, 2002). However, the stability of mental models is disputed: some researchers describe the existence of both long-term and short-term models (Johnson-Laird, 1989), whilst others define mental models as relatively enduring, with only subsections of the structure undergoing change (Doyle & Ford, 1998). In contrast to cognitive structure, mental models are seen as having defined limits (Johnson-Laird, 1983), though their boundaries may be poorly defined (D. A. Norman, 1983). According to Doyle and Ford (1998, p. 18), ‘a mental model must be small enough to be implemented in short-term memory, the capacity of which is generally considered to be seven plus or minus two “chunks” of information’, though they argue the size of the ‘chunks’ will vary with expertise. They argue the smallest possible mental model consists of two variables and two causal relationships (Doyle & Ford, 1998).

2.2.3 Coordination classes

A specialised description of an organisation of cognitive elements is the coordination class found in the knowledge-in-pieces model of conceptual change developed by diSessa and colleagues (diSessa, 2002; diSessa & Sherin, 1998). Coordination classes are likely to be composed of p-prims and are described as ‘...large, complex systems, rather than atomic elements’ (diSessa, 2002, p. 43). P-prims, or phenomenological primitives are ‘“pieces” of intuitive knowledge’ (diSessa, 2000, p. 91) that are

‘inarticulate,’ ‘not strongly related to dictionary lexicon’ and without ‘explicit propositional form’ (diSessa, 1993, p. 119). DiSessa argues coordination classes may well not exist in naïve thinking as the construct is seen as determining information across a range of contexts (diSessa, 2002). Thaden-Koch (2003) therefore proposed the term coordination system for organisations of knowledge that do not generalise across a range of contexts. In discussing the extent of coordination classes, diSessa and Wagner (2005, p. 137) state that ‘... the criteria for “completing a system” are not clear’. Though the issue is not discussed explicitly, the claim that coordination classes can function across a range of contexts implies they are relatively stable constructs.

2.2.4 Temporary organisations

The conceptual organisations discussed up to this point are described as, to some extent, stable: this section deals with constructions of conceptual compounds that are short-lived and unstable. Perhaps one of the earliest reports of these structures is found in Piaget’s (1979, pp. 16–17) description of children ‘romancing’ an answer in clinical interviews because ‘... they like the sound of it’. He cautions against discounting these constructed ideas, as they may provide evidence of past learning or anticipations of future constructs (Piaget, 1979). Taber (1995, p. 95) used the terms ‘mental flotsam and jetsam’ to refer to constructions which are ‘transient’; but he observes that such temporary constructions may occasionally lead to permanent shifts in conceptual structures.

The transience and lability of such temporary structures can be explained in the reconsolidation model of memory, which suggests concepts are relatively stable in long-term memory but become changeable when recalled to working memory (Alberini & LeDoux, 2013; Besnard, Caboche, & Laroche, 2012). Some concepts, though ad hoc and constructed in response to a particular context, may, through repetition, transfer into long-term memory (Barsalou, 1983). Niedderer (1997) describes a similar process through which unstable ‘actual constructions’ can transition into stable cognitive elements during the learning process. Just as Barsalou (1983) describes some concepts as ‘ad hoc’, Wittmann (2002, p. 113) reports some students’ responses to questioning on wave phenomena as being ‘on the fly’, meaning that additional properties are added, without much consideration, in response to the interviewer’s prompts. Wittmann (2002, p. 113) elaborates that the robustness of

‘just-in-time’ constructs is an open question: one that would require the use of sampling over an extended period to answer. A number of descriptions of these kinds of temporary organisational structures have emerged in science education including: Sabella and Redish’s (2007, p. 1027) ‘locally coherent’ knowledge structures; Paranfes’ (2012, p. 362) ‘temporary plateau of coherence’; and Sherin, Krakowski and Lee’s (2012) dynamic mental constructs. This research is unique in its attempt to describe the development of unstable conceptual organisations using high frequency sampling over an extended period of time.

2.2.5 Properties of conceptual compounds

The terms above, describe psychological entities that consist of a system of related concepts or other cognitive elements. Some of these constructs come with assumptions and restrictions on the stability, composition or number of component elements related. Therefore, the term ‘conceptual compound’ is proposed as a general term that refers to a representation of a system of two or more concepts that are activated and related together in a particular context. The term conceptual compound has been used to refer to concepts developed from the amalgamation of previously distinct concepts (e.g. Sichelschmidt & Günther, 1990), in contrast to its use here to refer to the activation of multiple concepts in a given context.

Conceptual compounds can be thought of as differing along three dimensions: the types of entities organised, the stability of the organisation, and the ‘extent’ of the organisation; that is, the number of components related. Variation in each of these dimensions may explain the range of different properties conceptual compounds can exhibit. A large range of entities has been proposed as the elements of conceptual compounds: ideas (Diekhoff, 1983); concepts (Doyle & Ford, 1998; Nersessian, 2013); p-prims (diSessa, 2002); mental representations, including word-like concepts and picture-like images (Thagard, 2007); resources (Sabella & Redish, 2007); and knowledge elements (Bao & Redish, 2006). A compound composed of tacit elements, such as p-prims, might be imagined to behave differently from the structures composed of ‘committed facts’ found in expert thinking. However, as it is difficult, in practice, to distinguish many of these constructs the analysis will focus mainly on the stability and the extent of compounds.

It may be the case that expert learners' cognition can be represented by a series of relatively stable relationships between concepts that are activated consistently across appropriate contexts by recalling elements of relatively stable structures in long-term memory. However, a novice learner may display greater variability in the groups of concepts they choose to activate in given contexts; and their available resources, and the relationships between them, may also be less stable than those of experts. A researcher only has access to the representations a learner chooses to 'bring to mind' in a particular context, but such constructs are not direct representations of long-term memories or physical substrates (Taber, 2013). The term conceptual compound is intended to highlight that the groups of concepts learners 'bring to mind' can be organised in various combinations and with varying degrees of stability across different contexts.

2.2.5.1 The stability of the compound

Defining the stability or lifetime of a collection of cognitive entities is challenging and few models of stability exist. Georgiades (2000, p. 124) defined 'durability' as how long a conception 'remains in effect'. Though they do not define the term, Licht and Thijs (1990) imply the persistence of preconceptions relates to the time period over which a particular understanding is employed by a learner. The lack of discussion of stability of both concepts and compounds of concepts may relate to a lack studies of conceptual change over extended time periods and with sufficiently high frequencies to describe change (Brock & Taber, 2017b). Describing the stability of conceptual compounds is more challenging than for concepts, as there are more ways in which a conceptual conglomerate can change; and, as they are compound entities, parts can remain stable while certain elements undergo change. However, as reported in the sections above, a number of different constructs of conceptual compounds make claims regarding the stability of the entity. Given that it is assumed that the application of concepts can be contextually triggered, the stability of a conceptual compound might be defined as the extent to which a group of concepts with a fixed set of relationships is repeatedly applied in a particular set of contexts.

2.2.5.2 The extent of the compound

Conceptual compounds are, by definition, formed from component entities; therefore, it may be possible to determine the extent of a compound, that is, the number of entities linked within the construct. However, neither the elements nor the structures have clearly defined boundaries, diSessa and Sherin (1998, p. 1170) describe compounds as ‘fuzzy’ due to their compound nature. Moreover, mental models evolve over time (Coll & Treagust, 2003), making the task of defining the extent of a compound challenging. Despite the difficulty in defining the exact extent of a structure, it will be useful to be able to differentiate constructions by the number of elements coordinated, described here as the extent of the construct. This distinction occurs in a number of descriptions of organisations of cognitive elements.

Johnson-Laird (1983, p. 398) described mental models as necessarily finite in ‘size’, though he does not define the concept of ‘size’. Doyle and Ford’s (1998, p. 18) claim that the size of a mental model is restricted by working memory, that is, seven plus or minus two ‘chunks’. In addition, they place a lower bound on the size of a mental model as two variables and two causal relations (Doyle & Ford, 1998). Other authors provide definitions linking the extent of a compound to the number of links between elements. For example, White and Fredericksen (1990, p. 14) link the ‘degree of elaboration’ with the number of qualitative rules used in a model, and Tsai and Huang (2001) relate the extent of a cognitive structure to the number of linkages between components.

Initially, students may be able to connect only a few component entities from a single domain to form an argument, whereas experts are better able to coordinate multiple elements from across contexts into a structure (Clark, 2006). Learning can be conceptualised as progress from conceptual compounds of a few elements with limited complexity into increasingly complex structures that subsume a greater number of elements (Wiggins, 2015). However, in certain contexts, it may not be the case that experts have more conceptual elements available than novices; rather, that they are better able to coordinate the information into appropriate constructs (Sabella & Redish, 2007). One particularly significant manner in which elements may be related in a conceptual compound is through causal relationships.

2.3 Learning about causality

Causal relationships are seen as significant in a number of models of learning in science education (see Figure 1.1). The concept of causality is difficult to define (Neufeld, 1990), and the mass of ‘misleading associations’ that surround the term led Russell (1912, p. 1) to suggest philosophy could do without the concept. One way of describing causality is as a relationship which links two events that occur at different points in time (Bohm, 1957/1984). However, as David Hume noted, the nature of the link between cause and effect is elusive, as the events may ‘... seem *conjoined*, but never *connected*’ (Hume, 1748/2007, p. 52). Contemporary accounts of causality have been divided into two frameworks: difference-making and causal process approaches (Woodward, 2007). Difference-making theories include the interventionist model, which suggests: ‘If manipulation on one factor (interventions) are associated with a change in a second factor, then the first causes the second’ (Sommerville, 2007, p. 48). Alternatively, in causal process approaches, causality is seen as a process that exists in some sense in the universe (Cartwright, 2004). The interventionist account of causation is seen as well-suited to the methods of experimental science (Lange, 2003), and is commonly used in psychological investigations of causality (Gopnik & Schulz, 2007a; Sloman, 2009). Therefore it will be the model used here, additionally, given their common usage by different writers, both the terms causality and causal relationship will be used to refer to the relationship between cause and effect.

The concept of causality is central to the scientific project of developing interpretations of natural phenomena (Mumford & Anjum, 2013), as scientific explanations often, though not always, have a causal character (Van Fraassen, 1980). An inherent aspect of causality is the asymmetric nature of cause and effect (Mumford & Anjum, 2013). However, the expression of relationships between physical variables in the form of equations containing an equality sign are symmetrical (Bunge, 2009; Iwasaki & Simon, 1994; Russell, 1912). Students may therefore learn to manipulate equations without developing an understanding of causality (Cohen, Eylon, & Ganiel, 1983). This is significant, as it has been argued that coming to understand science depends on acquiring causal knowledge (Lipton, 2004). The next section considers research regarding how information about causes and effects is learned.

2.3.1 Learning causal relationships

Psychologists have yet to reach a consensus as to how causal relationships are learned (Goldvarg & Johnson-Laird, 2001) though there has been a recent increase in research interest in the topic (Holyoak & Cheng, 2011). Researching the understanding of causality is challenging because causal relations are not directly observable in the physical world (Hume, 1748/2007); and people develop personal constructions of causality (Alessio, 2011), which may not be directly expressible in words (Lipton, 2009). Despite these difficulties, a body of research exists about learning causal relationships.

People have a tendency to assume causal explanations exist when making sense of events (Kahneman, 2011; Michotte, 1963), and prefer learning about asymmetrical causal relationships, that is, between variables that are either causes or effects rather than non-causal relationships (Holyoak & Cheng, 2011; Schauble, 1996). Learners may develop a tendency to overgeneralise causal explanations and to disregard information that disconfirms their model (Schauble, 1996). In addition, learners may reject strong correlations that do not conform to their causal expectations (Chapman & Chapman, 1969). Causality may play a role in defining conceptual structure, as cause features are perceived as more central than effect features in categorisations (Ahn, Kim, Lassaline, & Dennis, 2000). Causal networks are acquired in a 'piecemeal fashion' (Lagando, Waldmann, Hagmayer, & Sloman, 2007, p. 168), and short causal chains tend to be integrated into larger networks (Ahn & Dennis, 2000). It is known that young children's models of causality differ from those of experienced scientists (Grotzer, 2012; Piaget, 1930/1970): the next section examines reports of how students' understanding of causality develops over time.

2.3.2 Changes to understanding of causality over time

Whilst researchers have tracked changes in young children's understanding of causality (Sobel & Kirkham, 2006; White, 1988), little attention has been given to the development of understandings of causality in older students in particular contexts within science education. One of the earliest, and most influential, descriptions of the development of causality in the physical world is Piaget's model (1930/1970). He

described a series of seventeen stages in children's understanding of causality, shown in Table 2.1.

Table 2.1: Stages of causal development. Adapted from Piaget (1930/1970, pp. 258–273).

Stage	Name	Description
1	Pre-causality	Psychological motive for all events.
2	Finalism	All functions have a purpose.
3	Phenomenistic	Events experienced together are seen as causally related.
4	Participation	Similar kinds of objects are able to act on each other at a distance.
5	Magical causality	Links are established between thoughts, gestures and objects.
6	Moral causality	Explanations contain a moral imperative.
7	Artificialism	All events are willed or organised by human activity.
8	Animistic	Explanation via an internal conscious agent.
9	Dynamicism	Objects are considered to contain a driving force.
10	Reaction to the surrounding medium	Movement requires continual contact with an outside medium.
11	Mechanical causality	Causes are explained by contact and transfer of motion.
12	Causality by generation	One object is born from another.
13	Substantial identification	Causation by the transmutation of objects.
14	Condensation and rarefaction	Qualities of objects are caused by their relative densities.
15	Atomistic composition	Objects properties are explained by though their atomistic composition.
16	Spatial explanations	Explanations based on the spatial forms of objects.
17	Explanation by logical deduction	Deductive laws or principles are used to form explanations.

Piaget (1930/1970) described a general trend away from the self as the main agent in the world, through notions of concrete objects as causes, towards a final abstract understanding of causality. A similar progression is described by diSessa (1993), who suggests students may advance from assuming causality requires a human agent to the development of more elaborate causal chains including invisible and inanimate causes. A move from causality as a property of physical objects towards a more

abstracted notion of causes is also seen in Metz's (1991) three-stage model of progression in children's reasoning about gear trains. At first, the function of an object defines its causality, then the connections between elements define causality, then, finally, causality is understood through the action of mechanisms.

Subsequent commentators have criticised Piaget's contention that infants and young children are acausal, and that causal reasoning via logical deduction only occurs at relatively advanced ages (Gopnik, 2009; Gopnik & Schulz, 2007b). Gopnik's model of causal development assumes children are born with some innate, though 'sketchy', causal assumptions, which are then modified and developed as they encounter new experiences (Gopnik et al., 2004, p. 28). Researchers have also noted deviations from Piaget's developmental pattern; for example, older children may revert to types of explanations found in Piaget's earlier stages in unfamiliar situations (Berzonsky, 1971; Nass, 1956) - an example of a general pattern found within the Piagetian research programme, known as 'horizontal décalage', where a cognitive operation a learner has demonstrated in some contexts is less likely to be applied in less familiar domains (Kreitler & Kreitler, 1989). Given its important role in scientific understanding, it is surprising that, recently, little research attention has focused on the how students' causal thinking changes over time. The models that do exist suggest a transition from an association of causes with physical objects towards a more abstracted model; a transition that can be represented using the macroscopic, sub-microscopic and symbolic categories described in detail in the discussion section 5.2.3.2.

2.4 Coherence in conceptual compounds

The drive to detect order and patterns in sensory data is an entrenched feature of human cognition (Gibson, 2000; Heine, Proulx, & Vohs, 2006; Shermer, 2012). Though this tendency can be a powerful tool for developing understanding, it may also lead to the perception of patterns in stimuli that are entirely random (Murra & Di Lazzaro, 2010; Taleb, 2004). Both the appeal of coherence (Koponen & Huttunen, 2013) and the desire to avoid incoherent mental states (Piaget, 1953) have been described as driving conceptual change. The impetus for development may arise partly from the negative emotions associated with incoherence, and the positive feelings linked to the development of coherence (Thagard, 2006). These drives result

in coherent constructions acquiring a degree of stability: humans tend to seek to retain their existing constructs even when disconfirming evidence is presented (Heine et al., 2006).

2.4.1 Defining coherence

Coherence is a difficult notion to define (Garnham, 1997) and to assess (diSessa, 2008): a number of models of coherence are presented below. diSessa, Gillespie and Esterly (2004) proposed that coherence is defined by the manner in which concepts are specified, the relational structure between concepts, and the contexts in which concepts are triggered. The model presented here extends diSessa and colleagues' work by positing that coherence is driven by three factors: a) prior learning, b) contextual factors, and c) epistemological assumptions.

Some models focus on the role of the concepts or other knowledge as the driver of coherence. For example, Thagard and colleagues conceptualise coherence as occurring through constraint satisfaction, that is, ideas are coherent if they satisfy a number of inter-conceptual conditions (Thagard, 2000; Thagard & Verbeurgt, 1998). If one statement explains another, or one claim is deducible from another, a degree of coherence is assumed to exist between the assertions (Thagard & Verbeurgt, 1998). In these kinds of constructions the principles that define the relationship between concepts are seen as arising from the concepts themselves. For example, diSessa (2008, p. 35) argues it is the nature of concepts that drives coherence: concepts are coherent 'if one vaguely seems to imply the other, or even if they merely seem related in some unspecified sense'.

Murphy and Medin (1985, p. 291) argued accounts of coherence based on comparative relationships were insufficient; hence they defined a coherent group as one which 'makes sense to the perceiver'. They argued that theoretical knowledge plays an important role in constraining judgments of coherence; for example, an expert taxonomist's background knowledge might lead them to group shrimp, moths and spiders together, despite differences in their forms and habitats (Murphy & Medin, 1985). Similarly, Chi, Feltovich and Glaser (1981, p. 125) describe how expert physicists constructed categories based on 'deep structure', the physical principles or laws that transcended the surface details of a situation. External

constraint models focus on knowledge beyond the concepts themselves as constraining coherence: coherence arises from ‘extent to which category features go together in light of prior theoretical, causal, and teleological knowledge’ (Patalano, Chin-Parker, & Ross, 2006, p. 408). For example, the features ‘lives in water, eats fish, has many offspring’ go together better than the features ‘lives in water, eats wheat, has a flat end’, because of background knowledge about the nature of an aquatic habitat (Murphy & Wisniewski, 1989).

Antonovsky (1987, p. 19) argues people may have a general preference, a ‘sense of coherence’ regarding the extent to which they perceive their environment as being ‘structured, predictable and explicable’. Beliefs students hold about knowledge have been labelled ‘personal epistemology’ (Hofer, 2001), and learners may possess multiple, contextually-triggered epistemological beliefs (Hammer & Elby, 2003). Novice learners of physics tend to view the subject as a collection of discrete, contextually applied principles, in contrast to the universally coherent model of experts (Halloun & Hestenes, 1998). Beliefs about coherence may impact on learning; for example, Schommer and colleagues (1992) carried out a large survey which indicated a correlation between comprehension of a textbook passage and a belief in the coherence of mathematical knowledge. Hammer (1989) reported two case studies of learning about physics: in the first, a student’s belief that physics is fragmented is claimed to be linked with limited flexibility in application of ideas, in the second a student who expected a coherent account resolved misconceptions that another student did not. Two further case studies, Gupta and Elby (2011) and Bing and Redish (2009), report examples of students solving a physics problem. The students have the appropriate knowledge elements to understand the problem, yet initially fail to make sense of it, due to the activation of inappropriate epistemological resources.

The final element that drives coherence are factors related to the context. A context can be considered to consist of physical conditions, the people involved and their social relationships (White, 1985). White (1985) highlights a distinction between objective and subjective features of context; though observers may agree on the presence of certain conditions, for example physical features, there may be disagreement over others, such as the construction of social relationships. Finkelstein

(2005) similarly describes context as multi-layered and dependent on the interaction between participant, task, researcher and wider cultural factors. Learning has been described as an activity inherently situated in a context (Greeno, 1998; Lave, 1988); hence, the transfer of knowledge to novel situations may be challenging for students (diSessa & Wagner, 2005). A number of models of cognition propose that the activation of conceptual resources is context-dependent (Bao & Redish, 2001; diSessa, 1993). Such models allow the difference in performance between novices and experts to be explained by the possession of different knowledge elements, which act together ‘...sometimes coherently and sometimes not’ (Hammer, 2000, p. 53), in different contexts of activation (Sabella & Redish, 2007).

In order to subsume the broadest possible range of models, in this thesis, coherence will be taken to mean: a subjective judgement of the degree to which a set of conceptual resources fit together to make an assertion about a context. This construction may seem to shift the burden of definition to the word fit, as is seen in Murphy and Medin’s (1985, p. 291) definition of coherence as the extent to which ideas ‘hang together’ or ‘make sense’. As the sense of unity denoted by coherence is personal and contextual, no further explication is helpful in a definition. However, the review of literature above suggests three pressures, pre-existing concepts, epistemological assumptions and context, can be seen to constrain coherence (see Figure 2.4).

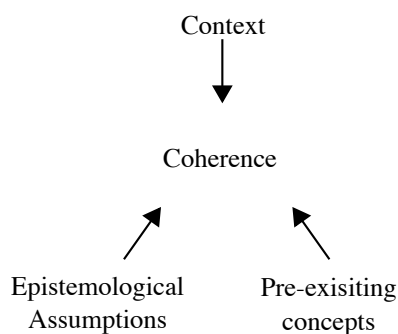


Figure 2.4: Three factors that constrain the formation of coherence.

This model suggests that all three of these factors may impact on the formation of coherence; but, according to the circumstances, different pressures may be dominant. The factors that drive coherence may be tacit, and an awareness of the links between

concepts may, on rare occasions, arise suddenly and be labelled an insight (Brock, 2015).

2.4.2 Emic and etic coherence

The elusiveness of a definition of coherence may stem in part from its subjective nature (Hoey, 1991). Different cultures of thinking may apply different rules concerning the acceptability of arguments (Kuhn, 1962); and students may perceive their concepts as coherent, because their criteria for coherence are different to those of scientists' (Driver, Guesne, & Tiberghien, 1985). This subjectivity suggests it will be useful to distinguish emic coherence (as judged by the actors) from etic coherence (as judged by external observers) (Pike, 1967). A significant debate in science education research has focused on judgements of etic coherence; that is, on describing the extent to which students' knowledge about the world seems coherent to observers (Özdemir & Clark, 2007). One model of conceptual change argues that both novice and expert understandings are relatively coherent (Vosniadou, 2002); another, suggested by diSessa (1993), suggests that novice thinking is relatively unstructured, and thus lacks a high level of coherence. The debate regarding etic coherence is one of degree of coherence rather than absolute positions (diSessa, 2008) and will be difficult to settle because the level of coherence of students' concepts varies with time and with the manner in which such concepts are elicited (Sherin et al., 2012).

Students develop positions that are personally coherent (emic coherence) but may appear contradictory to expert observers (Beveridge, 1985; Vosniadou & Brewer, 1992). However, students may struggle to explicate the processing underlying the formation of such emic coherences as individuals may possess limited insight into certain aspects of their own cognition (Nisbett & Wilson, 1977), and some elements of cognition may be tacit (Brock, 2015). Therefore, in this thesis, the focus will be on etic descriptions of the factors that constrain coherences.

2.4.3 The stability of coherent conceptual structures

It is reported that concepts which are coherent are acquired more easily (Rehder & Ross, 2001) and retained for longer periods (Ausubel, 2000). Conversely, incoherent conceptual compounds are susceptible to change (Dole & Sinatra, 1998). This observation can be explained using the 'meaning maintenance model' (Heine et al.,

2006), which suggests humans find it problematic when interpretative frameworks are disrupted, and will actively seek to re-establish equilibrium. Such processing may be non-conscious and lead to ‘a coherent pattern of activated ideas in associative memory’, which exaggerates consistency, neglects ambiguity and ignores absent evidence (Kahneman, 2011, p. 105). This tendency to partial interpretation of evidence to protect existing beliefs, is known as ‘confirmation bias’ and occurs across a range of domains (Nickerson, 1998, p. 175), for example, Pasteur, Faraday and Millikan are reported to have rejected or ignored anomalous data that threatened the frameworks they had constructed. The idea that scientists may be as fallible to confirmation bias as other people is central to Kuhn’s (1962, p. 78) construct of inertia in paradigm shift; he suggested that, rather than face conflict, scientists might ‘devise numerous articulations and *ad hoc* modifications’ to their theories. Though models of science as a discipline do not necessarily apply to patterns of change in learners’ ideas (Kuhn, 1993), learners’ tendency to defend coherent constructions of ideas is a two-edged sword for educators. If students perceive accepted scientific constructs as coherent such constructs will be retained and defended against contradiction. However, learners’ alternative coherences that differ from scientific models may be difficult to alter due to their emic coherence (Driver et al., 1985; Vosniadou, 2008a).

2.4.4 Coherence in students’ conceptual compounds in science

It is reported that children prefer theories that are logically and empirically consistent (Samarapungavan, 1992), though their judgements of consistency may differ from those of experts. Novices may perceive less coherence between some types of contexts than experts, and may develop personally meaningful categories to deal with data they perceive as incoherent (Brown & Clement, 1992; Chi et al., 1981). Conceptual change has been described as ‘...a cognitive attempt to resume coherence of the knowledge system that has been disturbed by new pieces of information’ (Hatano & Inagaki, 2002, p. 174), though change may produce understandings that differ from scientific models.

When a student encounters information that contradicts their current beliefs, Chinn and Brewer (1993) suggest there are seven patterns of response, only two of which, peripheral and complete theory change, involve changes to existing knowledge. They

propose that, rather than altering prior conceptual structures, students may ignore or reject the anomalous data. The drive to maintain coherence can be so strong that it can influence perceptions: Chinn and Malhorta (2002) report that only a quarter of children who predicted that two rocks of different mass would take different times to fall reported seeing the rocks hit the ground at the same time after being released simultaneously from the same height. Alternatively, students may modify their conceptual structures to maintain coherence with novel information. Vosniadou and Brewer (1992) described how children made peripheral modifications to their theories to maintain a belief in a flat Earth. Lawson and Worsnop (1992) hypothesise that students developed the belief that God placed fossils onto the Earth to defend their central belief in creationism. Joshua and Dupin (1987, p. 129) report students working with electrical circuits, who encountered data that contradicted their expectations, chose to cite apparatus failure to avoid a threat to their constructed understanding.

2.5 The rate of conceptual change

The focus of this thesis, making sense, describes the process of forming and modifying conceptual relationships; hence, this section examines the concept of conceptual change. Conceptual change has received substantial research interest for at least the last thirty years (Larsson & Halldén, 2010; Treagust & Duit, 2009; Vosniadou & Ioannides, 1998). During this period, conceptual change has been imagined in a number of different frameworks (Treagust & Duit, 2008). However, one facet of conceptual change that is conspicuous by the relatively limited attention it has received is the rate of conceptual change; that is, the time scales over which conceptual change might be expected to occur. A number of researchers describe conceptual change as generally gradual (Nussbaum, 1989; Smith et al., 1993; Vosniadou, 2008b) though there are reports of rapid forms of conceptual change (Brock, 2015; Chi, 1997; Clement, 2008). The next sections examine the notion of conceptual change and, in particular, models that suggest varying rates of change.

2.5.1 The nature of conceptual change

Though the meaning of conceptual change has developed over the last thirty years (Amin et al., 2014; 2008), it remains a challenging concept to define. Conceptual change may be an ‘umbrella’ term covering a range of different but unrelated processes (Rusanen, 2014; Rusanen & Lappi, 2013) for example, revision,

reinterpretation or construction of a conceptual system (Rusanen & Lappi, 2013). It is unsurprising, then, that there remains some disagreement over how conceptual change might be usefully represented within science education research (Rusanen & Pöyhönen, 2013). Differing assumptions about the nature of conceptual constructs and other factors (see Table 2.2) has led to the development of a variety of models of change (Treagust & Duit, 2008).

Table 2.2: Implied assumptions in models of conceptual change.

Authors	Definition of conceptual change	Some implied assumptions
Posner et al., 1982, p. 211	‘...the substantive dimensions of the process by which people’s central, organising concepts change from one set of concepts to another set, incompatible with the first.’	Concepts have a central core; change occurs from one set of concepts to another; incompatibility exists between initial and final concepts.
Chi & Roscoe, 2002, p. 4	‘...conceptual change is merely the process of reassigning or “shifting” a miscategorized concept from one “ontological” category to another “ontological” category.’	Conceptual change involves ontological recategorisation.
diSessa, 2006, p. 265	‘... students must build new ideas in the context of old ones; hence, the emphasis on "change" rather than on simple acquisition.’	Context of old ideas is significant; ideas are ‘built’ not acquired.
Vosniadou, 2007, p. 49	‘Theory-like knowledge structures allow the possibility that developmental change is theory change and this is exactly what conceptual change is meant to be.’	Conceptual change involves theory change; concepts are theory-like.
Rusanen & Lappi, 2013, p. 3332	‘...conceptual change is seen as a specific kind of learning process, in which ... conceptions of phenomena in a certain domain undergo a restructuring process that affects ontological commitments, inferential relations, and standards of explanation...’	Conceptual change involves change to ontological commitments, inferential relations and standards of explanation.

In order to minimise the assumptions upon which the construction is predicated, in this thesis, the term conceptual change will be taken to mean: the process in which one concept is used at a given time and in a given context, but at a different time an alternative concept is applied in the same context. The separation of change in a given context from change across contexts will be discussed in section 2.6, below. It has been argued that the different models of conceptual change share many common elements (Dagher, 1994; Özdemir & Clark, 2007); however, a number of authors have suggested dimensions that might highlight differences between models (Caravita & Halldén, 1994; Koponen & Huttunen, 2013; Özdemir & Clark, 2007; Tyson, Venville, Harrison, & Treagust, 1997). One distinction distinguishes between evolutionary and revolutionary change (Nussbaum, 1989; Özdemir & Clark, 2007; West, 1982; Wiser & Amin, 2001). This division, however, is used ambiguously: Duit (1994, p. 56) links evolutionary change with continuity and revolutionary change with ‘discontinuity’, however, for other researchers, the revolutionary model is defined as the complete replacement of one concept by another (Caravita & Halldén, 1994) and the change may be ‘time consuming and lengthy’ (Özdemir & Clark, 2007, p. 357). In general, however, there is limited discussion of the rate of conceptual change in different constructs of conceptual change. The next section considers models that imply a rate of conceptual change.

2.5.2 Models of conceptual change that suggest a rate of change

This section examines five models that make claims about the rate of conceptual change. One of the earliest models of conceptual change in science education is that of Posner and colleagues (Posner et al., 1982). Their construction of learning is based on a conceptual ecology, consisting of: anomalies, analogies and metaphors, epistemological commitments, metaphysical beliefs and concepts (Posner et al., 1982). Conceptual change is modelled not as the replacing of old theories with more adequate ones; but, rather, as ‘establishing a reflective equilibrium between new ideas, facts, and discoveries and his current set of concepts’ (Strike & Posner, 1982, p. 233). Given this complex conceptual ecology, conceptual change is seen as a ‘gradual and piecemeal affair’, which ‘involves much fumbling about, many false starts and mistakes, and frequent reversals of direction’ (Posner et al., 1982, p. 223) and it is argued that flashes of insight and sudden change are considered to be rare occurrences.

In Vosniadou's 'framework' model, concepts are seen as fragmented entities: 'we do not expect students to hold unitary, isolated, and context-independent misconceptions' (Vosniadou, 2013, p. 22), but the elements are seen as constrained within broad epistemological and ontological assumptions (Vosniadou & Brewer, 1992). It is argued that conceptual change involves the alteration of these frameworks in which concepts are embedded (Vosniadou, 2007b). It is unsurprising that the framework model of the concept leads to a gradual model of conceptual change for three reasons: a) it takes a long time to reorganise multiple concepts into a framework (Vosniadou, 2002); b) the frameworks are coherent and the result of years of everyday experience (Vosniadou, 1994); and c) the ontological, representational and epistemological changes that are expected to take place within the framework theory are necessarily slow and gradual (Vosniadou & Skopeliti, 2014).

diSessa's model of the concept has some similarities with the notion of an array of different elements proposed by Posner and colleagues (Posner et al., 1982). diSessa proposes 'a variety of types of mental entities', which are seen as existing at a smaller 'grain-size' than concepts (diSessa, 2002, p. 33). Concepts are not seen as 'unitary mental structure[s]', but are described as 'fuzzy', since they involve the interaction of many smaller elements (diSessa & Sherin, 1998, p. 1170). Given this understanding of the concept, conceptual change is seen as a reorganisation of conceptual ecology involving a continuity of resources that are refined and recombined into knowledge systems in a gradual progress towards expertise (diSessa, 1993; diSessa, 2002; Smith et al., 1994). However, diSessa's model allows for rapid switching between 'correct and flawed approaches' in a single problem solving episode, as conceptual structure is seen as being composed of both expert and novice elements (Smith et al., 1994, p. 125).

The three models of conceptual change examined so far suggest a generally gradual transition between concepts; however, one construction offers an explanation of rapid conceptual change. Chi's model of the concept proposes that concepts may acquire a 'label' to indicate membership of a category (Chi, 1997, p. 210). Though they may be implicit, such labels are conjectured to affect the manner in which the concept is used

(Chi, 1997). The proposed categories are seen as ontologically distinct, denoting that ‘the attributes of one category cannot be applied to members of another category’ (Chi & Slotta, 1993, p. 252). Such mutually exclusive categorisation allows for the possibility of rapid conceptual change through an ‘ontological shift’ of the attributes of a concept that is seen as underlying the ‘the “aha” phenomenon’ (Chi, 1997, p. 230). As ontological categories are seen as binary, it is impossible ‘...to gradually change a conceptualization from one ontological category to another’ (Slotta, 2011, p. 156). However, Slotta and Chi (2006) allow that experts can maintain intuitive categorisations alongside expert ontologies, therefore, in addition to discontinuous changes, Chi and Roscoe (2002) argue changes to mental models can happen in an incremental fashion through the accumulation of additions and alterations to conceptual structure.

Lastly, the complex dynamic system approach (Brown & Hammer, 2008, p. 124) assumes a conceptual ecology consisting of elements that are involved in constant ‘non-linear’ interactions (see also Koponen and Huttunen’s (2013) model). It is argued this assumption means learning might be expected to exhibit ‘a period of slow growth at the outset with more rapid progress later, as ideas connect to and build on the initial conceptual understandings’ (Brown & Hammer, 2008, p. 132). A trend in systemic models of conceptual change is for researchers to borrow terms such as ‘non-linear’ and ‘conceptual attractor’ (Brown & Hammer, 2013, p. 127; Luffiego, Bastida, Ramos, & Soto, 1994, p. 306; Sharp & Kuerbis, 2006, p. 141) and also methods of analysis (Koponen, 2014) from the study of dynamic systems. However, some commentators have argued that the application of dynamic systems models to cognition is problematic (Eliasmith, 1996; Keijzer & Bem, 1996). Though there may be some similarities between conceptual systems and the models produced by the dynamic systems approach (Smith & Thelen, 2003), the number of simplifying assumptions that need to be applied casts doubt on the usefulness of the analogy (Eliasmith, 1996). The mathematical terminology of chaotic systems may not be appropriately applied to the difficult-to-quantify psychological realm (Barton, 1994); and, though dynamic systems models might, to some extent, fit data, they provide few explanations or insights into cognitive processes (Keijzer & Bem, 1996).

2.5.3 Models of conceptual change that suggest multiple rates of change

Whilst the models above tend to link a construct of the concept with a single rate of conceptual change, a number of models exist which allow for multiple rates of change (see Table 2.3).

Table 2.3: Models of conceptual change that include multiple rates of conceptual change.

Author/s	‘Slow’ model	‘Fast’ model
Gilbert & Watts, 1983	Smooth Change	Catastrophic
Thornton, 1997	Extended conceptual transition	Punctuated conceptual evolution
Blown & Bryce, 2006	Weak/ Moderate restructuring	Radical/ Dynamic interactive restructuring
Clement, 2008	Accretionism	Eurekaism

Gilbert and Watts proposed three types of conceptual change which link a model of the concept with a rate of conceptual change. In the stepped change model, concepts are envisaged as ‘Euclidean point “misconceptions”’ (Gilbert & Watts, 1983, p. 88), which allow change to be ‘instantaneous’. In the smooth change model, an actional model of the conception leads to a construction of students in a constant process of revision of conceptions, and those ‘... that show the greatest potential are retained by frequent use’ (Gilbert & Watts, 1983, p. 89). Finally, the authors argue that the catastrophic model has the most potential as it based on a ‘continuous, or constructivist notion of conception’ (Gilbert & Watts, 1983, p. 91) and allows for both gradual change and the rapid change seen in “Ah, ha” experiences.

Blown and Bryce (2006) suggest four types of conceptual change, which differ by the time span over which they occur: a) weak restructuring: ‘a gradual realisation over several years’ (Blown & Bryce, 2006, p. 1449); b) moderate restructuring: the ‘gradual creation of alternative frameworks’ (Blown & Bryce, 2006, p. 1449); c) radical or strong restructuring: ‘changes over relatively short time spans’, that is,

‘from a few months to 1 or 2 years’ (Blown & Bryce, 2006, p. 1449); and d) dynamic-interactive restructuring: ‘very rapid changes’ that occur during an interview or over the course of a few minutes (Blown & Bryce, 2006, p. 1450).

Thornton (1997) draws an analogy between conceptual change and biological evolution, contrasting extended conceptual transition with punctuated conceptual evolution. Thornton implies a student may transition instantaneously to complete alignment with an expert position, though he admits that there is ‘... little evidence for this model’ (Thornton, 1997, p. 248). Finally, Clement (2008, p. 442) proposes that conceptual change may be gradual for extended periods, but also that episodes of stagnation and insight (sudden increases in understanding) might occur. Clement (1989, p. 365) explicitly describes a moment of a rapid conceptual change in a student engaged in solving a problem and argues that such insights can lead to ‘fairly sudden reorganizations in the structure of a mental model’ (Clement, 1989, p. 341). The next section examines the empirical evidence for claims concerning the rate of conceptual change.

2.5.4 Evidence for varying rates of conceptual change

The evidence from a number of researchers presents conceptual change as a largely gradual process. Nussbaum (1989, p. 538), for example, argues evidence indicates learning occurs gradually: ‘... the student maintains substantial elements of the old conception while gradually incorporating individual elements from the new one’. Vosniadou and Ioannides (1998, p. 1226) report the idea of a sudden shift in conceptual structure implied by early models of conceptual change ‘has not...been supported by empirical evidence’. Moreover, Vosniadou argues that what are claimed to be radical conceptual changes are really the end product of a ‘slow and gradual affair and not a dramatic gestalt type shift’ (Vosniadou, 2008b, p. xvi). In examining four theories of conceptual change, including those of Vosniadou, Chi and Roscoe and diSessa, Mayer (2002b) concludes that in all of these models conceptual change is constructed as a gradual process. Several researchers report that rapid changes in understanding are rare occurrences (Fisher & Moody, 2002; Vosniadou, 2008b; Vosniadou & Ioannides, 1998). However, it is possible to find reports of moments of rapid conceptual change in the literature (Brock, 2015), though such moments may be experienced as sudden, they might be the outcome of a gradual tacit process. Given

the existence of models of conceptual change at varying rates, the next section considers the concept of the rate of conceptual change.

2.5.5 Rate of change as a neglected component of conceptual change

Typically, studies of conceptual change have used cross-sectional or longitudinal designs with relatively long intervals, often several weeks or months, between probes, and a relatively low number of probes (Brock & Taber, 2017b). Few fine-grained studies of the rate of conceptual change have been carried out, perhaps because carrying out research that samples data related to conceptual change at a sufficiently high frequency to adequately represent change processes, as in the microgenetic method (Siegler & Crowley, 1991), is demanding for the researcher and participants.

The nearest notion to the concept of rate of conceptual change that exists in the literature is Georgiades' (2000, p. 126) notion of durability; that is: 'How long does a conception remain in effect, within the learner's cognitive repertoire?' This definition is somewhat vague, as the meaning of 'in effect' is not further defined. A central challenge to understanding the rate of conceptual change is that several models of cognition model learners as sometimes possessing multiple understandings of the same concept (Harrison & Treagust, 2000b; Mortimer, 1995; Taber, 2001a). In such models, the use of one concept in a given context, followed by the use of a different understanding in the context, may not be evidence of conceptual change, but, rather, the stable application of two elements of conceptual ecology (see the lower part of Figure 2.5). The methodological implications of this observation are discussed in detail in Section 4.3.3. Given the potential presence of multiple, contextually-triggered concepts, the rate of conceptual change is defined as: the rate at which the oftenness of application of a particular concept, in a particular context, varies over time.

The term 'oftenness' is used in preference to 'frequency' as the construct is not intended to be a quantitative measure, but, rather, a broad description of the pattern of change. Oftenness is taken to refer to participants' or researchers' subjective interpretation of how commonly a particular concept is triggered in a given context. The construct can be used to distinguish between the three patterns of change shown in Figure 2.5.

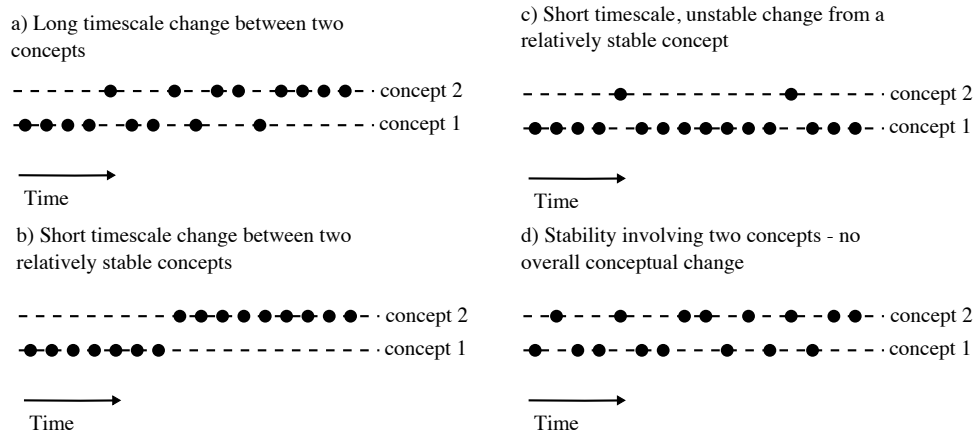


Figure 2.5: Examples of different patterns of conceptual change in a two-concept conceptual ecology. Time advances to the right along the x-axis. The black circles represent the application of a particular concept in a single context at a particular point in time.

It may be that conceptual change is generally like the representation shown in section a) of Figure 2.5; a gradual change in the likelihood of application of a particular concept. However, there are reports of sudden changes in understanding, or moments of insight (Brock, 2015), which may be evidence of stable (graph b in Figure 2.5) or unstable (graph c in Figure 2.5) change. It is important that researchers attempt to distinguish between change to concepts to which a learner holds limited commitment from more substantial and stable change (Taber, 1995). However, it is challenging to define a duration of observation that supports claims to stability (Brock & Taber, 2017b). The construct of rate of conceptual change also allows the apparently variable application of two concepts (graph d in Figure 2.5) to be considered as an example of stability rather than change. Though a learner may apply two concepts in a single context, if the oftenness of application of both concepts does not vary, no conceptual change is occurring.

If the rate of conceptual change is studied over an extended period of time, representations of change will be inherently bound up with the order and nature of the probes presented, much as the data in a case study are situated in a given context (Flyvbjerg, 2006). Comparisons between representations of the rate of conceptual change for different learners, even those produced from a series of identical probes, are challenging, and a researcher may need to make reasoned judgments about the

extent to which claims are comparable, as outlined in the concept of analytical generalisability (Kvale, 1996; Taber, 2000a).

2.6 Conceptual change and conceptual span

Though cognition may be parallel (Rumelhart & McClelland, 1986), consciousness imposes a sense of seriality to a ‘train of thought’ (Baars & Franklin, 2003, p. 167), and research tools tend to report data as sequence (see Figure 2.6).

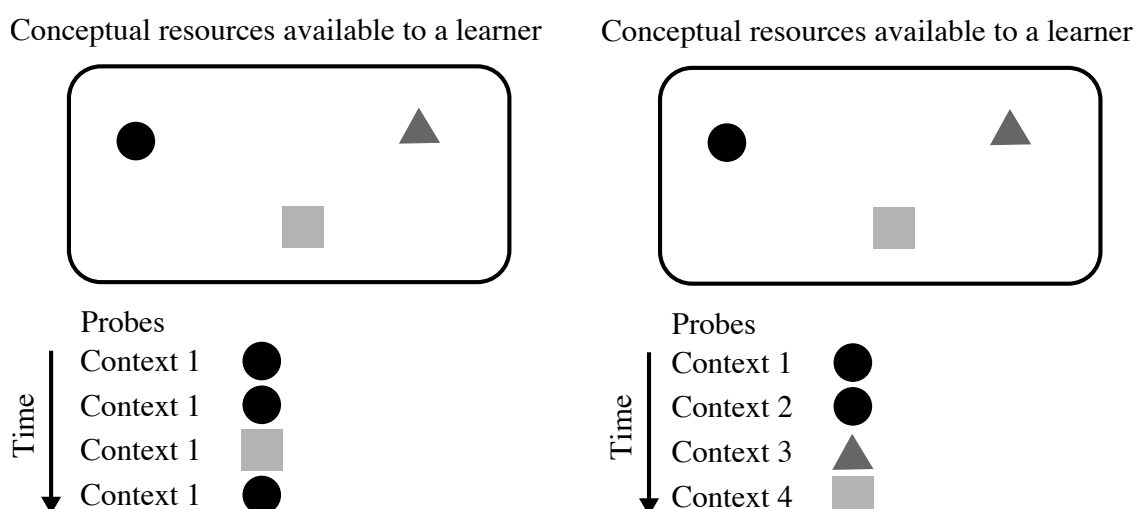


Figure 2.6: A representation of the effect of different choices of probes on the construction of a data sequence. On the left-hand side the same context is used repeatedly as a probe; on the right, multiple different contexts are presented.

Only a subset of a learner’s conceptual resources can be the focus of investigation at a given time (Taber, 2013), and the nature and order of probes presented to a learner will affect which conceptual resources are activated. A researcher may wish to examine the conceptual resources a student applies when exposed to the same context several times in order to understand patterns of conceptual change (see left-hand side of Figure 2.6). Whilst this approach may offer a valid representation of change in a particular context, it develops a limited representation of the resources available to the learner. Alternatively, the researcher may present probes, which trigger the same set of concepts, but are situated in a range of contexts, allowing an understanding of the contextual triggering of resources and, perhaps, accessing a broader range of conceptual resources. However, in this approach, it is impossible to distinguish between effects due to context and variation due to change over time (for a discussion of the nature of different sequences of probes, see Section 4.3.7). Therefore, two

dimensions might be seen as significant for reporting the nature of students' cognition: an assessment of variation in a given context over time, conceptual change; and a representation of the manner in which a concept is applied across different contexts, conceptual span.

2.6.1 Conceptual change

Though early descriptions of conceptual change modelled the process as the substitution of one concept for another (for example, Chi and Roscoe (2002)), it has been noted that experts and novices may not differ greatly in the conceptual resources they possess. Rather, there may be differences in the contexts in which concepts are activated (Brock & Taber, 2017a; Sabella & Redish, 2007) and contemporary models of change focus on changes to the conditions of activation of multiple conceptual resources across different contexts (diSessa & Sherin, 1998; diSessa & Wagner, 2005).

Two writers have argued conceptual change should be replaced with constructions that have a greater focus on contextual variation: Linder (1993) has suggested conceptual appreciation, an understanding of how the use of a concept is constrained by contexts, is preferable to conceptual change; and Mortimer (1995) proposed the conceptual profile construct, the set of different understandings of a concept a learner possesses. For example, a conceptual profile may consist of a learner's conceptualisations of heat as a substance in some contexts and as an abstract entity in others. In Mortimer's (1995) model, conceptual change is understood as changes to the likelihood of a particular understanding being triggered in a given context. However, such descriptions of conceptual change are methodologically problematic, as it is unclear whether reports of the use of multiple conceptual resources across a number of contexts should be taken as evidence of the activation of a single, static conceptual profile, or whether they may be used to make inferences about change. Therefore, the separation of conceptual change from conceptual span is felt to be a useful distinction. Conceptual change, as defined above, will be taken to mean the process in which one concept is used at a given time and in a given context, but at a different time an alternative concept is applied in the same context.

2.6.2 Conceptual span

Several studies report that students activate different conceptual resources in different contexts (Clough & Driver, 1986; Mishler, 1979; Palmer, 1993; Taber, 2008b; White, 1985). Transfer of learning is thought of as the ability to apply what has been learned in one context to another context (Haskell, 2001; Singley & Anderson, 1989), and has been reported as difficult to achieve (Gick & Holyoak, 1980, 1983; Haskell, 2001; Perkins, 2009; Singley & Anderson, 1989). However, as shown in Figure 1.1, the ability to transfer learning to appropriate contexts is a commonly cited component of understanding (Burns et al., 1991; Newton, 2001; Trout, 2002).

Various mechanisms of transfer have been suggested: the development of abstract schema (Gick & Holyoak, 1983), the construction of coordination classes (diSessa & Wagner, 2005), and engagement with the cultural practices in a domain (Brown, Collins, & Duguid, 1989). However, such models of transfer have been criticised for imposing an external expectation of the form of transfer: Lobato (2003, 2012) has argued researchers should be sensitive to learners' conceptualisations of the similarities and differences between contexts. Experienced scientists and novice learners may have differing categorisations of contexts (Chi et al., 1981). A task that involves two markedly different contexts for a novice may seem like two variations on a single context to an expert, and vice-versa.

Given the significance of the term context to the argument, it is worth considering its connotations. Both White (1985) and Finkelstein (2005) describe a context as consisting of three broad factors: physical conditions, the people involved and social or cultural conditions. However, as White (1985) hinted and Lobato (2003) described in detail, the interpretation of factors that delineate a context will be subjective. Here, the term refers to the stimulus presented to the student; changes in the other factors such as physical or cultural conditions are not considered. Only probes in which the same stimulus is repeated, for example the same question from the force concept inventory (Hestenes et al., 1992), are seen as identical contexts. Probes which might be seen by experts as possessing the same 'deep structure,' but which novices may perceive as having surface differences (Chi et al., 1981), for example, the oscillations of a pendulum and a mass on a spring, are described as different contexts in this

study. A discussion of the degree of similarity between probes can be found in Section 4.3.7.

The term ‘conceptual span’ has been used to refer to the range of contexts that are covered by a learner’s conceptual resources (diSessa & Wagner, 2005, p. 128). The related concept of ‘contextual coherence’ (Nieminen, Savinainen, & Viiri, 2012, pp. 722–723) refers to the ability of a student to apply a concept in a range of familiar and novel contexts. The span conceptualisation is preferred here as an ‘ability’ would appear to be a more difficult concept to report empirically than the range of contexts in which a concept is activated. In this study, the concept of conceptual span will be developed to create a clear separation between the application of a concept across contexts and change in a concept over time in a particular context. Conceptual span will therefore be taken to refer to the range of contexts to which a learner applies a concept over an interval during which it is assumed that no significant changes occur to conceptual structure. The notion of a static interval is introduced in greater detail in section 4.3.4.

2.6.3 Studies of conceptual change in a fixed context

A common means of assessment in science education is to present a set of probes across a range of contexts at multiple moments in time, as occurs in studies that construct change from the repeated application of concept inventories (e.g. Hake, 1998). However, there are relatively few studies that explore conceptual change by presenting a probe in a single context to a student multiple times. Those studies tend to apply the microgenetic approach, which samples data at a frequency which is assumed to be high compared to the rate of change of the phenomenon of interest (Siegler & Crowley, 1991), and present participants with an identical measure over a number of sessions. Though some of these studies have examined strategy use (Kuhn & Phelps, 1982; Kuhn, Schauble, & Garcia-Mila, 1992), others have focused on changes in knowledge (Johnson & Mervis, 1994), reasoning (Schauble, 1996) and knowledge structures (Izsak, 2000). It is interesting to note that even when identical probes were presented to students, Kuhn and Phelps (1982, p. 40) noted significant variability in participants’ responses and they argued this variability should be treated as ‘an important subject of substantive investigation, rather than a methodological source of error’.

2.6.4 Studies of conceptual span

Studies of conceptual span focus on changes in application of concepts to different contexts over a single static interval, a period of time over which no significant changes to conceptual structure occur. For example, Taber (2008b) investigated students' conceptual integration related to forces and energy across several contexts, for example, an apple hanging from a tree, the solar system and a parachute jump, in a single interview. In that case, the interview may be imagined to be a single static interval, that is, a representation of conceptual structure at a single point in time. Several studies (Clough & Driver, 1986; Ioannides & Vosniadou, 2002; Palmer, 1993) of contextual variability assume a single data collection event, which has some extension over time (perhaps 30-60 minutes), can produce a static representation of conceptual resources. Such studies are useful for providing information on the features of different contexts that trigger differing interpretations.

2.6.4.1 Conceptual span in novices and experts

Conceptual change and conceptual span represent different facets of a learner's developing understanding. One approach to examining both dimensions of change is to carry out cross-sectional research into the application of concepts across contexts, for example, Ioannides and Vosniadou (2002) claimed to have detected a degree of consistency in novice students' application of concepts across contexts. However, two quasi-replication studies reported much lower levels of consistency (diSessa et al., 2004; Özdemir & Clark, 2009). These differing interpretations of the applications arise from different models of conceptual change (Özdemir & Clark, 2007): the knowledge-in-pieces model (diSessa, 1988, 1993), and the framework model (Ioannides & Vosniadou, 2002; Vosniadou, 1994). The framework model suggests that the responses of learners who have not been exposed to formal education will be 'relatively consistent' (Vosniadou, 2008a, p. 14); but, when students encounter formal scientific teaching, there may be a period of inconsistency as they develop new models (Vosniadou, 2008a). In diSessa's (2002, p. 53) model, though novice thought is not seen as completely lacking in consistency of application across contexts, it is seen as consisting of 'relatively independent' p-prims which are 'contextually bound'. As expertise develops, the elements of conceptual structure become organised into structures, known as coordination classes, that allow a consistent approach across contexts (see Figure 2.7).

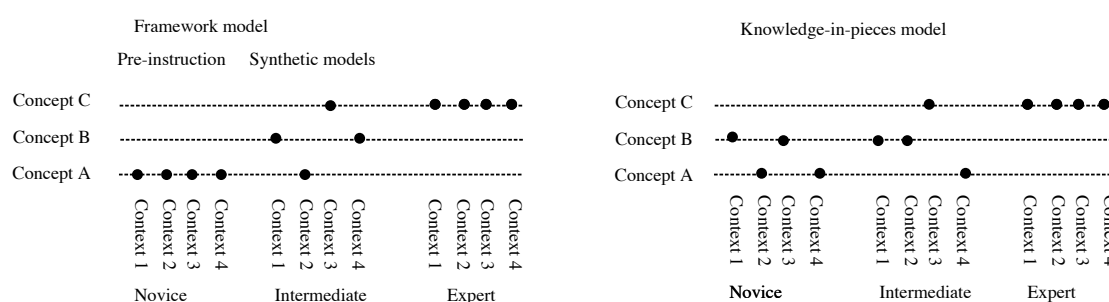


Figure 2.7: Representations of contextual span at different stages of development in the framework and knowledge-in-pieces models. The black circles represent the use of a particular concept in a given context.

The representation of expert conceptual consistency in Figure 2.7 includes an assumption that is acknowledged by several researchers: expert learners have a large conceptual span (Ainsworth, 2008; diSessa, 2002; diSessa & Wagner, 2005; Kuhn & Phelps, 1982; Parnafes, 2012). Evidence from students' answers to the force concept inventory suggests there is a correlation between consistent application of learning across different representations of questions and overall score (Nieminen et al., 2012). Experts' superior performance on novel transfer tasks is an assumption that underlies certain forms of higher order questions on assessments (Zoller, 2010). However, expert conceptual span is challenging to define, as even expert physicists, under certain circumstances, revert to alternative understandings (Goldberg & Thompson-Schill, 2009; Kelemen, Rottman, & Seston, 2013), and it is difficult to describe precisely the span of contexts that represents expert behaviour (Clark, 2006; diSessa & Wagner, 2005). In this study, the students encountered both novel and repeated contexts over the course of the sessions, in order to probe both conceptual change and conceptual span.

2.6.5 Studies that separate conceptual span and conceptual change

There are relatively few studies that present evidence of conceptual span and conceptual change as two separate dimensions. Two such studies are Tao and Gunstone's (1999) investigation of computer-based learning, and Clark's (2006) longitudinal study of learning in thermodynamics. In Clark's (2006) study, students were interviewed seven times over a period of approximately 13 weeks to probe their

understanding of thermodynamics. The probes were a sequence of laboratory activities and simulations without repeated contexts and therefore might be thought of as investigating conceptual span. A pre- and post- test of understanding was carried out which might be imagined to be a measure of conceptual change. Clark (2006) describes the case of one student who became increasingly able to connect conceptual elements together to form an explanation. A representational tool called an 'element map' (Clark, 2006, p. 468) was developed to display the activation of different conceptual elements within an interview. Though the separation of conceptual span and change is not explicitly discussed, and the argument might have been strengthened by a discussion of the nature of claims regarding change that were proposed, the study does present evidence of changes to conceptual span, and data related to conceptual change.

A different approach is to investigate change across a small number of contexts, each of which is repeatedly encountered a number of times. Tao and Gunstone (1999) focused on three contexts, a model car, a spaceship and a skydiver, and used computer simulations, interviews and written tests to examine students' understanding of forces in these situations. In this research, the time engaged with each context is, implicitly, assumed to be a static interval, and changes between static intervals in the same context are considered. Their data led Tao and Gunstone (1999) to conclude that conceptual change initially occurs in a particular context before the occurrence of context-independent change. The clear separation of conceptual change, variation in application of a concept in a single context, from the application of concepts across contexts, conceptual span, in this study presents a broad and valid representation of change. It is proposed that this two-dimensional construct of changes to conceptual ecology will clarify descriptions of change.

2.6.6 The two dimensions of change

The investigation of change related to conceptual resources is challenging, as it requires both investigation across multiple contexts, in order to probe the extent of structure and to understand contextual triggers and transfer, and also a comparison between identical contexts to support claims of conceptual change. Therefore, a method which investigates understanding across multiple contexts, but also includes some repetition of probes (as in Tao and Gunstone's (1999) study), might be an

effective approach for considering the development of conceptual resources (Caravita & Halldén, 1994). The use of the concept of the static interval (See section 4.3.4) allows researchers to clearly separate two dimensions of change. For example, as illustrated in Figure 2.8, a learner might be exposed to four different contexts to provide evidence of conceptual span. Then, in order to assess conceptual change, the learner's understanding could be reassessed in the previously encountered contexts, in this case context 1 and 2. Application of learning to novel contexts, 5 and 6, adds information on the student's ability to transfer learning. By investigating both conceptual span and conceptual change a fuller representation of changes to conceptual resources may be developed.

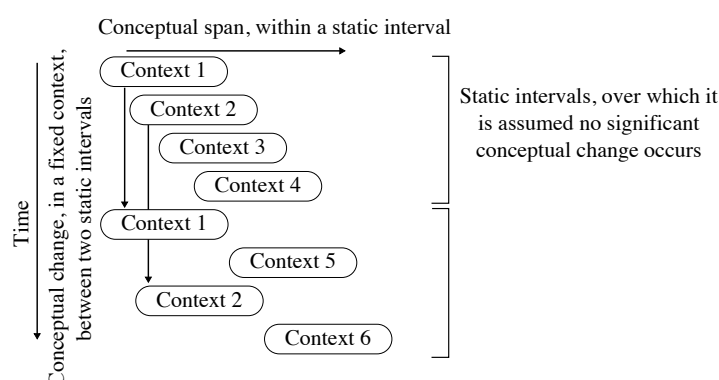


Figure 2.8: Conceptual change and conceptual span as two dimensions of variation in the application of conceptual resources.

2.7 Research questions

As shown in Figure 2.0, the construction of the concept of making sense leads to the research question below, which can be broken down into six sub-questions.

How do 16-17 year-old students form and modify conceptual compounds to develop coherent causal systems that may be transferred to novel contexts in physics?

- How do ontological categories vary over time?
- How do compounds of concepts form and disperse over time?
- How do causal relationships develop over time?
- What factors cause collections of concepts to cohere together?
- How can the rate of conceptual change be constructed in students' responses?
- How can conceptual change be distinguished from the activation of concepts across contexts?

3.0 Methodology

Research can be conceptualised as ‘systematic self-critical inquiry’ (Stenhouse, 1981, p. 103), and a large number of approaches to research have been proposed (Nisbet, 2005) but there remains no consensus on the most effective manner in which to investigate the social world (Baranov, 2004). Different approaches to inquiry arise as researchers necessarily adopt implicit or explicit premises (T. S. Kuhn, 1962), hence no research can be considered to be free of assumptions (Golby, Martin, & Porter, 1995). Such axioms can be classified as: ontological, relating to the nature of entities which exist (Effingham, 2013; Sommers, 1963); epistemological, assumptions regarding the nature of knowledge and its justification (Dancy, 1985; Moser, 2002); and axiological assumptions concerning values and ethics (Mertens, 2014; Weinberg, 1970). No particular combination of assumptions, sometimes labelled a paradigm (Lincoln & Guba, 2005), should be seen as superior to another; rather, different suppositions are suitable for answering different types of research question (Gawronski & De Houwer, 2014). A researcher has a duty to explicate and justify the assumptions made in their work (Caelli, Ray, & Mill, 2003; Creswell & Miller, 2000; Guba, 1981; Krauss, 2005), via methodological justification, the examination of the premises of a particular approach to research (Schwandt, 2007). In particular a methodology should aim to develop a ‘coherent and consistent argument’ (Taber, 2007, p. 44) and ensure a good ‘match’ between the assumptions of the work and the phenomenon of interest (Krauss, 2005, p. 761).

Holloway and Todres (2003, p. 347) argue for consistency between the argument in different sections of a research paper, a concept which they describe variously as ‘goodness of fit,’ ‘logical staged linking’ or ‘how the whole thing “hangs together.”’ Failure to achieve this can lead to ‘method slurring’ (Baker, Wuest, & Stern, 1992, p. 1355), in which approaches with different philosophical assumptions are erroneously combined. The aims of research, its theoretical assumptions and the methods used must be justified as leading to a coherent argument as illustrated in Figure 3.0.

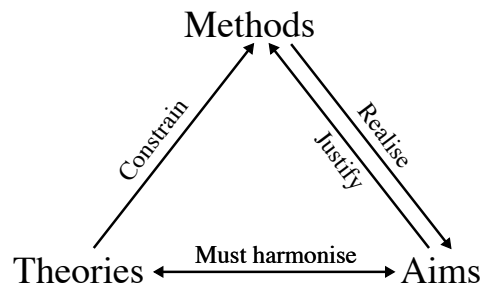


Figure 3.0: Relationship of methodology and methods seen in the triadic network of justification in Laudan (1986, p. 63).

The next sections will make the case that the assumptions of constructivism fit well with the aims and methods of this research.

3.1 Assumptions adopted in this work

The assumptions made in this thesis are outlined below in three categories: ontological, epistemological and axiological (Coe, 2012).

3.1.1 Ontological assumptions

Ontology is the study of what kinds of entities exist (Effingham, 2013). A range of different ontological assumptions is compatible with constructivism. Some writers have argued constructivism is agnostic over the existence of external reality (Staver, 1998). A similar observation was made by Quale:

Thus, the theory [radical constructivism] does not deny the possibility of an objective reality, existing independently of all subjects; but it does assert that it is in principle not possible to obtain cognitive knowledge of such an entity, and hence it is irrelevant in the context of cognitive learning. (Quale, 2007, p. 233)

Among several slightly different claims regarding ontology, von Glasersfeld argues that constructivism ‘... has nothing to say about what may or may not exist’ (von Glasersfeld, 1996, p. 113). It has been claimed that the proposition that knowledge is constructed by individuals or groups does not make any assumptions about the nature of reality (Noddings, 1990).

Other versions of constructivism for example, Kumar's realist constructivism (2011) and Cupchik's (2001) constructivist realism, adopt an unambiguous assumption that an external reality exists (Blackburn, 2005). Models such as these can be seen to be the source of Matthews' (1992) argument that constructivism, or some forms of it, are versions of empiricism, and that '...talk of 'making sense' is quintessentially empiricist' (Matthews, 1992, p. 305). Empiricism, here, is taken to mean the development of knowledge through the acquisition of sense data about 'material objects' that are assumed to exist (Matthews, 1992, p. 302). Matthews (1992) suggests the difference in positions between at least some versions of realism, empiricism and constructivism, may be relatively small.

Alternatively, it has been observed that certain forms of constructivism, for example, von Glasersfeld's radical constructivism, incoherently adopt both a realist and solipsistic stance (Martínez-Delgado, 2002). However, it seems that solipsists, thinkers who believe only one's own experience exists (Blackburn, 2005), are rare (Russman, 1987); in a survey of philosophers, only 4.8% of respondents expressed a position sceptical of an external world (Bourget & Chalmers, 2013, p. 476). As Martínez-Delgado (2002) observes, even the radical constructivism of von Glasersfeld is not purely solipsistic: von Glasersfeld (1996, p. 118) implies that 'ontic reality' impinges on actions to some extent. It seems that, amongst constructivists in science education, there is a general consensus that assumes an external reality impinges to some extent on awareness. Though at least one model of constructivism 'explicitly rejects... notions of absolute existence' (Quale, 2008, p. xv), the relativist ontological position is 'not representative of most work' in science education (Taber, 2009, p. 166). The existence of an 'external reality' will be assumed in this work; however, the extent to which it is possible to gain knowledge of such a reality is debated, as will be considered in the next section.

3.1.2 Epistemological assumptions

A central epistemological claim of constructivism is that access to reality is imperfect (Taber, 2009). Just as with the straw man of solipsism, critics of constructivism have exaggerated constructivists' arguments concerning the fallibility of the link to the external world. For example, Kitcher (2001, p. 156) argues that constructivists make

use of an ‘inaccessibility of reality argument’; that is, they regard all objects as ‘epistemically inaccessible’. However, arguing that there is no access to external reality is by no means the same as a claim that access to an external reality is mediated or imperfect. Some philosophers and psychologists (Putnam, 1990; Reid, 1997; Searle, 2015) have proposed versions of direct realism, the claim that there are ‘no entities mediating perception of objects’ (Copenhaver, 2004, p. 62). Yet, even realists such as Kitcher (2001, p. 167) argue that ‘[r]ealists should also acknowledge that our judgments of success are fallible’, as they occur through our limited ‘perceptual powers’ (Kitcher, 2001, p. 191). Evidence from studies of perception suggest that ‘direct’ (unmediated) and ‘indirect’ perception form a continuum with no clear division between the two processes (J. Norman, 1983, p. 731; Ulman, 1980, p. 377). For example, ‘seeing’ is not simply a matter of perception, but also of mental representation (Fodor & Pylyshyn, 1981, p. 190). Models of direct perception struggle to explain how knowers can come to develop faulty representations (Fodor & Pylyshyn, 1981). The next sections consider a particular example of faulty representations, Gettier’s (1963) cases, to develop a critique of the justified true belief model of knowledge that might seem to arise from direct realism.

The term ‘knowledge’ is widely used in educational discourse (Taber, 2013), for example, researchers refer to students’ knowledge structures (Driver & Oldham, 1986; Novak, 1990; Osborne & Wittrock, 1983) or students’ and teachers’ knowledge of various concepts (Chinn & Brewer, 1993; Hogan, 2000; Justi & Gilbert, 2002; Van Driel & Verloop, 2002; Zohar & Nemet, 2002). However, the concept of knowing, and the related construct of knowledge, are problematic, as they have been used with a range of different meanings (Aaron, 1971). For example, Price (1969, pp. 42–43) draws a distinction between possessing or having knowledge, ‘a disposition’ and the ‘mental occurrence’ of activating that knowledge at a particular time. Despite these different meanings, a model of knowledge as justified, true belief, was taken for granted by the majority of philosophers until the middle of the twentieth century (BonJour, 2001).

3.1.2.1 The Platonic model of knowledge

It has been claimed that the Platonic definition of knowledge is ‘standard’ and ‘widely accepted’ (Boghossian, 2006, p. 15). Matthews (2002, p. 127) argues that the view of

knowledge as justified true belief has been ‘epistemological orthodoxy’ since Plato proposed the definition. In the *Theaetetus*, Plato’s Socrates is reported as arguing that knowledge is distinct from belief because knowers have an ‘account’ of their true beliefs that believers do not possess (Plato, trans. 2004, p. 115). Plato proposed that justification tethers beliefs:

For true opinions, as long as they remain, are a fine thing and all they do is good, but they are not willing to remain long and they escape from a man’s mind, so that they are not worth much until one ties them down by (giving) an account of the reason why....After they are tied down, in the first place they become knowledge, and then they remain in place. (Plato, trans. 1981, p. 86)

Though it had become widely accepted, the justified true belief model of knowledge has encountered a number of challenges, and it has been reported that ‘[m]ost philosophers’ (Turri, 2010, p. 247) no longer accept the Platonic account of knowing.

3.1.2.2 Russell’s challenge to the Platonic model

Though Gettier’s (1963) thought experiments are seen as the most significant challenge to the justified true belief model of knowledge (Dew & Foreman, 2014), and are discussed in detail below, a number of commentators have noted that a case described by Russell prefigured Gettier’s critique (Bigelow, 2006; Heathcote, 2012). Russell (1948, p. 170) argued that there is an ‘inevitable vagueness and inexactitude’ associated with the concept of knowledge, and he proposed a thought experiment concerning a clock:

“Knowledge” is sometimes defined as “true belief”, but this definition is too wide. If you look at a clock which you believe to be going, but which in fact has stopped, and you happen to look at it at a moment when it is right, you will acquire a true belief as to the time of day, but you cannot be correctly said to have knowledge. (Russell, 1948, p. 113)

Russell's example includes both the features of Gettier problems introduced below: luckiness and fallibility of justification (Hetherington, 2011). However, the thought experiment was 'little noticed at the time' (Bigelow, 2006, p. 204), and it was not until the second half of the twentieth century that epistemologists began to seriously question the justified true belief model of knowledge.

3.1.2.3 Gettier's critique

In 1963, Edmund Gettier published a three-page paper which has had an '[e]normous impact' (Foley, 2002, p. 178) on epistemology, and demonstrated that the traditional model of knowledge was '...at the very least seriously incomplete and quite possibly even more badly mistaken' (BonJour, 2001, p. 40). The impact of the Gettier's paper was far-reaching, and there is, as yet, no consensus amongst philosophers as to how to resolve the objections it raised (Hetherington, 2011).

Gettier (1963) proposed a thought experiment that considered two people, Smith and Jones, who have applied for a job at a company. The president of the company has told Smith that Jones will get the post, and Smith is also aware that Jones has ten coins in his pocket. Smith therefore holds the justified belief that the person who will get the job has ten coins in their pocket. However, it turns out that Smith gets the job and, though he was unaware of it, he also had ten coins in his pocket. Gettier argued that Smith's belief that a person with ten coins in their pocket would get the job is both true and justified, and therefore might be considered knowledge. However, there is a 'virtual consensus' amongst philosophers that Smith's belief is not knowledge (Turri, 2013, pp. 1–2). Many different Gettier cases have been proposed, but two features appear to be common to all the examples:

- (1) *Fallibility*. The justificatory support is *fallible*. It indicates strongly—without proving conclusively—that the belief is true.
- (2) *Luck*. Within each case, the well-but-fallibly justified belief is true. (Hetherington, 2011, p. 121, *Italics in original*)

Over the years since Gettier proposed his thought experiments, no consensus has emerged about how to overcome the challenge to the Platonic definition of

knowledge (Bigelow, 2006). A range of different strategies to resolve the contradiction have been proposed, a small sample of which are summarised below:

- Knowledge should be redefined to require *infallible* justifications for beliefs.
- A belief should not be considered knowledge if the justification occurs through an accidental occurrence.
- Knowledge may not be justified by a false belief.
- A belief must be caused by appropriate evidence.
- The intuition that Gettier cases do not represent knowledge should be discarded.

(Hetherington, 2011, pp. 122–128)

Despite these suggestions, contemporary epistemologists report there are still no ‘easy answers’ to Gettier’s challenge (Pritchard, 2016, p. 131).

3.1.2.4 Some Gettier cases in science education

Consider the cases below, which contain the two elements of Gettier cases, fallible justification and lucky truthfulness, in the context of students’ beliefs related to science education. In each case, though the student holds a justified true belief, it might be felt they do not possess knowledge.

Case 1

A student’s pre-formal experiences of the world have led them to believe that all motion requires the action of a resultant force. A teacher asks the student if a resultant force acts on an accelerating rocket and they reply that a force does indeed act.

Case 2

A student’s parent assists them with a piece of homework on equilibrium related to a book that is at rest on a table. The parent tells the student that the reaction force and the book’s weight are equal and opposite as they form a Newton’s third law pair. In class, the teacher asks the student about the size of the reaction force and weight acting on a person standing on the ground and the student replies that their magnitudes are equal.

Case 3

A student has the belief that, in an ionic bond, an electron is transferred from one atom to another causing an attractive electromagnetic force between the particles. The student then encounters an exam question in which they are asked what force is responsible for ionic bonding. The student responds that the electromagnetic force causes the bond.

3.1.2.5 Knowledge and belief in science education

The cases described above are doubtless contrived, and are not common occurrences in the science classroom. However, they are significant for a number of reasons. First, they highlight the problematic nature of the term knowledge; Matthews, writing with Southerland and Sinatra (2001, p. 349), had claimed: ‘those that wish to make a strong distinction between knowledge and beliefs are on shaky ground from a psychological standpoint as no empirical distinction has been demonstrated’. He later critiqued constructivist thinkers for confusing belief with knowledge arguing that ‘...a psychological matter is confused with an epistemological one, and the consequence is educational havoc’ (Matthews, 2002, p. 126). Gettier cases highlight that making a distinction between knowledge and belief may not be straightforward. Therefore, as Taber (2013, p. 176) suggests, ‘...whilst the ‘reasoned true belief’ version of knowledge may be useful in philosophical discussions, it does not seem to ‘do the job’ in supporting research in science education’.

Second, there may be a class of beliefs that students possess which match accepted scientific understandings in some ways or under certain conditions, and for which students feel justifications exist (see the three cases above). As these kinds of beliefs contain elements that both match and contradict scientific models, they will be referred to as mixed beliefs (see Figure 3.1, below). For example, consider the belief that an object in motion experiences a resultant force (Viennot, 1979), as described in case one, above. In the case of accelerating objects, this belief might be considered to be both justified and ‘true’ (here ‘true’ is taken to mean matches accepted scientific models), but, in other cases, for example, an object travelling at constant velocity, is not ‘true’, though a student may feel some form of justification for the belief (a discussion of sources of justification may be found below). The existence of justified

‘true’ belief in the case of accelerated motion is analogous to the belief in Russell’s stopped clock example; the belief has a fallible justification, and is ‘lucky’, in that it just happens to be correct in a particular situation.

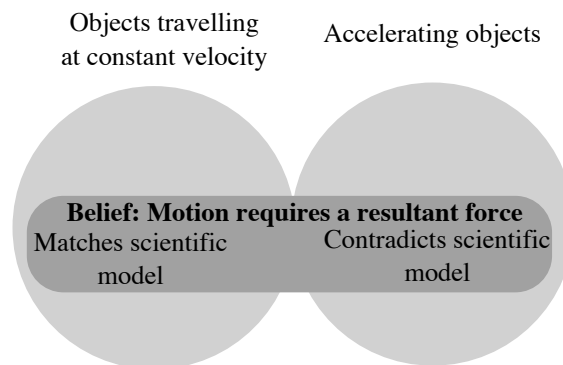


Figure 3.1: An illustration of a mixed belief: the belief that motion requires a resultant force may be a justified ‘true’ belief in the case of accelerating objects, but a ‘false’ belief in the context of an object travelling at constant velocity.

The notion of a mixed belief suggests the knowledge status of a belief is dependent on the contexts to which it is applied. Consider the following thought experiment proposed by Wedgewood (2002), which supports this notion: imagine two possible worlds, w_1 and w_2 , in which you have the same experiences and form the same beliefs:

Now suppose that in w_1 you are bedeviled by an evil demon who ensures that many of your experiences are misleading, with the result that many of the beliefs that you hold in w_1 are false. In w_2 , on the other hand, almost all your experiences are veridical, with the result that almost all the beliefs that you hold in w_2 are true. Intuitively, this makes no difference at all. Exactly the same beliefs are rational and irrational in both worlds. (Wedgewood, 2002, p. 349)

Wedgewood argues that, as the rationality of a belief depends only on ‘internal facts’ related to the thinker’s mental states, justification might be considered to occur within the mind of the thinker, rather than through relation to the external world (Wedgewood, 2002, p. 350). The evil demon example is interesting, as it echoes the

experiences of a student inside and outside of the formal classroom. The belief that objects require a resultant force to be in motion may be a justified by a student's experiences of motion outside of the classroom; however, within the boundaries of school science, the concept is a 'false' belief when considered in general.

Knowledge of the contexts to which a belief is applicable can also seemingly affect its knowledge status. Consider a mixed belief in the case of knowledge of Ohm's law. Ohm's law has been described as a *ceteris paribus* law, that is, one which is a valid description only if some conditions are met (Cartwright, 1980). Imagine a student who believes that current is universally proportional to potential difference, because this is what their teacher has implied, and what the practicals they have carried out have justified. The student's belief may be considered justified and 'true' in cases where temperature is constant, but 'false' in other circumstances. Awareness of the temperature dependent nature of the law appears to change the belief about the relationship of current and potential difference from a mixed belief to a justified 'true' belief.

3.1.2.6 A psychological model of knowledge

The case made here is that the model of knowledge as justified true belief is not a useful one for science education (Taber, 2013). The Gettier cases described above suggest that, at least in some cases, justified true beliefs seem intuitively to differ from instances of knowledge. Though Matthews (2002) has criticised constructivist models of cognition for conflating knowledge and belief, it is difficult to understand how a distinction between these two types of entity is sustainable. Gettier cases challenge the notion that justification can act as a 'tether' (Plato, trans. 1981, p. 86) which distinguishes knowledge from mere belief. Indeed, a difficulty of science education arises because some beliefs may be justified and, in certain circumstances, true, whilst in general being thought of as alternative conceptions (see Figure 3.1).

The psychological construct of the concept would appear to be a useful way to model a learner's constructions related to science. As Quine has argued, '[e]pistemology, or something like it, simply falls into place as a chapter of psychology' (Quine, 2000, p. 297). Claims about students' views on science are all claims about psychological states and therefore it seems unsustainable that 'knowledge' of Newton's first law, for

example, should be accorded different epistemological status from a belief that motion requires a force. The fact that one concept more closely resembles the accepted scientific model does not change the nature of the belief. There is no evidence to suggest that there is any difference in representation between conceptual constructs with differing levels of epistemological warrant (Southerland et al., 2001, p. 336). This argument is not intended to imply that the two concepts are equally desirable in educational terms, rather it is important to acknowledge both are beliefs about the physical world which are supported by some form of justification. Taber (2009) has argued claims for the pedagogic importance of students' beliefs should not be conflated with claims for their scientific appropriateness. Some philosophers have suggested, since the proposition of the Gettier cases, that they '...face the unpleasant reality that we simply have no use for a definition of propositional knowledge' (Kaplan, 1985, p. 363). Though it may be time for researchers in science education to abandon the term knowledge, as it is widely used in the literature, the term will be used in this thesis. However, it will refer to a psychological construct with varying degrees of justification and no assumption of a 'truth' criterion.

3.1.3 Axiological assumptions

It has been suggested that research is never value free (Boyd, 2000), and that even an assumption of value-neutrality is a value claim (Greenbank, 2003). Researchers must address axiology, that is, the manner in which values are ascribed (Blackburn, 2005), as a researcher's values may affect the decisions they make (Flynn, 1995; Greenbank, 2003). Therefore, a clear statement of values is an important form of methodological clarification. A number of different classification systems for values have been proposed (Rokeach, 1973; Schwartz, 1994), which cover a range of topics, including those related to relationships and pleasure. As the focus of this work is on developing a model of students' learning, the most significant issue is the manner in which value has been attached to different models of learning.

The seemingly theoretical debate over the nature of learning has recently become a political debate in the United Kingdom, with the former Secretary of State for Education arguing for reforms premised on the importance of 'knowledge acquisition' (Gove, 2013). This speech prompted a hundred education academics to sign a letter that appeared in a national newspaper arguing changes to the curriculum would lead

to ‘rote learning without understanding’ (Basseley et al., 2013). In a recent speech, the former Schools Minister, Nick Gibb, claimed there exists an: ‘...anti-knowledge - and, I would argue, anti-evidence - position in education debates’ (Gibb, 2016).

This debate has existed for some time in the United States, with proponents of constructivist education arguing that:

To us, rote learning and the conformity it engenders may be likened in some respects to a form of intellectual slavery. In contrast, we value and respect individual human minds and believe that, in a democracy, learners deserve an educational system that encourages, supports, and rewards divergent and creative thinking; deep understanding; and novel ways of problem solving. Further we believe that such a system is ultimately in our best political, social, and economic interests collectively. (Mintzes & Wandersee, 1998a, p. xix)

A recent movement has argued that rote learning and drill-like practice have a place in learning (Willingham, 2009), and approaches that are perceived as neglecting knowledge have been criticised:

This supposed liberation from “mere” information and rote learning is one of the most precious principles of American educational thought, and lies at its very core. Its proponents disparage those who favor a definite, cumulative course of study for children as “traditional,” “hidebound,” and “reactionary,” to mention only the more polite terms. (Hirsch, 2006, p. 40)

This argument seems to be misconceived through the exaggerated characterisations of the differences between the positions adopted by the two sides in the debate. For example, Hirsch (2000), accepts that pre-existing knowledge structures enable the acquisition of novel ideas, a central claim of constructivists (Mintzes & Wandersee, 1998b, p. 76). This debate has surfaced recently in the context of the perceived

learning styles of Asian students. Marton and colleagues (2005) describe the apparent ‘paradox’ that, though Chinese students’ approach to learning was interpreted as relying on rote learning, the students often acquired good understandings of topics. They report that the students saw memorisation and understanding as two parts of the same learning process; therefore, the meaning of terms such as memorisation and understanding may be culturally contingent (Marton, Watkins, & Tang, 1997). A simple dichotomy between memorisation and understanding may be misleading (Entwistle & Entwistle, 2003), as, for Chinese students at least, ‘...having an understanding of something implies memory, just as (meaningful) memory implies understanding’ (Marton, Watkins, & Tang, 1997, p. 32). As Kosso (2002) has argued, knowledge without understanding is undesirable, but understanding requires a base of knowledge. Similarly, Toulmin (1961, p. 108) asserted: ‘The business of science involves more than the mere assembly of facts: it demands also intellectual architecture and construction’. Valuing epistemological outcomes, such as making sense, should not be seen as diminishing the importance of the acquisition of propositions about the world. However, a number of authors (de Regt et al., 2009; Elgin, 1996; Martínez, 2013) have argued that understanding, not simply propositional knowledge, should be the goal of scientific education. Therefore, the assumption adopted in this work is that there is something epistemologically valuable in the process of making sense.

3.1.2 Summary of the assumptions made in this work

Following the discussion above, the assumptions in Table 3.1 are adopted in this work:

Table 3.1: Assumptions adopted in this thesis.

Ontological assumption	• An external reality exists
Epistemological assumptions	• Knowledge of external reality is partial and personally constructed
Axiological assumptions	• Both knowledge and understanding are valuable epistemological goals in science education

Given the assumptions shown in Table 3.1, constructivism would appear to be a good fit with the axioms of the research (see section 3.5 for a fuller analysis of the

coherence of constructivism to this research). The next section considers different forms of constructivism and their potential coherence with this work.

3.2 The nature of constructivism

Constructivism is often linked to the notion of meaning-making (Bodner, Klobuchar, & Geelan, 2001; Crotty, 1998; Mintzes & Chiu, 2004), and so might be considered a good fit for the research questions being studied. The notion of constructivism has been associated with a number of meanings (Bickhard, 1997; Geelan, 1997; Taber, 2009), and the different models will be considered in the next sections.

3.2.1 The epistemological focus of various constructivism

The term constructivism has different connotations in different contexts (Taber, 2009). Irzik (2000) differentiates between cognitive and epistemic constructivism, and a similar distinction is suggested by both Colliver (2002) and Taber (2009), who separates constructivism as a theory of learning in science education and other fields from its application to an epistemological position (See Table 3.2).

Table 3.2: Different epistemological foci of constructivism.

Philosophical constructivism	Psychological constructivism
Assumptions of philosophical constructivism (Doolittle & Hicks, 2003, p. 6)	The ‘Hard Core’ assumptions of constructivism in science education (Taber, 2009, p. 124)
<ul style="list-style-type: none"> • Knowledge is not passively accumulated, but rather, is the result of active cognizing by the individual. • Cognition is an adaptive process that functions to make an individual’s cognition and behavior more viable given a particular environment or goal. • Cognition organizes and makes sense of one’s experience, and is not a process to render an accurate representation of an external reality. • Knowing has its roots in both biological/neurological construction and in social, cultural, and language-based interactions. 	<ul style="list-style-type: none"> • Learning science is an active process of constructing personal knowledge • Learners come to science learning with existing ideas about many natural phenomena • The learner’s existing ideas have consequences for the learning of science • It is possible to teach science more effectively if account is taken of the learner’s existing ideas • Knowledge is represented in the brain as a conceptual structure • Learners’ conceptual structures exhibit both commonalities and idiosyncratic features • It is possible to meaningfully model learners’ conceptual structures

Notice that, in philosophical constructivism, the focus is on cognition and knowing, whereas the theory within science education focuses on the learning experiences of individual learners. It has been argued these two positions are independent of each other: one may adopt a constructivist view of learning (knowledge is constructed by the individual learner) and yet not adopt constructivism as a philosophical position (Colburn, 2000).

Tobin and Tippins (1993) present an alternative differentiation between constructivism as a method and as a referent. They argue some authors have used

constructivism to refer to a method of teaching (Tobin & Tippins, 1993); and, elsewhere, Tobin (1993, p. ix) has described constructivism as ‘a paradigm for the practice of science education’. Other researchers have described constructivism as an ‘approach to teaching and learning’ (Parson, 2013, p. 71) and a ‘method’ (Osborne, 1996, p. 63). Alternatively, Phillips (1995) distinguishes between constructivism as applied to individual psychology or as a public discipline. Colliver (2002) and Taber’s (2009) two-category taxonomies of constructivism might therefore be extended to include an additional category of constructivism as a description of classroom practice (see Figure 3.2).

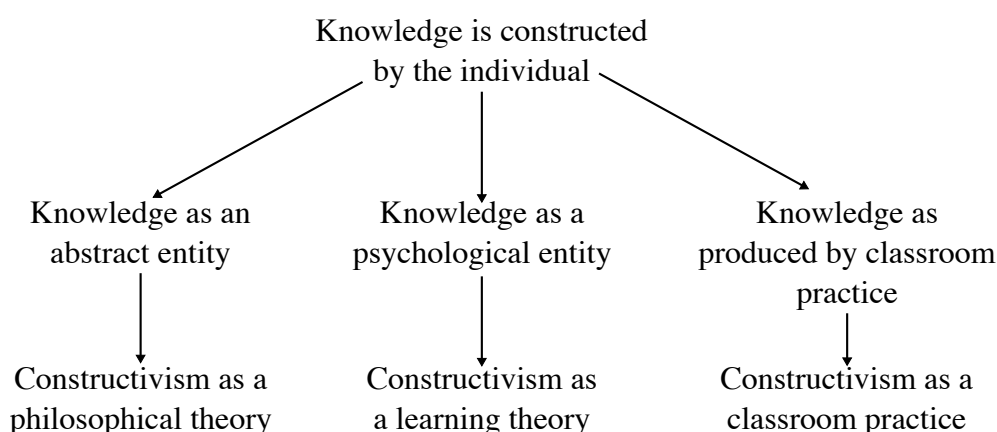


Figure 3.2: A taxonomy of constructivisms.

The three branches of the taxonomy in Figure 3.2 should not be seen as entirely distinct, as each is based on assumptions about the nature of knowledge. The next section examines how different versions of constructivism establish knowledge claims.

3.2.2 Knowledge claims in variations of philosophical constructivism

In an editorial, Good (1993) noted the existence of at least 15 varieties of constructivism. One axis over which such models of constructivism might be differentiated contrasts the justification of constructions in the models, and runs from theories which see knowledge as largely constrained by the external world to conceptions in which knowledge is determined by knowers (Phillips, 1995). A variety of these positions, and the criteria they propose for judging claims, are discussed in the sections below.

3.2.2.1 Relativist constructivism

Relativism has been defined as an epistemology that argues there can be no evaluation of beliefs against an external reality, and, therefore, that no framework exists for measuring the truth, rationality or reality of claims (Bernstein, 1983; Hollis, 1993). A number of authors have claimed that constructivism, or at least some varieties of constructivism, are underpinned by a relativist epistemology (Irizik, 2000; Matthews, 1992, 2002; Nola, 1997).

The targets of accusations of relativistic constructivism are in some cases poorly defined. For example, the work of members the Strong Programme, such as Bloor (1991) and Collins (1981), have been critiqued for their relativistic positions (Irizik, 2000) but do not link their arguments to constructivism. A second source of claims of relativism in constructivism arises from pedagogic models which have been interpreted as implying that an exam question may have multiple acceptable answers (Scerri, 2003, p. 470). However, Taber (2009) has pointed out this view is not one typically held by constructivists, and has clarified the difference between pedagogical and scientific significance of students' alternative ideas. An analogous argument might be made in regard to constructivists' approach to modelling learning. For example, Geelan (1997, p. 16) has described how a profusion of perspectives is 'both more flexible and more powerful' than a single model and describes the tension between two opposing views as 'a source of creativity and productivity' (Geelan, 1997, p. 22). Geelan's views do not propose that multiple models are simultaneously 'true', but, rather, that for complex systems, such as learning and thinking, a variety of different models may provide the richest representation (Taber, 2013).

It has been claimed that, in radical constructivism, criteria for comparing models do not exist, as would be expected of relativism; however, a more nuanced connection between knowledge and reality is actually reported. Though von Glaserfeld has been accused of relativism (Matthews, 1994, 2002), he is careful to avoid statements that criteria for judging claims do not exist:

Constructivism, as I explained earlier, has nothing to say about what may or may not exist. It is intended as a theory of knowing not

as a theory of being. Nevertheless it does not maintain that we can successfully construct anything we want. (von Glasersfeld, 1996, p. 113)

Indeed, elsewhere, Matthews (1992) has argued that constructivism is no more than a version of empiricism. Quale (2008, p. 239), who has adopted an explicitly relativist approach to constructivism, nonetheless admits that is ‘perfectly permissible... to assign truth values to propositions’, though those evaluations are seen as personal and contextual. It is challenging to find genuine relativist epistemologies of constructivism (i.e. those that argue there are no criteria for comparing knowledge claims (Bernstein, 1983; Hollis, 1993)), but, rather, different version of constructivism propose a range of different constructions of ‘truth’ criteria.

3.2.2.2 Pragmatic constructivism

Unlike relativism, which posits no truth criteria, the pragmatic models of knowledge conceptualise theories as instrumental; that is, ‘they become true and they are true to different degrees based on how well they currently work’ (Johnson & Onwuegbuzie, 2004, p. 18). It has been suggested that von Glasersfeld’s radical constructivism is a type of pragmatic constructivism (Bickhard, 1997), as von Glasersfeld’s truth criteria of viability (1996) is a measure of the extent to which a concept can make accurate predictions about the outcome of events. Von Glasersfeld (1996) however, aligns radical constructivism with a coherence construction of truth (discussed below). A clearer potential example of pragmatic constructivism is found in Kelly’s (1955, p. 30) personal construct theory; Kelly argues constructs should be tested to determine their ‘usefulness’ for anticipating events. Pragmatic epistemologies have been critiqued by Russell (1946/1996, pp. 728–729), who observed that the fact that a concept is useful does not make it true. For example, pragmatic models of constructivism may struggle to assist students in the early stages of learning about science, when their alternative conceptions of the world seem more useful, and therefore more ‘true’, than accepted models. An additional critique highlights that pragmatic notions of ‘usefulness’ are subjective and challenging to define (Hartwig, 2007, p. 486).

3.2.2.3 Coherence dependent constructivism

An alternative to a pragmatic judgements are those based on assessments of coherence. Von Glasersfeld (1996, p. 68) argued that his radical constructivism was a coherentist theory, and that the ‘validity’ of concepts was not determined by their usefulness, but, rather ‘...their non-contradictory fit into the largest possible conceptual network’. One interpretation of constructivism is that the model is founded on a coherentist understanding of truth, rather than on correspondence to an external reality (Staver, 1998). However, coherence models of ‘truth’ have long been criticised on the basis that, simply because a set of ideas are coherent, this does not make them true (Russell, 1907, p. 33). Defining the nature of coherence is challenging (Garnham, 1997), and, as interpretations of coherence may be subjective (Hoey, 1991), learners may develop highly coherent networks of ideas that differ from accepted scientific models (Driver et al., 1985; Wertheim, 2011). Given the critiques of relativist, pragmatic and coherentist constructivism, this work will instead adopt a realist constructivist epistemology, which fits with the ontological assumptions discussed above.

3.2.2.4 Realist constructivism

At the heart of realism lies the assumption that an external world exists that is independent of our thoughts and feelings (Boyd, 1983). Putnam (1975, p. 73) remarked that realism ‘is the only philosophy that does not make the success of science a miracle’, because it involves an alignment with an external reality. Realist interpretations of constructivism are implied in the works of a number of writers in science education (Bodner, 1986; Driver & Oldham, 1986; Redish, 2004). Others, for example Kumar (2011, p. 529), have proposed explicit models of ‘realist constructivism’ in which a ‘knowledge-reality correspondence’ is accepted. Realist varieties of constructivism accept a link between knowledge and the external world, though typically argue the link is mediated in some manner, for example, through personal or social experience (Khagram et al., 2010). Cupchik’s (2001) model of constructivist realism proposes that ‘real’ phenomena will be constructed and interpreted by different individuals and communities in different manners. A particularly well-developed realist model of constructivism is found in Gilbert and Swift’s (1985) Lakatosian research programme for studying alternative conceptions. This model asserts that the world is real, but all observations of that reality are

inherently theory laden. Realist models of constructivism face the challenge of describing how knowledge develops through the twin constraints of a single external reality and multiple personal perceptions. A useful analogy that addresses this issue is Bodner's (1986) description of locks and keys. He suggests that, just as many versions of a key may fit the same lock, many different conceptualisations may have a sufficient 'fit' with reality (for example, the different models of learning shown in Figure 1.1).

3.3 Criticisms of constructivism

In order to defend the adoption of realist constructivism outlined in the previous section, several common critiques of constructivism will be considered and addressed in the following sections. The critiques are divided into those that address philosophical and psychological constructivism. A number of critiques of pedagogic constructivism have been proposed (for example, that its practices are culturally imperialist (Bowers, 2007)). However, as the focus of the thesis is on a model of learning, such criticisms will not be addressed in detail here.

3.3.1 Philosophical constructivisms

3.3.1.1 Knowledge claims and the charge of solipsism

Perhaps the commonest, and most serious, charge against philosophical constructivism is the accusation of solipsism levelled by a number of writers (Fox, 2001; Martínez-Delgado, 2002). Solipsism is the belief that only one's own experience exists, and no link to any external referent may be established (Blackburn, 2005). Solipsism has been described as 'existentially irrelevant' as to reject the assumption that we share our experiential world with other people would be '...a sign of mental aberration' (Quale, 2007, pp. 242–243). Whilst the critique of solipsism may be valid for relativist models of constructivism, it does not apply to the realist version assumed in this thesis, as it assumes knowledge claims are, to some extent, constrained by an existing external reality.

3.3.1.2 The blurring of knowledge and belief

Matthews (2002) has criticised constructivist philosophies for not adequately distinguishing between knowledge and belief (see Section 3.1.2). He argued a psychological matter (belief) is confused with an epistemological one (knowledge);

such that if the term ‘knowledge’ in constructivist accounts were replaced with the word ‘belief’, the claims would become sustainable. This critique is premised on the Platonic model of knowledge (Matthews, 2002), and, as discussed above, has been shown to be insufficient (Gettier, 1963). Matthews’ charge is not without justification; there has been a period in which terms related to learning have been used ambiguously in the constructivist literature (Taber, 2013). Lax usage, however, does not undermine the philosophical premises of constructivism. Taber (2009) argues that the term knowledge is inappropriate in a constructivist framework that has rejected a direct link to the external world, and that the concept of belief underemphasises the justifications students possess for their notions. Therefore he proposes conception as a suitable intermediate construct (see discussion of a psychological model of knowledge in section 3.1.2.6, above).

3.3.1.3 The charge of ‘anything goes’

Another common criticism of constructivism is the claim that, as truth criteria are poorly defined, all constructions are equally valid (Nola, 1997; Scerri, 2003). However, again, this charge may be valid in relation to explicitly relativist models of constructivism, but as can be seen in realist, pragmatic and coherentist models of constructivism, care has been taken to formulate constructs that constrain the acceptability of statements. Indeed, even Matthews (1992) implies that constructivism is closer to empiricism than to relativism.

3.3.2 Psychological constructivism

Though the critiques of philosophical constructivism are generally aimed at the straw man of relativist constructivism, some of the critiques of psychological constructivism present greater challenges.

3.3.2.1 The impossibility of personal knowledge

A key claim of constructivism is that individuals develop personal and idiosyncratic understandings of the world (Brooks & Brooks, 1993; Taber, 2009; von Glasersfeld, 1996). However, a number of critiques of personal understanding seem to dispute this axiom. Wittgenstein (1953, pt. §243) argued the words of an individual’s private language would refer to entirely personal entities, such as feelings and moods, and could therefore not be understood by another individual. Without private language, it is argued, there can be no personal concepts (Heller, 2009, p. 24) However, as

constructs are ‘woven into relational context’, therefore, ‘it does not serve us to suppose that they are internalized into individual minds’ (Wortham, 1996, pp. 81–82). Though individuals may possess personal frameworks and translating from one system to another might sometimes be difficult, it is rarely impossible (Popper, 1970). The claim of constructivists is that an individual’s concepts are unique, not that they are unintelligible to others: individual constructs may vary but be explicable in a common language.

3.3.2.2 The origin of concepts

The problem of concept acquisition presents another possible threat to psychological constructivism. Plato (trans. 2002) first proposed an apparent paradox inherent in learning: if one is aware of what one is trying to learn, then no learning is necessary: if one is unaware of the target information, no learning is possible. The problem has since been restated by Jerry Fodor (1983), who pointed out that learning a concept involves the manipulation of a concept that has yet to be acquired. This apparent paradox can be resolved as it is observed that the acquisition of a novel concepts tends not to happen in a single step, and may be achieved by the development of existing conceptual resources (Margolis & Laurence, 2011). Carey (2009) has provided support for this argument by suggesting that certain innate representational primitives exist which participate in a process of bootstrapping more complex concepts from simpler elements.

3.4 An appropriate theoretical framework

This section makes a case for the close alignment between the assumptions of realist constructivism and the constructions of learning developed in this project. In this work, the existence of an external reality is assumed, but, it is argued, access to that reality is imperfect; hence, knowledge is constructed rather than directly ‘discovered’. In Table 3.3, below, the major assumptions of constructivism in science education (Taber, 2009) are shown to fit closely with the model of making sense proposed in this thesis.

Table 3.3: The fit between assumptions of constructivism and the model of making sense presented in this thesis.

The 'Hard Core' assumptions of constructivism in science education (Taber, 2009, p. 124)	Assumptions of the making sense model of learning
• Learning science is an active process of constructing personal knowledge.	• Making sense is seen as both an idiosyncratic and an active process.
• Learners come to science learning with existing ideas about many natural phenomena.	• The conceptual compounds developed in the making sense process are expected to include ideas that both match and differ from accepted scientific models.
• The learner's existing ideas have consequences for the learning of science.	• Background knowledge and epistemological assumptions are assumed to guide the manner in which new coherences are formed.
• It is possible to teach science more effectively if account is taken of the learner's existing ideas.	• It is not a necessary assumption for the work that an understanding of learner's ideas will lead to more effective teaching though it is hoped that the model of making sense will lead to novel pedagogical approaches (see Section 6.4).
• Knowledge is represented in the brain as a conceptual structure.	• Though it has been emphasised that conceptual structure is a model, and, therefore, like all models, is to some extent an imperfect reflection (Box & Draper, 1987, p. 424), it is nevertheless accepted as useful model. The model of making sense is premised on the construction and modification of conceptual compounds.
• It is possible to meaningfully model learners' conceptual structures.	• Though it has been argued that researchers should avoid developing models of mental processes to which they have no direct access (Skinner, 1977), it has been observed that the constructivist research programme has 'achieved a good deal, and continues to suggest potentially fruitful directions for further research' (Taber, 2009, p. 356).
• Learners' conceptual structures exhibit both commonalities and idiosyncratic features.	• The making sense model assumes that learners' conceptual compounds will share both common elements and idiosyncratic features. The multiple-case design (Yin, 2009, p. 53) adopted in this research allows both the distinctive and shared features of learners' thinking to be discussed.

3.4.1 The nature of knowledge constructed in this research

Different forms of research produce different kinds of knowledge claims (DePoy & Gitlin, 2016), and researchers should attempt to explicate the nature of knowledge produced by their research (Fenstermacher, 2002). The conceptualisation of knowledge produced in this work is constructed to cohere with the model of learners' knowledge, described above. Therefore, knowledge produced in research is seen as a 'construction' arising out of a process of 'conscious, systematic, and disciplined sense-making' (Lincoln & Guba, 2013, p. 62). The knowledge constructed in educational research might be conceptualised as representations of researchers' personal mental models (Taber, 2013). In constructivism, different researchers might be expected to develop different interpretations of data related to complex phenomena (Guzzetti & Hynd, 1998), and the existence of a plurality of models is seen as productive (Geelan, 1997). Acknowledging that multiple constructions of data are possible does not imply that all models are equally useful (Colliver, 1999). Rather, in realist constructivism, interpretations are, partially, constrained by the nature of reality (Kumar, 2011). In particular, the interpretations of data produced are conceptualised as embedded in the contexts in which they were produced (Flyvbjerg, 2006); hence, claims about the generalisability of the knowledge produced are limited to cases which researchers perceive are related (Taber, 2000a).

3.5 Fitting methods to assumptions

It is assumed that there should be a coherence between the theoretical assumptions, aims and methods of a piece of research (Laudan, 1986). It is argued that, once researchers have stated their ontological and epistemological assumptions, they have a duty to adopt research methods that fit with their methodology (Boote, 2008). This does not necessarily mean that certain approaches to data collection are forbidden within certain philosophical approaches (Niaz, 2008); rather, a clear case must be made that the methods construct data in a manner that fits the assumptions of the research.

The methods will be described in detail in the next section, however the assumption that learning is an idiosyncratic process (Taber, 2009) suggests that an approach that is sensitive to individual variation would be suitable. The case study approach is described as being sensitive to such idiosyncrasy (Yin, 1981) and, in general,

qualitative methods are seen as useful in the early stage of theorising a concept (Johnson & Onwuegbuzie, 2004). For example, Taber (2008b, p. 1918) argues enquiry into conceptual integration, a process that may resemble making-sense, requires ‘in-depth study of particular teaching and learning contexts’ in order to explore ‘the nuances of thinking of individual learners’.

Secondly, making sense is a process that might be expected to occur over an extended period of time, however, research in science education has often used ‘one shot’ approaches to data collection, giving relatively impoverished data (Taber, 2000b, p. 402). Similarly, diSessa (2008, p. 45) has argued that ‘deep learning takes time’, yet ‘stunningly little process data is taken into account in conceptual change research. By and large, the paradigm has employed before and after snapshots’ (diSessa, 2002, p. 37). An approach that can study processes and capture change requires a high density of observations. The microgenetic method’s focus on ‘details of subjects’ behavior in specific contexts’ means it ‘is the only approach that makes it possible to derive the kind of fine-grained information essential for grasping change processes’ (Calais, 2008, p. 3). To gain insight into the extended process of learning, one-off observations will not do; rather, ‘the learner must be followed for a significant period of time so that shifts in the landscape of cognitive structure may be detected. An in-depth case study approach is required’ (Taber, 2001a, p. 735). Hence, this thesis adopts a microgenetic case study approach that samples data over an extended period of time.

In addition to the fit of the research methods and assumptions in research, the processes of analysis should also be coherent with the methodology of a work (Van den Bergh, 2015). Analysis has been described as both developing understanding (Fossey, Harvey, Mcdermott, & Davidson, 2002; Stenhouse, 1981) and making sense of data (Miles & Huberman, 1994; Sullivan, 2009), processes which, in this research, are seen as personal and subjective, and therefore fit well with the constructivist view of knowledge adopted. The quantitative criterion of replicability is not expected in qualitative data analysis (Merriam, 1995), and some constructivists expect and celebrate the development of multiple interpretations of data (Geelan, 1997). As will be discussed in the section on generalisability (Section 4.7.3), the analysis produced is

seen as a reasoned interpretation developed by the researcher, with sufficient data reported and clear descriptions of the processes of generation of analysis outlined to allow other researchers to engage critically with the ideas generated (Taber, 2000a).

3.6 The relationship of the researcher to the research

In a constructivist model of research, data are imagined to be constructions of the research process involving the interaction of the researcher and the participants (Kvale, 2007). Therefore, there is an onus on the qualitative researcher to provide sufficient information for a reader to make reasoned judgements about the manner in which the interactions between the researcher and participants may have channelled the data (Atkins & Wallace, 2012; Etherington, 2004; Fine, Weis, Weseen, & Wong, 2000). The term ‘positional reflexivity’ refers to the relationships between the researcher and participants that shape the analytical activity (Macbeth, 2001, p.35).

One significant issue that occurs in this research is that, during the collection of data, I acted both as a part-time teacher and a researcher at the school the participants attended (see, also, Section 4.8, for a consideration of ethical implications). I had taught all of the students at some time during their time at the school but was not a class teacher for any of the participants during the process. Wong (1995) has argued that a tension exists between the role of researcher and teacher. In particular, the roles have conflicting aims: the researcher wants to understand learning; the teacher, to support it. However, Wilson (1995) has critiqued Wong’s position, arguing that there is not a clear distinction between the roles, as both have a concern with understanding students’ learning. I saw my role as primarily that of a researcher, but understood that the interview process would cause changes in students’ understanding (Brock & Taber, 2017b). In that sense, the process can be thought of as a form of dynamic assessment (Sternberg & Grigorenko, 2002), in which the learners receive feedback on their comments and the researcher is seen as an active participant in the process. As one-to-one interactions between a teacher and a student focused on making sense of a particular context do occur in the normal course of school activities, the interviews could be constructed as ‘quasi-naturalistic’ interactions (Lincoln & Guba, 1985, p. 8). Though the interventions in the sessions, and my role as a teacher known to the students, doubtless had some effects on the data constructed, it is difficult to describe the precise nature of such influences.

4.0 Methods

4.1 The challenges of modelling making sense

The historical focus of science education research has been on cataloguing isolated alternative concepts but, it is argued, the research programme needs to advance to models that examine the interaction of multiple conceptual entities (Amin et al., 2014). The table below (Table 4.0) outlines the difficulties of investigating making sense and describes how they are addressed in this research.

Table 4.0: Approaches to addressing specific challenges in the research

Challenge	Facet of method to address this challenge
Conceptual constructs may be contextually sensitive (diSessa, 1993; Sabella & Redish, 2007).	Assess understanding across both a set of repeated contexts, to assess change, and novel contexts to assess transfer.
Learning may occur at multiple rates (Clement, 2008; Gilbert & Watts, 1983).	Collect data using relatively high-density sampling for an extended period.
Probes may access a subset of available conceptual resources (Taber, 2013, p. 87).	Use a range of contexts to probe an extended area of conceptual structure but ensure measures access broadly similar sets of concepts.
Some processing may be tacit (Nisbett & Wilson, 1977).	Interpretations were based only on the data produced by the probes (e.g. transcripts of interviews, concept maps, etc.). However, in some instances, differences between the researcher's and the participant's interpretations might indicate knowledge the student could not articulate (See Section 5.2.4.1.1).

Therefore, the investigation of making sense might suggest an approach that uses both non-identical measures and repeated probes with a high density of sampling for an extended period of time to capture detail of the processes of change. In order to trial the method, a short pilot, using high frequency sampling, was carried out.

4.1.1 Reflections from pilot study

Pilot studies are recommended (Taber, 2007) to assist in designing and tuning methods of data collection (Yin, 2009). The intention of the pilot was to trial a method that used a range of identical and non-identical probes, and to sample data at a relatively high frequency. Table 4.1 outlines the pilot interviews that were conducted. The names given are pseudonyms.

Table 4.1: Pilot Interviews.

Student	Date	Topic
Anna	25/1/13	Current
Bimal	28/1/13	Current
Anna	1/2/13	Potential Difference
Bimal	6/2/13	Potential Difference
Bimal	11/2/13	Potential Divider
Chris	6/3/13	Induction

The pilot was intended to demonstrate the potential of the use of multiple sessions containing non-identical probes to investigate how students make sense. For example, in the excerpt below, Bimal attempts to reconcile two contradictory models of the current flowing into and out of a motor lifting a load: current as a quantity that is consumed versus current as a conserved quantity.

B: [Pause] Um [pause] part of me is saying yes, they're different
and there's part of me saying no, because of Kirchhoff's law.

I: What's the bit of you that says they you want them to be
different?

B: Because if it's a greater load, more current will be used to lift it.

I: Yes.

B: Work done. But I am not sure.

I: But your other side is saying...

B: That because of Kirchhoff's law input equals output.

I: Yes.

B: [pause] I think I will go with Kirchhoff's Law it's a law!

(Bimal, Session 1, 179-190; I labels interviewer's comments; B Bimal's
comments)

In the third session, Bimal was shown a variable resistor and asked to predict the current flowing in and out if the slider were set in two different positions. Initially, he argued that the current entering and leaving would be equal; but, when considering the situation with increased resistance, he argued that the current leaving the resistor would be less than that entering. These data begin to develop a crude representation of the contingencies of activation of two of Bimal's understandings of current.

Though the pilot demonstrated the potential of the method for uncovering the complexities of understandings, it also raised two issues: First, careful consideration needed to be given to the choice of situations used in the interviews. For example, it was assumed that the context of an inductor circuit would be a novel context for Chris, but that turned out not to be the case. The situations were chosen to be sufficiently novel that students would need to engage in active organisation of concepts in the interview, rather than simple recall. At all times in the research, this was a difficult goal to achieve, but, as I gained information from previous interviews, I was able to target more effectively subsequent probes to the students' current understandings in an approach similar to Campione and Brown's (1985) 'dynamic assessment' (see section 4.4.1.1).

Second, the pilot indicated the challenge of interviewing students whilst they made sense: the students could typically make some sense of a situation with no support, but further probes often uncovered additional or alternative understanding. Different follow up prompts were used with different students depending on their responses to the situations. The interview then remains 'naturalistic', not because there is 'no manipulation by the inquirer' (Lincoln & Guba, 1985, p. 8), but because the manipulation is similar to the intervention of a teacher in a 'natural' classroom situation.

4.2 Overview of the approach

A complex process such as learning requires eclecticism in research approach (Pring, 2000; Taber, 2008c). It is argued that every research tool has a particular way of constructing data (Smagorinsky, 1995) therefore a range of tools were used to allow triangulation between constructions developing a richer picture of the data (Taber,

2009). Within a semi-structured interview, a variety of tools (see Table 4.2) were used: a) Unstructured concept maps (Nicoll, 2001, p. 876); b) Questions adapted from concept inventories (Engelhardt & Beichner, 2004; Hestenes et al., 1992); c) Interviews about events (White & Gunstone, 1989), in which students are presented with a piece of apparatus and asked to develop an explanation of the physics; d) Physics problem card sorts (Chi et al., 1981) and e) Questions about personal beliefs related to physics (Adams et al., 2006). The nuances of these individual approaches are discussed in section 4.5. The extended duration of the interview period allowed the researcher to respond to emerging themes in the data (Strauss & Corbin, 2008, p. 144). Though an outline design for the research was developed before the start of data collection (Taber, 2007), case study research is expected to deviate from the original research plan (Yin, 2009); and, within the structure set out below, the researcher adopted a flexible approach to investigate unexpected occurrences (Taber, 2007). Two topics in which students would be expected to have existing conceptual structures of some complexity, dynamics and electricity, were selected for the sessions. In order to be able to investigate change over longer periods of time, and to avoid boredom in the students, these two topics, electricity and dynamics, were addressed in four alternating sections of roughly five interviews, with an additional final session (see Table 4.2). The probes were chosen to investigate the same underlying conceptual areas repeatedly in different contexts. The forces and dynamics sessions investigated students' understanding of the link between force and motion; the electrically focused sessions examined the relationships between potential difference, current and resistance. As will be argued in the next section, the data generated are seen as inherently bound up with the order and nature of the probes presented (Yin, 1981).

Table 4.2: Summary of student sessions. The individual probes are identified by lower case letters, and listed in Appendix 8.7.2.

Context	Session Number	Session Focus	Date
Forces and dynamics	1	Force concept questions (a, b, c, d, e, f), discussion about learning.	30/9/13
	2	Simple pendulum apparatus (g), forces on a car question (h).	7/10/13
	3	Mass on a spring apparatus (i), forces on an astronaut question (j).	14/10/13
	4	Loop-the-loop apparatus (k), forces on a swung ball (l), scales in a lift question (l), beliefs about physics questions (see Appendix 8.7.4).	21/10/13
	5	Reflections on making sense, concept map, ball in a bowl apparatus (m).	4/11/13
Electricity	6	Electrical concept questions (n, o, p, q, r, s, t, u), defining concepts and their links.	11/11/13
	7	Circuit question (v), variable resistor (w), the potential divider simulation (x), the motor under load apparatus (y).	18/11/13
	8	Potential difference circuits simulations and questions (z, aa, ab, ac).	25/11/13
	9	Internal resistance simulation (ad), the capacitor and potential difference apparatus (ae).	2/12/13
	10	Concept map and Wheatstone bridge apparatus (af).	9/12/13
Forces and dynamics	11	Concept map, forces on vertically projected object question (ag), Situation card sort (see Appendix 8.7.3.1).	6/1/14
	12	Causality questions, problem card sort (see Appendix 8.7.3.2), pseudo forces in a braking car question (ah).	13/1/14
	13	Questions about concepts' properties, leaping from crouch question (ai).	20/1/14
	14	Weightlessness questions (aj), force concept ontology table (see Section 4.4.5), reflections on pre-drawn 'student' concept map (Appendix 8.7.5).	27/1/14
	15	Concept map, force concept questions (a, b, c, d, e, f), ball in bowl (m), pendulum (g), and mass on a spring apparatuses (i).	3/2/14
	16	Comment on previous concept map, dynamics concepts card sort, forces on astronaut (j), ball in bowl apparatus (m).	10/2/14
Electricity	17	Beliefs about physics (see Appendix 8.7.4), electricity concept questions (l, m, n, o, p, q, r, s, t), sliding wire potential divider apparatus (ak).	24/2/14
	18	Circuit problems (z, al, am), burette and capacitor analogy apparatus (an).	3/3/14
	19	Electricity concept ontology table (see Section 4.4.5), sequence of circuit problems (ao).	10/3/14
	20	Discussion of causal links between electrical concepts (Appendix 8.7.7), comments on own concept map, circuit problems (ap).	17/3/14
	21	Electrical concept map, electrical concept ontology table (see Section 4.4.5), electricity concept questions (l, m, n, o, p, q, r, s, t), circuit with two sources of EMF problems (aq).	24/3/14
Forces and dynamics	22	Reflection on process, force concept map, force concept questions (a, b, c, d, e, f), pendulum (g), U-shaped track (w), mass on spring (i), forces on an astronaut (j), force concept ontology table (See Section 4.4.5).	31/3/14

Summary of data collected	
Total number of sessions completed	Pilot: 6 Main project: (4x22)+(1x10) [One student withdrew after ten sessions, see below] Total: 104
Mean length of session	25 minutes

4.3 Overarching approaches

Two broad frameworks were used to guide data collection. One, the case study approach, matches the situated and idiosyncratic model of learning assumed; the second, the microgenetic method, structures assumptions about the investigation of change. The assumptions of these frameworks are considered in the next two sections.

4.3.1 Case study

Both the term ‘case’ (Ragin, 1992, p. 1) and ‘case study’ (Gerring, 2007, p. p6; VanWynsberghe & Khan, 2008) have been used with a variety of meanings. However, the differing definitions generally emphasise the study of unique features of a phenomenon in a particular context (Yin, 1981). Research which focuses on a full portrayal of ‘of a unique, temporally circumscribed reality’ (Windelband, 1894, p. 12) has been labelled ‘idiographic’ in contrast to ‘nomothetic’ research which aims to understand ‘general lawfulness’. The term ‘case’, in this thesis, will be taken to mean ‘an instance of a class of events’ (George & Bennett, 2005, p. 17). Therefore a case study focuses on the ‘particularity and complexity’ (Stake, 1995, p. xi) of a particular ‘phenomena specific to time and place’ (Ragin, 1992, p. 2). Case studies develop a ‘nuanced view of reality’, rather than aiming to produce grand theories (Flyvbjerg, 2006, p. 223) and, therefore, fit well with constructivist epistemology (Baxter & Jack, 2008). Within a constructivist understanding, learning is seen as, to some degree, idiosyncratic (Taber, 2009, p. 124) and ‘messy’ (Taber, 2013, p. 126) hence case studies are argued to be a suitable tool for studying the complexities of learning in science (Taber, 2000a). The microgenetic method is reported to produce ‘untidy’ data (Flynn, Pine, & Lewis, 2006, p. 4) and therefore the case study approach is seen as a good fit for microgenetic research (Parnafes & diSessa, 2013, p. 6). Therefore, an approach in which particularity is seen as a strength (George & Bennett, 2005; Schofield, 2002; Stake, 1995) is an appropriate choice for this research project.

A researcher studying a case study has to make a decision regarding the manner in which are cases bounded. Cases are expected to have some kind of ‘unity’ (Abbott, 1992, p. 63); hence, it is important for researchers to clearly define the boundaries of cases (Yin, 2009). As learning progressions are assumed to be, to some extent, idiosyncratic (Taber, 2009), in this thesis, the data produced in interviews with individual students will be taken to represent separate cases of learning. However, it has been argued that multiple case studies, which examine cases that are ‘categorically bound together’ (Stake, 2006, p. 6), are more compelling and robust than single case designs (Yin, 2009). Two different conceptualisations of multiple case studies are possible: either the individual cases are seen as relatively discrete entities or they can be treated as embedded in a single overarching context (Yin, 2009). In this thesis, the participating students are seen as relatively discrete cases that share some commonalities in learning processes, making up a multiple case study.

A significant challenge of multiple case studies is that the particularity of individual cases may be lost in seeking generalities (Stake, 2006). Hence, Eisenhard (1989) suggests that researchers should focus on the characteristics of individual cases first before examining patterns that link a group of cases together. Multiple case study research faces an acute version of the researcher’s dilemma (Pope & Denicolo, 1986); the particularity of each case must be maintained whilst some commonalities of the cases are proposed. It is hoped that the inclusion of many sections of verbatim transcript of individual cases of learning will maintain a sense of particularity whilst supporting claims about similarities between the cases.

4.3.1.1 Sampling

The selection of cases, or sampling, is crucial to the outcome of a case study (Seawright & Gerring, 2008). Many approaches to sampling have been proposed: random, stratified, extreme/deviant case, critical case, and paradigmatic sampling (Flyvbjerg, 2006, p. 230). Randomised approaches to sampling, as used in quantitative research, may lead to unrepresentative samples when choosing from small groups, for example, a school, so purposive sampling is recommended for case studies (Seawright & Gerring, 2008). Sampling approaches in qualitative research are ‘not rigidly defined’ (Coyne, 1997, p. 623), and sampling decisions may therefore be

‘a matter of discretionary, judgemental choice’ (Yin, 2009, p. 58) providing the researcher asserts a case for their decisions.

The school the researcher taught at, a comprehensive state secondary school near London in the United Kingdom, was chosen for a pragmatic reason: ease of access. Students aged 16-17 years were selected as it was assumed, and the pilot study confirmed, that the complexity of their conceptual structures allowed for the potential for relatively extended incidents of making sense: they possessed multiple coexisting concepts, yet were still acquiring new concepts and developing the relationships between existing concepts. The choice of students in their penultimate year of secondary education, rather than students in their final year, enabled observation to continue over a time when the students were not involved with external examinations.

An appropriate sample size for qualitative research is one which allows adequate answers to research questions to be developed (Marshall, 1996). A sample size of five was chosen for a number of reasons. Siegler (2006) suggested microgenetic researchers balance the number of participants and number of sessions: if the number of participants is low then a high density of observations is required, and vice-versa. As the aim of the research was to track learning over a relatively large number of sessions (22) compared with that common in microgenetic research in science education (only one microgenetic study in science education, Nuthall & Alton-Lee (1993) involved a greater number of observations (see Appendix 8.1)), a relatively low number of participants was judged to be acceptable. As Taber (2007) has suggested, sampling is often driven by pragmatic considerations: given participants’ commitments and the researcher’s part-time work as a teacher, combined with the aim of maintaining an approximate one week interval between sessions, a sample size of five students was seen as appropriate. Though the modal number of participants in microgenetic research studies in science education is fifteen (see Figure 4.1 and 4.2), the small sample size is justified as researchers studying change processes have argued that adding extra data collection probes is preferable to adding extra participants when studying change in individuals (Siegler, 2006; Sliwinski, 2011). It was expected that, due to the high level of commitment required from the students, a number were likely to drop out; so, an initial group size of five would be likely to

result in at least two students at the end of the process, which would enable comparison of cases. However, it transpired that only one student, Amy, chose to leave the process after ten sessions, citing the time pressure of upcoming mock exams as her reason for finishing her involvement.

Two commonly used approaches to qualitative sampling are: theoretical sampling, ‘...that will maximise opportunities to discover variations among concepts and to densify categories’ (Strauss & Corbin, 2008, p. 201); and purposeful sampling, in which the cases selected are ‘...those from which one can learn a great deal about issues of central importance to the purpose of the research’ (Patton, 1990, p. 169). As these definitions might suggest, the terms theoretical and purposeful sampling are often used interchangeably. However, Coyne (1997) clarifies the distinction by arguing theoretical sampling is a subset of purposeful sampling in which sampling occurs in accordance with theory arising from the data. In this study, no developed theory was useful for guiding selection, so the purposeful sampling strategy of extreme (Yin, 2009, p. 47) or maximum variation (Flyvbjerg, 2006, p. 230) cases was used. Students were identified by discussions with their teachers, and members of the following categories were selected: a) two students who appeared to make sense of physics easily; b) two students who appeared to struggle with making sense in physics c) one student who lay in the middle of these two positions. All the students selected consented to involvement after learning about the project (see Appendices 8.4 and 8.5). In order to preserve the students’ anonymity, and because the analysis does not refer to the teachers’ construction of the students’ abilities, the pseudonyms are not linked to a particular category description.

A common and significant criticism of the case study approach is that statistical generalisations are limited when drawn from small sample sizes (Flyvbjerg, 2006; Yin, 2009). This criticism is addressed in Section 4.7.4 on generalisability, below. A second criticism claims case studies are carried out with ‘insufficient precision’, and that ‘investigators...have allowed a biased view to influence the direction of findings’ (Taylor, Dossick, & Garvin, 2010, p. 303). It is hoped that a clear statement of research methodology, methods and means of analysis will mitigate the possibility of such criticisms in this study (see discussion of validity in section 4.7.2).

4.3.2 The microgenetic method

As making sense is conceptualised as a change process that occurs over both short and long timescales, the microgenetic approach to data collection was used to develop a representation of change. The microgenetic approach has been defined by three characteristics:

- (a) Observations span the entire period from the beginning of the change to the time at which it reaches a relatively stable state.
- (b) The density of observations is high relative to the rate of change of the phenomenon.
- (c) Observed behaviour is subjected to intensive trial-by-trial analysis, with the goal of inferring the processes that give rise to both quantitative and qualitative aspects of change. (Siegler & Crowley, 1991, p. 606)

In contrast to the pre-test/post-test paradigm, which reveals only whether an observable change over an interval has occurred, the microgenetic method can give information on the processes of change (Goldin-Meadow & Wagner Alibali, 2002). Researchers in science education have taken up the microgenetic approach to investigate a range of phenomena, and around thirty studies claim to have used the method (See appendix 8.1). The application of the method to science education raises five significant issues:

- a) Can the microgenetic approach be used within research designs collecting and analysing either, or both, qualitative and quantitative data? (Section 4.3.2.2)
- b) When examining data that describe changes in students' representations of their thinking how can researchers define intervals over which change does and does not occur? (Section 4.3.2.3)
- c) What is an appropriate sampling rate for a microgenetic study of learning? (Section 4.3.2.4)
- d) How is it possible to manage the high variability that may occur in data sampled at a high frequency? (Section 4.3.2.5)

e) What kinds of sequences of probes are appropriate within the microgenetic approach? (Section 4.3.2.6)

The next section examines some of the assumptions that may be made when data relating to cognition are constructed as a series of events over time.

4.3.2.1 The sequential division of data about cognition

Data in science education research are constructed representations, and do not fully reflect the nature of cognition (Taber, 2013): though cognition may be parallel (Rumelhart & McClelland, 1986), many forms of data have an apparent sequential nature; for example, the utterances in interviews and even concept maps are produced as, and might be constructed as, serial chains of concepts interlinked with themselves. The serial nature of data can be seen as arising from processes occurring at three levels, shown in Figure 4.0.

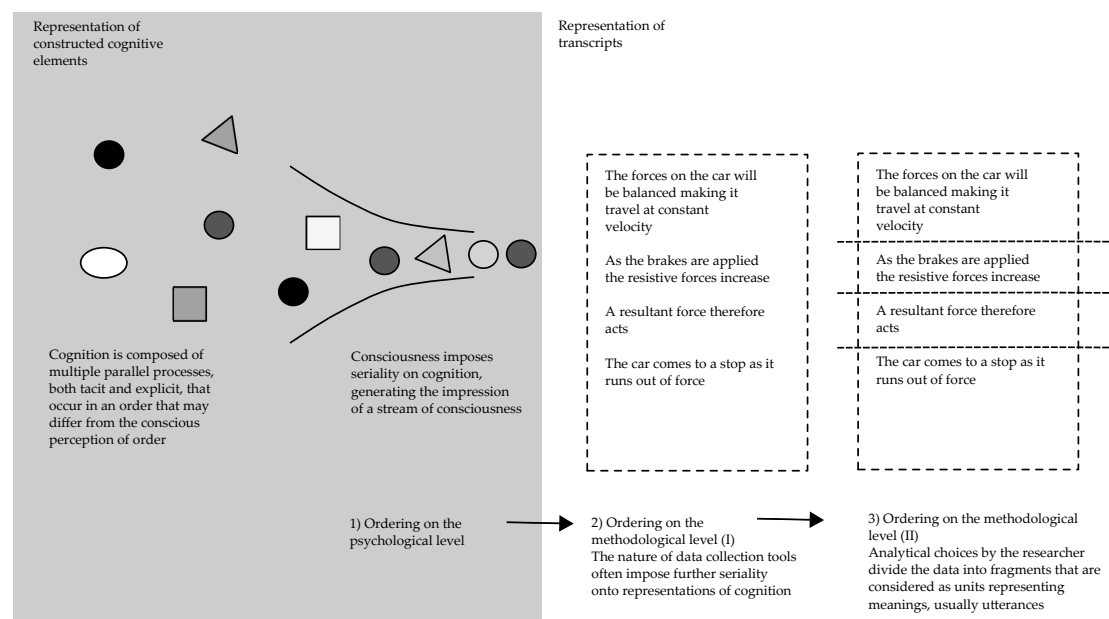


Figure 4.0: The channelling of cognition into serial-in-time reports. Reproduced from Figure 1 in Brock and Taber (2017b, p. 6).

Cognition is complex (O'Brien & Opie, 1998, p. 13): processing may be parallel (Rumelhart & McClelland, 1986), involve tacit elements (Brock, 2015; Polanyi, 1966; Taber, 2014) and the conscious experience of the order of cognitive processes over short timescales may be misleading (Dennett, 1991). Consciousness imposes a sense

of 'seriality' onto the parallel nature of cognition (Baars & Franklin, 2003, p. 167)- as illustrated in the left-hand section of Figure 4.0.

In addition to psychological ordering, research instruments cause an additional layer of sequencing (right-hand side of Figure 4.0): the particular stimuli, their forms and the order in which they are presented, cue what a participant 'brings to mind'. Probes of consciousness at different times will then produce different representations: cognition at a given time is partly, but not wholly, dependent on the nature of the stimuli encountered (Dennett, 1991). In the final stage of ordering, a researcher may deliberately define temporal divisions or static intervals in a sequence of data (see section 4.3.3.4). The next section examines existing microgenetic studies in science education.

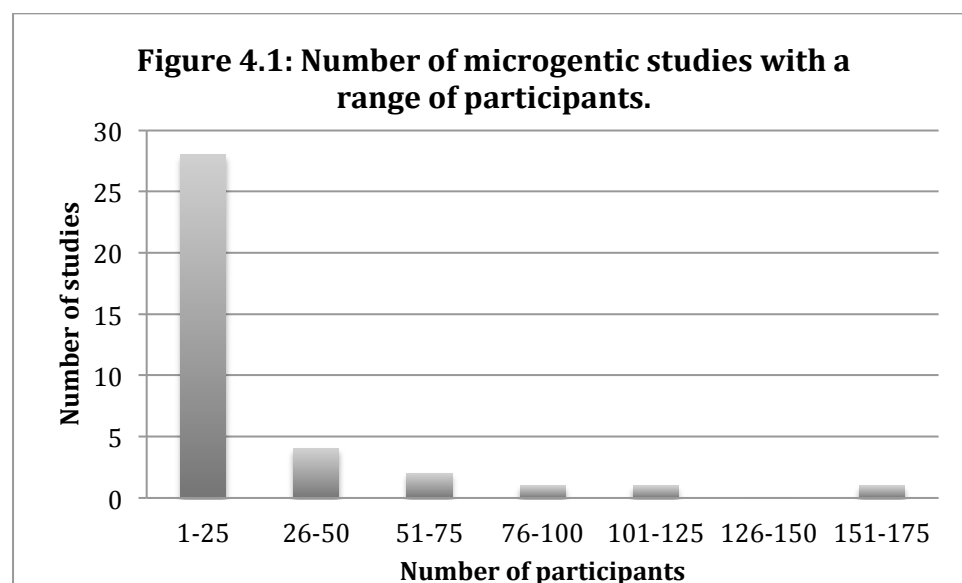
4.3.2.2 The microgenetic method in small scale studies in science education

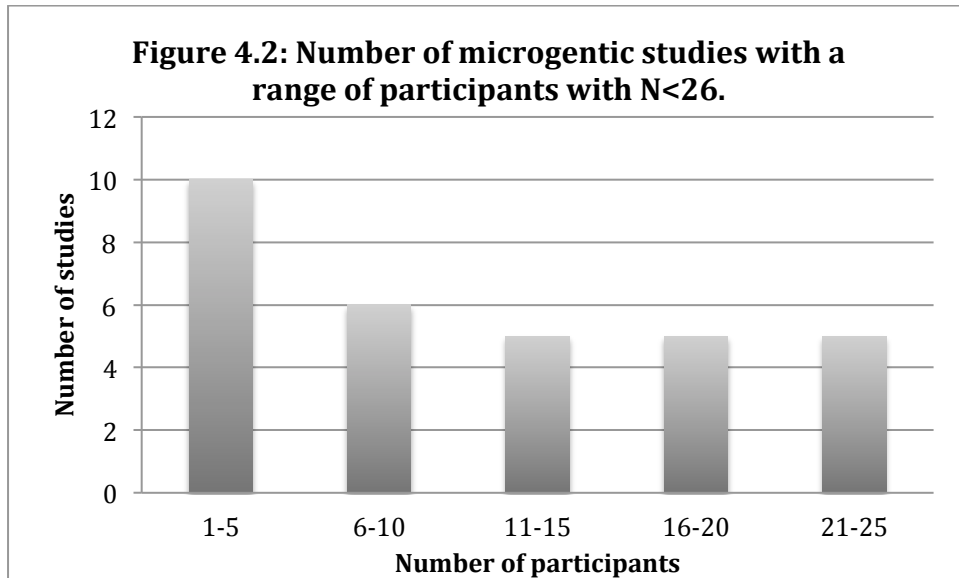
A catalogue of microgenetic studies in science education was created (Appendix 8.1.2) using a set of search criteria (Appendix 8.1.1). The papers listed in Appendix 8.1.2 provide a context in which to examine how the microgenetic method has been understood in science education. One author who has commented on the use of the approach, Chinn (2006), made a case that certain kinds of small-scale, qualitative, repeated measures studies are not microgenetic because the data collected are not analysed on a moment-by-moment basis, probes in the studies are not counterbalanced (a technique used to reduce practice and task effects by changing the order of the probes presented to individual participants (Gaito, 1961)) and the sample size in the studies is too small for statistical analysis.

Whilst Chinn has identified some useful indicators for including studies in the microgenetic canon, his indicators should not be considered as absolute criteria and a case is made, below, for the value of the microgenetic approach in studies designed to collect qualitative data from small numbers of participants. The criticisms relating to sampling rate, moment-by-moment analysis and counterbalancing of tasks are not inherent issues of small-scale, qualitative studies and may equally be applied to some quantitative microgenetic studies.

Parnafes and diSessa (2013) have argued that the microgenetic method fits well with a case study approach as high-density sampling will lead to ‘... a high degree of individual and contextual variation’ (Parnafes & diSessa, 2013, p. 7) which is best suited to examination through the sensitivity to idiosyncrasy of case study research. Small numbers of participants are usual in microgenetic research, even single participant studies are not uncommon (Siegler, 2006). Though small-scale studies have been criticised for their limited generalisability (Feldon & Gilmore, 2006), Parnafes and diSessa (2013) argue that microgenetic case studies may have stronger ecological validity and develop greater insights than strictly controlled, laboratory-based studies. The microgenetic focus on individual variability means ‘...it makes little sense to average performance over individuals’ (Kelso, 1995, p. 161) and, rather than larger sample size, a high frequency of observation may ‘minimize measurement error’ (Lee & Karmiloff-Smith, 2005, p. 257).

The mean number of participants in the studies listed in appendix 8.1.2 is 25 and the mode is 15. The frequency distribution of participants in these studies is shown in Figures 4.1 and 4.2. Note that Kuhn, Schauble, and Garcia-Mila (Kuhn et al., 1992) and Johnson and Mervis (1994) consist of two discrete studies, involving different numbers of participants, and those studies have been individually counted. Kuhn (2010) and diSessa (2014) could not be included in these graphs, as the number of participants is not stated.





(Reproduced from Figures 2 and 3 in Brock and Taber (2017b, p. 13))

The number of participants leads to a distinction in analytical approach: in studies with high N (Chinn, O'Donnell, & Jinks, 2000; Feldon & Gilmore, 2006; Opfer & Siegler, 2004) analysis tends to be largely quantitative. In smaller scale studies, a greater variety of analysis types are found: largely qualitative analysis (Wiser & Amin, 2001), mainly quantitative approaches (Van Der Steen, Steenbeek, Van Dijk, & Van Geert, 2014) or a mixture of both (Nuthall, 1999). Clearly, different approaches are appropriate for different kinds of investigation. Chinn's (2006, p. 444) argument against qualitative microgenetic studies might be valid if statistical generalisability were the only goal of research. However, this research is not aiming for statistical generalizability; instead, it aims to provide in-depth detail about particular cases (Taber, 2000a) and therefore the emphasis on the richness of individual experience in this research is argued to be an excellent fit for the microgenetic approach.

4.3.2.3 The static interval and the observation of different phenomena

The microgenetic method's focus on the occurrence of change requires researchers to describe the interval over which change is considered to occur. In analysing qualitative data, for example transcripts of interviews, classroom dialogue and think-aloud protocols, researchers commonly divide the transcript into what they perceive are a sequence of somewhat distinct episodes that may be considered to represent change (see Figure 4.3). This division of the data set into sections is typically driven

by the analyst's interpretation of an alteration in the focus of the constructed representation. A common assumption is that a particular subsection of the data, for example a number of utterances in an interview transcript, represents a point in time, that is, a particular phase in the development of the participant. In microgenetic research, however, the assumption is that there may be significant shifts that occur during data collection such that a transcript might be a record of several distinct phases in the development being explored. This raises an issue about how data, perhaps a transcript with a long sequence of utterances alternating between an interviewer and participant (labelled as I and P in Figure 4.3), can be fragmented during analysis in order to represent potential change.

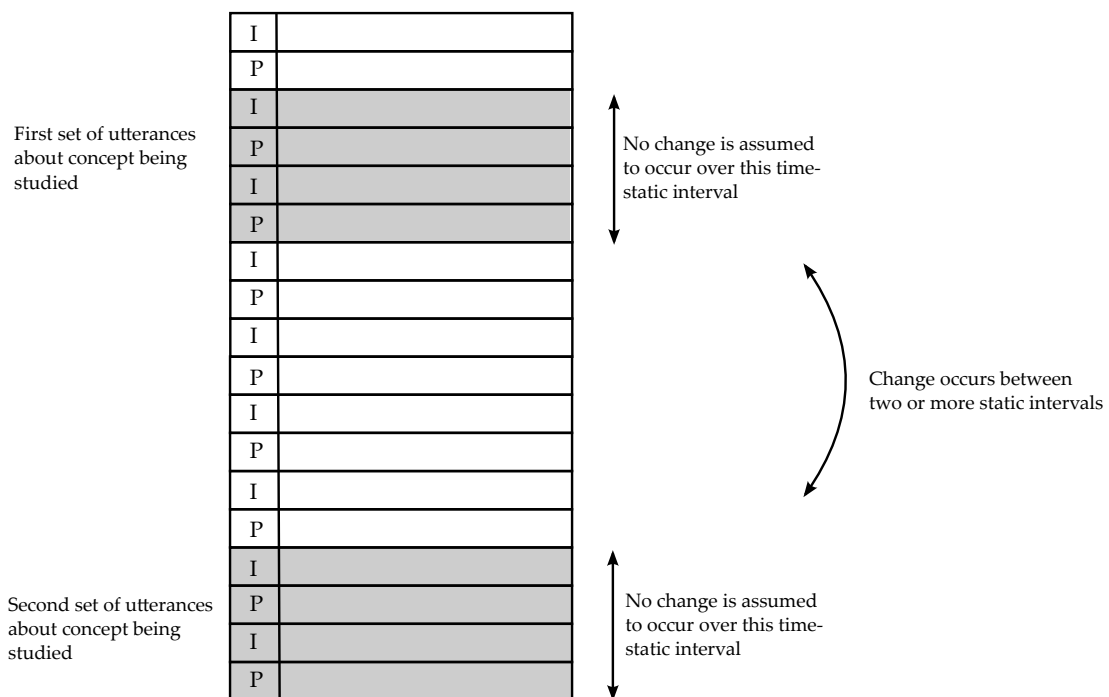


Figure 4.3: An illustration of the concept of static interval. The image displays a section of transcript. ‘I’ and ‘P’ refer to the interviewer’s and participant’s utterances respectively. Reproduced from Figure 4 in Brock and Taber (2017b, p. 14).

In order to report change, researchers will describe a perceived difference between data collected at two or more different times. This approach assumes that change occurs in the interval between these two sections of data but, crucially, the sections of data themselves, the start and end points of the change, are assumed to be essentially

static: change occurs *between* the sections rather than *during* the sections. These periods in which no change is assumed to occur are referred to here as static intervals (see Figure 4.3). There follows a discussion of two papers, Parnafes and diSessa (2013) and Taber (2008b), to illustrate the concept of the static interval. Parnafes and diSessa's (2013) investigated students' understanding of simple harmonic motion. In their analysis, the authors describe a student as reaching two different conclusions about the concept of 'fastness', in the contexts of an oscillating pendulum and a rod (Parnafes & diSessa, 2013, p. 24). Parnafes and diSessa argue:

This is a canonical case of lack of alignment; while Rachel believes she is determining the same kind of information in both situations, 'fast or slow,' she is actually determining two different kinds of information. (Parnafes & diSessa, 2013, p. 25)

By contrast, during the computer simulation, it is reported that the introduction of friction '... led to the discovery of an important new relationship' (Parnafes & diSessa, 2013, p. 26). The pendulum and the rod are seen as two contexts triggering different interpretations of 'fastness', as in Mortimer's (1995) conceptual profile model, but the developing understanding of periodicity is seen as a 'discovery' rather than a shift of frame.

The case being made is not intended to criticise Parnafes and diSessa's (2013) interpretations of the data, but rather to highlight a shift in interpretation of the interval over which change occurs has taken place. The two different models of fastness are implied to coexist within the same static interval, but the shift in understanding of periodicity is described as a discovery; hence, it implies a transition between static intervals. A discussion of the difficulty of distinguishing conceptual change from the presence of multiple concepts is outlined in the next section.

Taber (2008b) presents a different division of time: he interviewed students to examine their application of knowledge of forces and energy to a variety of contexts: an apple hanging in a tree, the solar system, and a stretched spring, amongst others. He reported a number of incidences in which students possessed conceptual resources

that matched the scientific position but chose not to activate them in a particular context. In Taber's (2008b) study the intention was to explore thinking related to the same underlying scientific ideas in different contexts, and so the study was not intended to be microgenetic. However, it is possible to conceptualise the work as a study of potential change: the student is presented with multiple sequential tasks that, from a formal scientific perspective, access similar conceptual resources.

Taber (2008b) and Parnafes and diSessa (2013) used similar methods: a single interview including multiple probes of a student's understanding of an underlying conceptual structure. However, the authors characterise their data differently: in particular, they make implicitly different assumptions about the division of reports of cognition over time. In terms of the concept of the static interval, the interview is considered either a single static interval, describing an unchanging conceptual structure applied in several contexts (as in Taber, 2008a), or the interview is interpreted as containing multiple static intervals, describing an evolving understanding (as in Parnafes & diSessa's (2013) report of a discovery). Both of these interpretations are justifiable, however, it is important that authors clearly define their assumptions related to the intervals over which change does and does not occur.

A researcher's choice of static interval will depend on the phenomenon being investigated. When studying the acquisition of strategies, for example, Adolph and colleagues (2008) examined infants learning to walk, static intervals of relatively short duration are appropriate, as the behaviours, for example walking or crawling, are well defined and occur over short time periods. However, the situation is more complicated if the investigation focuses on scientific concepts: as Parnafes and diSessa (2013, p. 15) state, '[l]earning a concept simply cannot happen in a single try, as a new strategy usually appears'.

The relationship between phenomenon and static interval may explain the historical focus in science education research on individual concepts rather than wider explorations of conceptual structure (Taber, 2009). The extended length of time that would be required to probe a conceptual structure makes it difficult to maintain the assumption that change is not occurring over the observation period. In this thesis,

static intervals for addressing different research foci are described in the analysis sections, but are summarised in Figure 4.4, below.

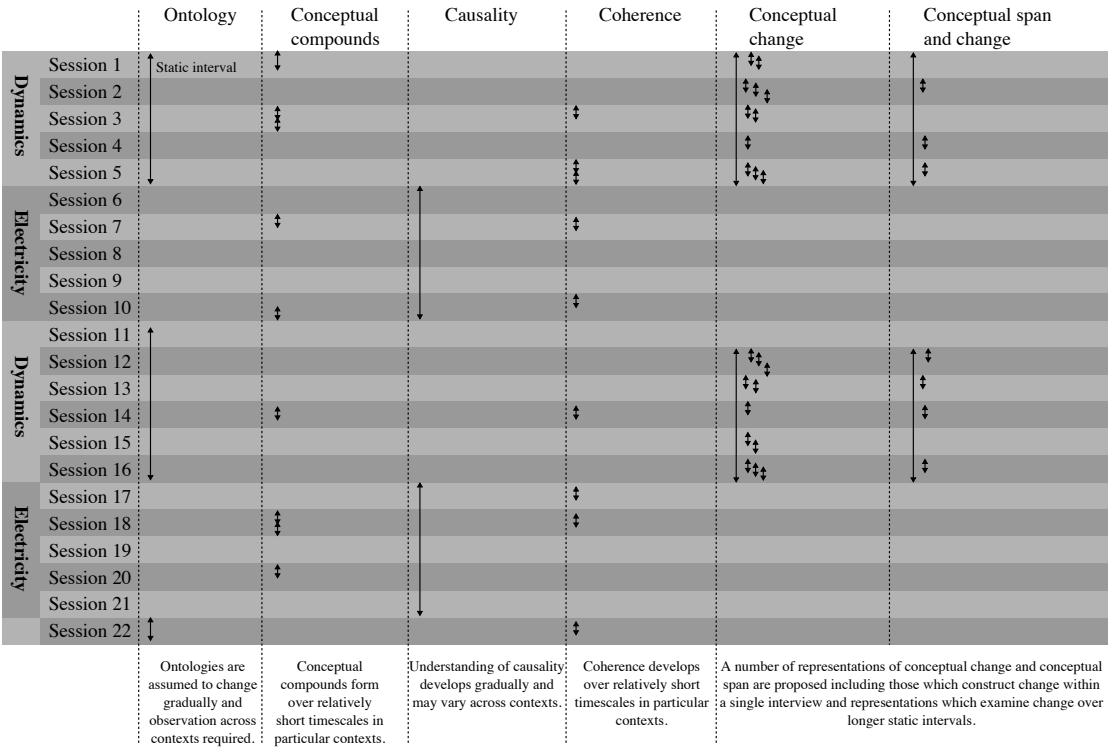


Figure 4.4: Summary of choice of static interval. The arrow-headed lines represent the static intervals applied in different strands of the thesis. It is assumed that it requires multiple probes, across several sessions, to develop a representation of a student’s ontology of force, as ontologies are multifaceted and potentially contextually sensitive. By contrast, the construction of a conceptual compound may occur in a single context within a session, and change might be constructed as occurring within or between sessions.

4.3.2.4 Sampling rate and the rate of change of learning

Researchers typically attempt to describe change by observing a selection of episodes in an extended process. In order, therefore, to construct a fair representation of the change, Siegler and Crowley’s (1991, p. 606) second criterion for microgenetic studies makes the cases that: ‘The density of observations is high relative to the rate of change of the phenomenon’. Microgenetic studies may be seen as a subset of longitudinal studies, in which ‘...two or more measures or observations are made at different times of the same individuals or entities’ (White & Arzi, 2005, p. 138). Most longitudinal studies, for example, are seen as developing ‘snapshots’, rather than the ‘near continuous flow of information in movies’ (Siegler, 1995, p. 226) seen in

microgenetic methods: moment-by-moment analysis is seen as the ‘gold-standard’ of the microgenetic approach (Parnafes & diSessa, 2013, p. 7). When observing change, an overly low density of observations will result in a loss of detail in the data produced (Adolph et al., 2008; Kuhn, 1995).

In order to fulfil Siegler and Crowley’s (1991) condition, researchers need to make and justify claims for the rate of change of the phenomenon they are observing. As has been discussed in section 2.5, various rates of conceptual changes have been suggested in science education research. It is hypothesised that change to ontologies (Chi, 1992, 2013) and understandings of causality (Grotzer, 2012) happen gradually, hence lower sampling rates are acceptable for those phenomena (See Figure 4.4). By contrast, given the reported range of timescales of conceptual change (See section 2.5.4), both a high density of observation, weekly sampling, to capture short timescale change in conceptualisations, and an extended period of observation, a total period of observation covering approximately six months, to capture gradual shifts in cognitive structure (Taber, 2001a), were used to collect data related to conceptual change, span and the formation of conceptual compounds.

4.3.2.5 Noisiness and stability in the microgenetic method

A concern relating to data collected over short timescales is a difficulty in distinguishing ‘signal’ from ‘noise’ (Silver, 2012). In the case of learning, this might be thought of as distinguishing ‘genuine systematic change’ in conceptual structure from transient fluctuations (Lee & Karmiloff-Smith, 2005, p. 257). Taber (2008a, p. 1028) argues researchers should ‘...distinguish between thinking that reflects stable ‘alternative conceptions’ from thinking that constructs a viable but labile response to which the learner has little commitment’, and so be able to discriminate ‘significant progression’ from ‘mental flotsam and jetsam’ (Taber, 1995, p. 5). The distinction between ‘signal’ and ‘noise’ is especially acute in the microgenetic method as the approach is reported as uncovering ‘untidy’ change (Flynn, Pine, & Lewis, 2007, p. 4).

Though stable cognitive elements are often the focus in studies of learning (Petri & Niedderer, 1998; Taber, 1995), transient processes may nonetheless be significant (Siegler, 2006). An understanding may appear ad hoc and short-lived within a

particular set of data, but if observations are continued over an extended period, it is possible the apparent flotsam might develop into a stable conceptual entity. In the absence of sufficient data researchers should be cautious in discounting the significance of apparently transient elements (a construction of unstable constructs in the data is found in Section 5.2.2.1.1).

An additional difficulty is that a student may possess multiple co-existing understandings that are stable and selectively active over short timescales (Harrison & Treagust, 2000b; Mortimer, 1995; Taber, 2000b) in response to particular contextual cues. However, when sampling occurs at high densities, it becomes difficult to determine if a report of several different consecutive concepts is evidence of multiple concepts reported serially, or of conceptual change. An extended period of sampling, across a range of contexts, may assist in distinguishing the presence of multiple concepts from conceptual change. It has been reported that substantive shifts in conceptualisation may take weeks, months or years to occur (Shuell, 1990), and it is difficult to define a precise duration of observation that would satisfy claims regarding conceptual change. The notion of moving towards ‘theoretical saturation’ (Glaser & Strauss, 1967, p. 61) may be more appropriate than a defined interval. The ideal form of investigation would include microgenetic sampling over an extended period of time to provide evidence of the diversity and stability of conceptual entities. In this thesis the data were collected at intervals of one week, to capture short timescales changes; and for an extended period covering approximately six months in order to understand the stability of changes.

4.3.2.6 The use of repeated measures

In defining the conditions of microgenetic studies, Chinn (2006, p. 441) states a participant ‘...typically encounters similar tasks and measures repeatedly’, and implies studies that do not use counterbalanced tasks should not be considered microgenetic. Counterbalancing is a technique intended to reduce practice and task effects by changing the order in which the probes are presented to individual participants (Gaito, 1961). This section considers the methodological choices researchers face when choosing the types of probes to use in microgenetic studies. Measures may be thought of as existing on a continuum of similarity (see Figure 4.5), including identical probes and probes which are apparently different but investigate

the same conceptual area. The extreme case of non-identical probes that investigate unrelated conceptual areas is not considered here as it seems an unlikely choice for a researcher. However, defining similarity is not straightforward and may depend on expertise. For example, to an expert, a problem concerning the motion of the mass on a spring and a problem about a block sliding down a slope, may be perceived as similar, because their solution methods share the same ‘deep structure’ of energy conservation (Chi et al., 1981, pp. 125–127). Measures that appear non-identical may be argued, at least to an expert, to be similar if they share a ‘deep structure’ (see

Figure 4.5)

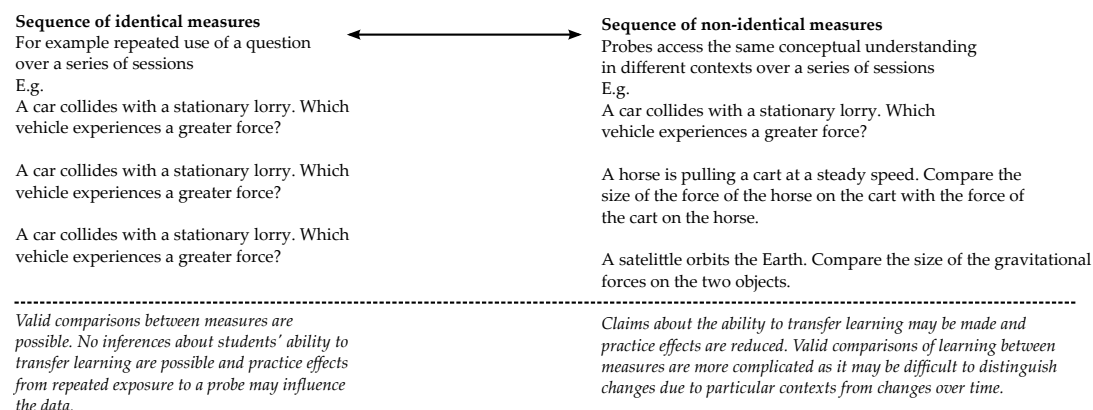


Figure 4.5: The continuum of similarity of measures. Reproduced from Figure 5 in Brock and Taber (2017b, p. 21).

The nature of the effects of assessment may vary for measures at different places on the continuum (Figure 4.5). Siegler and Crowley’s (1991) use of relatively similar measures in an investigation of addition strategies was criticised by Pressley (1992, p. 1240), who argued microgenetic studies lead to a confounding of ‘...time of assessment with experimental effects associated with assessment’. The high density of novel experiences encountered may differ from typical learning experiences (Miller & Coyle, 1999). At the other end of the continuum, where identical measures are not used (such as Parnafes and diSessa, 2013), it is impossible to separate effects due to context from changes over time (see Figure 4.5). If the intention of a study is to produce a narrative of a particular learner’s developing understanding across different contexts, this effect is unavoidable, and non-identical measures are a necessary choice. The data then, as in the case-study approach (Flyvbjerg, 2006), are inherently bound up with the nature and order of probes and the interaction with the researcher. The use of non-identical but isomorphic probes is similar to the kind of assessment

that a student might routinely encounter in the classroom, and so it might be argued to have stronger analytical generalisability (Kvale, 1996; Taber, 2000a) than a small-scale study using identical measures.

Expert conceptual structures appear to allow the transfer of principles to novel situations (Haskell, 2001; Mayer, 2002a); hence, it has been argued a microgenetic study of learning should involve a variety of related, but non-identical, tasks that share similar underlying structures (Kuhn, 1995, p. 136). Complex forms of learning are applicable across a range of contexts, and controlling for context would be mistaken (Maxwell, 2004). In this thesis, both identical probes and non-identical probes (see Table 4.2) were used to produce a broad representation of making sense (see Section 2.6). It is argued that the non-identical probes (see Appendix 8.7.2) allowed the researcher to develop an understanding of the students' activation of conceptual resources across a range of contexts in which experts might be expected to consistently activate a particular set of conceptual resources.

4.4 Tools

The previous sections have addressed the over-arching approaches that inform the research, that is, case study and the microgenetic method. The next sections (4.4.1-4.4.7) focus on the particular methods used to collect data.

4.4.1 Interviews

Interviews may be conceptualised as a process in which 'knowledge' is constructed in the interaction of the participants (Kvale, 2007, p. 1) and both parties are seen to be active in the meaning making process (Holstein & Gubrium, 1995). Therefore, an interview is not a 'pipeline for transmitting knowledge', but, rather, a process that leads to the creation of meaning from the interaction of participants (Holstein & Gubrium, 1995, p. 3). Interviews are not passive processes but can cause conceptual change: 'an interviewee's thinking will change and drift, as they draw on and recombine various conceptual resources' (Sherin et al., 2012, p. 170). Such shifting conceptual dynamics may be 'messy' and so an interview should not be conceptualised as a tool that allows for a simple 'read out' of participants' understandings (Sherin et al., 2012, p. 172). Responses may be highly sensitive to the context of probes (Southerland, Smith, & Cummins, 2005) and therefore replication

of responses between repeated measures should not be expected (Holstein & Gubrium, 1995). This kind of contextual variability is not seen as a hindrance, but a reflection of the contextually sensitive nature of cognition; the data produced are conceptualised as inherently bound to the contexts in which they were generated.

In semi-structured interviews, the researcher has an aim for the material they wish to cover, but will allow discussion to be guided by the participant's responses; therefore, topics of discussion may vary considerably in individual interviews (Fylan, 2005). Semi-structured interviews can be seen as occupying the centre of a continuum running from highly structured interviews to entirely unstructured interviews, in which initial responses may determine the focus: a flexible but unpredictable approach (Leech, 2002). Semi-structured interviews are seen as useful for addressing complex research questions, such as those in this project, as they allow responsiveness to emerging understandings (Fylan, 2005) and enable the exploration of inconsistencies or contradictions (Barriball & While, 1994). A sample set of interview probes is shown in Appendix 8.7.1. Within the interviews a number of conceptual questions were drawn from the Force Concept Inventory (Hestenes et al., 1992) and Determining and Interpreting Resistive Electric Circuits Concepts Test (DIRECCT) (Engelhardt & Beichner, 2004). The inventories were not used as instruments in their entirety, but as a source for probes which were repeated a number of times over the course of the interviews (see Appendix 8.7.2). As part of the interview process, students were asked to give their own reflections on the process of making sense, as Taber (2008b, p. 1936) suggests an exploration of students' own views about conceptual integration would be an important direction for work in this field.

4.4.1.1 Interviews about events and instances

Given the assumption that making sense is constrained by a particular context (Dykstra et al., 1992; Redish, 1999; Sabella & Redish, 2007), it has been argued that interviewing across a range of contexts will present the richest model of conceptual structure (see Section 4.2.1). Ausubel (2000, p. 110) argued that asking students to state principles may lead to the elicitation of rote-learned material, and instead suggested probes of comprehension are presented in 'a somewhat different context than the originally encountered learning material'. Making-sense is particularly

challenging to assess as it is a personal act (Craig-Lees, 2001), and our ‘private understandings’ may be idiosyncratic and differ from canonical representations (West, Fensham, & Garrad, 1985, p. 30). A number of approaches have been suggested which are suitable for the investigation of making sense. Osborne and Gilbert (1979) developed a method to probe the construction of meaning, the interviews-about-instances approach. In this technique, a student is shown one of a set of drawings that represent instances of the use of a concept, for example, situations linked to electric current, and the student is asked if the drawing represents an example of their meaning of the concept (Osborne & Gilbert, 1979). A related approach is the interviews-about-events method in which a practical apparatus acts as the basis of questioning (Solomon, 1993; White & Gunstone, 1992). The distinction between these two methods is blurred, as, in the instances approach, cards may represent practical situations (White & Gunstone, 1992). In the interviews-about-events approach, the interview is seen as ‘a conversation that is managed in order to bring out the student’s understanding’ (White & Gunstone, 1992, p. 66), and it is recommended the sequence of the interview should be guided by the discussion (White & Gunstone, 1992). The interview is set up as a dialogue or open discussion and emphasis is placed on there being no single correct answer. For this reason, Osborne and Gilbert (1980) advise against the interviewer being the student’s current teacher (see section 4.4.2 and 4.7 for a discussion of this issue). Further variants are the Describe, Observe, Explain task (Champagne, Gunstone, & Klopfer, 1985) and the similar Predict, Observe Explain task (White & Gunstone, 1992), in which students are presented with some physical apparatus, asked to predict and justify the effect of some manipulation, and then compare their prediction with the outcome of the manipulation.

The interviews about instances approach can be seen as a form of dynamic assessment, as: a) the interviewers’ questions are not entirely pre-determined; b) some form of feedback is given on a learner’s attempts to develop an understanding; c) the interviewer does not adopt a neutral or detached role; rather, the process is seen as a ‘two-way interactive relationship’ (Sternberg & Grigorenko, 2002, pp. 28–29). This approach is cited as evolving out of Vygotsky’s concept of the zone of proximal development (ZPD) (Grigorenko & Sternberg, 1998) in which a distinction is drawn

between actual development that a learner can achieve alone, and potential development, which is achieved in collaboration with peers or adults (Vygotsky, 1978). The use of a dynamic approach, in a particular context, allows the researcher to elicit a student's initial interpretation of a situation and then, through cycles of scaffolding prompts, to uncover other facets of the student's understanding. Similarly, the graduated prompt approach (Campione, 1989; Campione & Brown, 1987) permits a researcher to provide a sequence of prompts to move a learner closer to solving a problem, and, in the process, acquiring information about their understanding. This kind of responsive assessment is both time-consuming and challenging for the researcher who must pitch prompts at the appropriate level (Berk, 2001).

A typical progression of questioning would begin with the presentation of a scenario, either a physical piece of apparatus, a written description or a computer simulation, such as, a marble travelling round a looped track. The participant was initially asked an open-ended question to allow them to make sense of the situation; for example, "How can the marble travel upside down at the top of the loop?" The initial prompt was intended to allow students to talk for an extended period, without interruption, in order to present their initial ideas in that context. The interviewer developed some probes in the moment, to respond to facets of the participants' initial argument. Often these might involve: asking for greater detail, probing areas of inconsistency, or eliciting underlying assumptions. A list of the pre-determined questions asked in each scenario is given in Appendix 8.7.2. For this research, two broad conceptual areas, dynamics and electricity, were chosen to be the focus of the interviews. These areas were chosen as both presented a number of situations (for example, instances of simple harmonic motion or direct current resistive circuits) in which the same underlying principles could be applied across a range of situations with surface differences (Chi et al., 1981).

4.4.1.2 The naturalness of the approach

Naturalistic inquiry 'focuses on how people behave when they are absorbed in genuine life experiences in natural settings' (Frey, Botan, & Kreps, 1999, p. 257). Several researchers draw a distinction between 'classroom and laboratory' settings (A. L. Brown, 1992; Maki & McGuire, 2002; Sheen, 2008). Laboratory settings have been assumed to possess the advantage of greater, though not complete, control of

variables; hence, they allow stronger claims to reproducibility and validity to be made (Berkowitz & Donnerstein, 1982; Brewer, 2000). Alternatively, research in naturalistic settings may be seen to have greater external validity than laboratory studies as naturalistic research is more likely to resemble commonly occurring situations (Gilliland & Chan, 2000; Wilson, Aronson, & Carlsmith, 2010). However, these assumptions are somewhat simplistic and therefore contested (Anderson & Bushman, 1997). For example, there is no reason to suppose a trade-off between internal and external validity (Jiménez-Buedo & Miller, 2010). As Brown (1992) has argued, both types of settings can provide research advances. This research could then be conceptualised not as a series of clinical interviews, but, rather, as recordings of quasi-naturalistic interactions (Lincoln & Guba, 1985), that resemble, to some degree, typical one-to-one student-teacher interactions.

4.4.2 Think-aloud protocols

Though it is sometimes assumed, both explicitly and in the choice of language researchers use, that spoken utterances can give direct reports of cognition, the reality is more nuanced (Taber, 2013). For example, the think-aloud protocols developed by Ericsson and Simon (Bernardini, 2002, p. 242) have been described as ‘a very direct method to gain insight into the knowledge and methods of human problem-solving’ (Somerén, Barnard, & Sandberg, 1994, p. 1) and as a ‘...way of accessing rich information that is unattainable through other means’ (Ku & Ho, 2010, p. 255). However, the relationship between reports of cognition and cognition itself is not simple: as early as 1830, Comte (quoted in Vermersch, 1999, pp. 18–19) argued ‘[t]he thinking individual cannot split himself [sic] in two’ to observe their own cognition, and therefore the method of introspection was ‘radically faulty’.

More recently, Nisbett and Wilson (1977) pointed out there was little evidence that people are capable of commenting accurately on their own cognitive processes. Moreover, the processes of cognition are unlikely to be easily expressible in language (Nielsen, Clemmensen, & Yssing, 2002). When asked to think-aloud whilst performing a task, some participants reported that:

...they think faster than they can speak...and that thinking
aloud interferes with their interaction with the interfaces and

the task...they felt they were being observed, evaluated and judged and that it influenced their performance. (Nielsen et al., 2002, p. 102)

The contention that thinking aloud affects performance is contested; for example, Ku and Ho (2010) report evidence that students' performance was not affected by thinking aloud. Think-aloud protocols are accepted by a large part of the psychological community, and have been in use in a variety of different research programmes (Branch, 2000). The extent to which verbalisation affects cognition is likely to be variable, and to depend on the nature of the task, the particular verbaliser and other factors. The data from this investigation are presented as artefacts of the interview process, that is, as a representation of cognition whilst verbalising. In the spirit of analytical generalization (Taber, 2000a), the onus will be left to the reader to decide the extent to which verbalisations may be extrapolated to cognition in other situations (see Appendix 8.6 for a sample interview transcript). The technique was described to the students before the start of the first interview, and they were given the opportunity to practice the technique (Liu & Li, 2015).

4.4.3 Concept maps

The concept map may be seen as a tool that provides insights into a person's interpretations of the relationships between concepts (Nesbit & Adesope, 2011). It is, therefore, an appropriate tool for understanding how students develop conceptual compounds. In particular, concept maps are capable of reflecting the 'interconnectedness' and 'fuzzy overlap' between concepts (Carley & Palmquist, 1992, p. 603), a good match for the model of the concept described in section 2.1.2. Concept mapping is a poorly-defined technique, and multiple methodological approaches exist (Carley & Palmquist, 1992). For this work, a rather general definition of a concept map as 'a network that includes nodes... linking lines and linking phrases which describe the relationship between nodes' (Yin & Shavelson, 2004, p. 3) is used to allow students as much representational freedom as possible.

Much research data show the valuableness of concepts maps for representing cognitive development (Novak & Musonda, 1991), and concept maps have been used for a number of different purposes in educational research, including: to compare

'expert' and 'novice' students' knowledge (Chi et al., 1988), to track changes in knowledge (Novak & Musonda, 1991; Pearsall, Skipper, & Mintzes, 1997), and to identify misconceptions (Gonzalez, 1997; Regis et al., 1996). Though it has been argued that a single concept map does not capture dynamic behaviour (Liem, Beek, & Bredeweg, 2010), a map might be pragmatically conceptualised as capturing a static interval in the progression of cognition. Several studies (Francisco, Nakhleh, Nurrenbern, & Miller, 2002; Hay, 2007; Novak & Musonda, 1991; Pearsall et al., 1997; Roth & Roychoudhury, 1993) have used two or more concept maps, created at intervals, to examine developments in learning. In the studies cited above, the interval between concept maps ranges from one week (Hay, 2007) to one year (Novak & Musonda, 1991).

A choice was made to use 'non-hierarchical' (Nicoll, 2001, p. 867), or 'student-generated' concept maps (Schau, Mattern, Zeilik, Teague, & Weber, 2001, pp. 137–138) in which students are free to choose the concepts and type of structure in their concept maps, allowing the students to create unique and idiosyncratic representations of their understanding. Such 'non-hierarchical' or 'network' concept maps are recommended for topics, such as the ones in this study, that do not have an obvious hierarchy (Nicoli & Mortimer, 2014; Shavelson, Lang, & Lewin, 1994). Students were asked to create non-hierarchical concept maps of the same topic on a number of occasions (see Table 4.2), and inferences were drawn from changes in the represented concepts and relationships. Before the construction of their first concept map, the students were introduced to the process, and drew a practice concept map.

4.4.4 Concept ontology table

Relatively few measures exist to develop representations of students' ontology in science education. Mariani and Ogborn (1991, 1995) used questionnaires in which students were asked to indicate which properties (for example, 'is immaterial', 'has a real existence', 'causes movement') they believed were associated with scientific concepts. Alternatively, the interviews-about-instances approach might be thought of as providing representations of students' ontologies (Osborne & Gilbert, 1979). Mortimer and colleagues used surveys and interviews to develop representations of students' conceptual profiles, that is, the totality of approaches a student possess for interpreting a concept (Mortimer & El-Hani, 2014). In this research, a novel prompt

to stimulate the discussion of the nature of concepts was developed for the major concepts in dynamics and electricity (shown in Table 4.3) and was applied in interviews number 14 and 22 (dynamics) and 19 and 21 (electricity). The tools were developed based on a number of reported ontological alternative conceptions possessed by students: force causes motion (Viennot, 1985), force is a property of an object (Dykstra et al., 1992), current is ‘used up’ (Shipstone, 1984), there is no connection between potential difference and the flow of current (Periago & Bohigas, 2005), and voltage and current are conflated, suggesting voltage may flow (Shipstone, 1984).

Table 4.3: Ontology tables.

a) Dynamics

	Force	Velocity	Energy
What does it cause?			
What causes it to change?			
How would you use this term in a sentence?			
Is it a property an object posses?			
Can an object possess this concept in multiple values?			
Does it have multiple types?			

b) Electricity

	Current	Potential Difference	Resistance
What is this concept?			
What causes it?			
Is it a property of a component?			
Is it used up in a circuit?			
Is it conserved?			
Is it measured at a single point?			
Does it flow?			

4.4.5 Card sorting

The ranking of concepts has been an established technique in research since Stephenson's (1953) Q-sorts and Kelly's (1955) repertory grid tool. In general, sorting techniques are useful for examining constructs of categorisation and are quick and easy to use (Rugg & McGeorge, 1997). Two card sorts were developed, based on the technique used by Chi, Feltovich and Glaser (1981), in which the participants were asked to sort a set of situations and a set of problems (see Appendices 8.7.3.1 and 8.7.3.2) into categories by similarity, then to explicitly state the nature of the categorisation developed. This approach was used in interviews 12 and 16. A sorting activity based around categorising concepts as causes or effects (see Appendix 8.7.3.3) was used in interviews 11 and 20 and, though the tool was difficult for students to engage with, prompted some interesting comments that are reported in the analysis of students' ideas on causality (see section 5.2.3).

4.4.6 Personal ontology questionnaires

As has been discussed (see section 2.4.1.4.3), students' beliefs about the nature of knowledge, 'personal epistemologies' (Hofer, 2001) may have an impact on the manner in which learning occurs. Therefore, a sub-set of prompts related to personal epistemology from the Colorado Learning Attitudes about Science Survey (CLASS) (Adams et al., 2006) was used as a basis for discussion in interview four. A sub-set was chosen as time was limited, and an open-ended discussion was preferred over the application of a survey. The questions, which are listed in Appendix 8.7.4, were chosen as they were felt to be relevant to the conceptualisation of making sense.

4.5 Recording and Transcription

All interviews were recorded using a digital audio recorder and transcribed by the interviewer, typically within a few days of completion. This allowed themes arising in one interview to be followed up in the next, thus enabling analysis and data collection to proceed in parallel (Merriam, 2009). However, transcripts do not represent a complete and 'true' record of the interview: the process is dependent on the decisions of the transcriber (Miles & Huberman, 1994, p. 51). Transcribing is an interpretive process, as a researcher makes decisions about which information should be included and excluded (Kvale, 2007), which are channelled by the researcher's assumptions (Green, Franquiz, & Dixon, 1997). In a constructivist frame, the transcripts are not a

direct reflection of a person's thinking, or even a complete record of the conversation, but rather a social construct, mediated by the participants, the context and the data collection tools (Smagorinsky, 1995). As case study research is premised on developing a detailed description of a particular individual (Ragin, 1992; Stake, 1995), in this research, as far as possible, verbatim transcripts were produced. Therefore repeated words, verbal stumbles and pauses are included in the students' transcripts (Kvale, 2007). Where students made gestures that were interpreted to be relevant to their argument, for example, indicating a point on the apparatus or diagram (see Appendix 8.6, utterance 12), these have been included in square brackets (Powers, 2005). The transcripts were divided up into utterances, units of 'spoken interaction', which were numbered to allow reference to specific parts of a transcript (Lankshear & Knobel, 2004). The division of transcripts into utterances is seen as an interpretive process, and a new utterance was taken to begin when a significant (i.e. meaningful) communication was made by a previously silent speaker.

4.6 Making claims about the data

Maintaining rigour in qualitative research is challenging, and multiple approaches exist (Creswell & Miller, 2000; Lincoln & Guba, 1985; Maxwell, 1992). Various researchers have argued that the concepts of quantitative research such as validity and generalisability are not appropriate for qualitative work (Guba, 1981; Lincoln & Guba, 1985; Merrick, 1999). Consequently, a variety of substitute terms for supporting rigour in qualitative research have been proposed: authenticity (Lincoln & Guba, 1986), credibility (Guba, 1981), plausibility (Hammersley, 1993) transferability (Guba, 1981) and trustworthiness (Lincoln & Guba, 1986), to name just a few. A review of types of validity alone identified at least eight distinct constructs (Altheide & Johnson, 1994). The strategy of developing 'parallel criteria' in qualitative research to mirror those in quantitative has been called 'defensive and limited given it's reliance on quantitative terms' (Merrick, 1999, p. 27); however, following the argument of LeCompte and Goetz (1982) and Merriam (1995), as the terms reliability and validity are widely understood, they are adopted in this thesis, though they are defined in a manner that fits with a constructivist project.

4.6.1 Validity

Validity has been defined in numerous ways (Altheide & Johnson, 1994); but, it may be thought of as the extent to which ‘the features ascribed to the phenomena being described are actually held by those phenomena, and perhaps also whether they are possessed to the degree indicated’ (Hammersley, 2007, p. 44); or, to put it another way, validity measures the extent to which explanation can be supported by the data (Cohen, Manion, & Morrison, 2007). In qualitative research there are no defined procedures for supporting validity (Maxwell, 1992); rather, validity criteria need to be situated in a particular theoretical tradition (Creswell & Miller, 2000). In realist constructivist research, it is assumed personal constructs are tested by interaction with reality (Gilbert & Swift, 1985), and therefore, the naturalistic conception of validity measures the closeness of fit between theoretical propositions and respondents’ and researchers’ representations (Guba, 1981). Numerous strategies for increasing validity in qualitative research have been suggested:

Triangulation: The validity of a claim is strengthened if multiple sources of evidence are used to support an assertion (Baxter & Jack, 2008, p. 556; Guba, 1981, p. 87; Shenton, 2004, p. 65). The triangulation in this study can be thought of as between-methods triangulation (Denzin, 1978, p. 301), an approach which argues that convergence between methods ‘...enhances our belief that the results are valid and not a methodological artifact’ (Bouchard, 1976, p. 268). A range of different methods were used, including think-aloud protocols, concept maps, interviews about instances and card sorts, to support the validity of the construction of claims to making sense.

Clear Statement of theoretical positions: As qualitative research is open to a plurality of theoretical frameworks, validity is judged within the philosophical positions of the particular research (Creswell & Miller, 2000). Therefore, if a reader is to make a judgement of validity, a clear statement of underlying assumptions is required (Creswell & Miller, 2000; Guba, 1981; Mauthner & Doucet, 2003). The methodology section clearly outlines the assumptions of this work.

Rich Description: Presenting lengthy quotations in the participants’ words is a strength of qualitative research and a key to securing validity (Creswell & Miller,

2000; Onwuegbuzie & Leech, 2007). Verbatim quotation allows readers to form their own judgements about the validity of conclusions, and ensures the participants' voices are represented as faithfully as possible (Corden & Sainsbury, 2006). This research makes use of extended verbatim quotation.

Prolonged and persistent engagement: The extended application of microgenetic sampling used in this study led to prolonged and persistent observation of students, ensuring an 'adequate representation' of learning was developed (Onwuegbuzie & Leech, 2007, p. 239). The high density of observation in the microgenetic approach may increase validity by avoiding the misrepresentation of change that may occur with the 'snapshots' produced by longitudinal methods (Granott & Parziale, 2002, p. 11).

Ecological validity: 'laboratory' settings, in which it is claimed variables are tightly controlled, may include conditions that are unrepresentative of 'natural' situations (Bracht & Glass, 1968; Bronfenbrenner, 1976). Hence, validity may be increased by setting research in conditions that are similar to normally occurring situations (Bronfenbrenner, 1976). The kind of interaction between researcher and participant in this research, which involves dynamic probing of the student's ideas, is argued to resemble typical teacher-student interaction, and therefore have some degree of ecological validity.

Using extreme cases: The strength of a conclusion may be supported by checking if it holds even in extreme cases (Miles & Huberman, 1994; Onwuegbuzie & Leech, 2007). Students who regularly and rarely displayed sense-making strategies were selected based on discussions with teachers. It is hoped that the examination of such extreme cases will support the model of making sense presented.

4.6.2 Reliability

Exact replicability cannot be expected from human behaviour (Merriam, 1995); therefore, the concept of reliability, which is nonetheless challenging to achieve, is applied to qualitative research (LeCompte & Goetz, 1982; Merriam, 1995; Seale & Silverman, 1997). Reliability may be judged against different criteria: internal reliability is judged by the extent to which multiple observers would agree within a

single study (LeCompte & Goetz, 1982); external reliability is a measure of the extent to which independent researchers might construct the same interpretations in the same or similar settings (LeCompte & Goetz, 1982). Given that a constructivist interpreter might expect the possibility of multiple constructions of one data set (Merriam, 1995), agreement between researchers is not necessarily a goal of constructivist research; indeed, interpretive pluralism has been proposed as an aim of the programme (Feyerabend, 1975; Geelan, 1997). An alternative construction of reliability is Guba's (1981, p. 86) notion of dependability in which researchers strive for 'stability of data,' a concept which suggests researchers should not expect invariance in data, but rather adopt a sensitivity to possible instabilities due to different interpretations of the data. The dependability of a study is therefore enhanced by the use of multiple sources of data and the establishment of a clear 'audit trail' (Guba, 1981, pp. 86–87). The high density of sampling and extended period of observation has allowed some distinction to be drawn between stable and unstable elements in the data (see Section 5.2.5).

4.6.3 Generalisability

Generalisability may be defined as 'the extent to which one can extend the account of a particular situation or population to other persons, times, or settings than those directly studied' (Maxwell, 1992, p. 293). A common criticism of small-scale research is that it lacks generalisability (Flyvbjerg, 2006, p. 221; Merriam, 1995), and some researchers argue the concept ought to be discarded in such research. Denzin (1983, p. 133) claims interpretivists 'rejects generalisation as a goal', and Guba and Lincoln (1982, p. 238) argue '[g]eneralizations are impossible since phenomena are neither time- nor context-free'. However, Williams (2000, p. 210) argues such denials are disingenuous because interpretive research tends to make or imply 'generalizing statements' without providing justifications for the contexts to which extrapolations can be made.

As an alternative to the rejection of generalisability, researchers have adapted the quantitative concept to qualitative research. For example, Kvale (1996) and Taber (Taber, 2000a), proposed the idea of analytical generalisation, a 'reasoned judgment about the extent to which the findings from one study can be used as a guide to what might occur in another situation' (Kvale, 1996, p. 223). Qualitative notions of generalisability may be more contextual and nuanced than the quantitative version:

Guba's (1981, p. 81) 'transferability' indicates a generalisation that is not expected to apply in all times and all places, but, rather, a 'working hypothesis that may be transferred from one context to another'. Other reinterpretations of the concepts include: moderatum generalisations (Williams, 2000), fuzzy generalisations (Bassey, 1999) and naturalistic generalisations (Stake, 1978). In such constructions of generalisability 'the validity of the extrapolation depends not on the typicality or representativeness of the case but upon the cogency of the theoretical reasoning' (Mitchell, 2006, p. 39), and the onus is on the reader to 'judge the soundness of the generalization claim' (Kvale, 1996, p. 233). A requirement of qualitative research therefore is that sufficient, rich data is presented to allow the reader to draw their own conclusions regarding generalisations (Taber, 2000a). Therefore, no specific claims are made regarding the contexts in which the findings of this research might apply, though section 4.4.2 has discussed the extent to which the methods used might resemble typical situations, and the onus is on the reader to judge how the findings of the research may transfer to other circumstances.

4.7 Ethical considerations

Ensuring research is ethical is an important and necessary part of data collection (Laine, 2000; Soltis, 1989). Informed consent is amongst the most central of ethical principles (BERA, 2011; Howe & Moses, 1999; Yin, 2009). Therefore, the nature of the research was explained to the participants in the pilot and main study, and an information leaflet was given to participants, their parents, and the headteacher of the school (see Appendix 8.4). The right to withdraw at any stage of the research was made clear to participants (BERA, 2011), as outlined on the consent forms (Appendix 8.5). Privacy is an intrinsic component of human dignity (Howe & Moses, 1999); therefore, the confidentiality of students' identities and data must be safeguarded (BERA, 2011; Yin, 2009). As per the BERA ethical guidelines (2011), data will be held according to the regulations in the Data Protection Act (1998). Participants are identified by pseudonyms and transcripts were edited to ensure that individuals could not be identified from the extracts quoted (Grinyer, 2009).

Whilst I was not concurrently a teacher of the participants during the research process, that I had taught the students in earlier years, and retained the role of a member of staff at the school, raised 'ethical tensions' (BERA, 2011). In particular,

for the teacher/researcher, there may be a conflict between observation and promoting change in interactions with students (Wong, 1995). However, the adoption of a dynamic testing approach, in which assessment and feedback are intertwined (Grigorenko & Sternberg, 1998), reduced the tension, as the aims of the teacher and researcher role overlap to a greater extent than in traditional static testing research. However, working with students in one's own institution raises concerns about the manner in which the imbalance of power in the relationship may cause students to give the answers they feel are expected of them (Tight, 2012). This effect might be assumed to be less significant in work which focused on learning about science rather than opinions about an institution, though the nature of the relationship between the researcher and participants may have affected the students' choice to participate, and continue participating, in the research.

The use of the microgenetic approach raises particular ethical issues: repeated interviewing can lead to boredom and reduce motivation (Flynn et al., 2006). Richards and Schwartz (2002) claim the inconvenience and costs involved in participating in in-depth interviews are often underestimated. Therefore, interviews should be considered 'gifts' from the participants (Limerick, Burgess-Limerick, & Grace, 1996), and researchers have responsibilities to those they interview 'in terms of both the time and mental exertion' asked of them (Taber, 2008a, p. 1922). The British Educational Research Association Ethical Guidelines require that researchers do everything possible to reduce a sense of intrusion, and that they eschew practices that will cause emotional or other forms of harm (BERA, 2011). As has been discussed, the dynamic testing approach provided students with structured feedback which gave opportunities for learning and the students generally experienced the process as a positive learning opportunity (see Section 5.3). Ethical research requires an 'equitable distribution of benefits and burdens' (Kahn, Mastroianni, & Sugarman, 1998, p. 2), and it appears that the participants perceived the sessions as to their benefit, which, to some extent, mitigated the burden of microgenetic interviewing (see Appendices 8.2 and 8.3 for the Faculty of Education's ethics checklist and risk assessment form).

A final ethical consideration is that the theoretical construction developed by the researcher sufficiently represents that of the participant (Bressler, 2002; Karnieli-Miller, Strier, & Pessach, 2009). The autonomy of participants should be respected, as Taber and Student (2003) argue that a valid representation of the voice of the participant in research is both a methodological and ethical imperative. It is hoped that the use of extended verbatim quotation goes some way to meeting this aim.

5.0 Data and analysis

The discussion of themes emerging from the analysis of the data is organised around the six sub-questions related to the concept of making sense (see Figure 5.0).

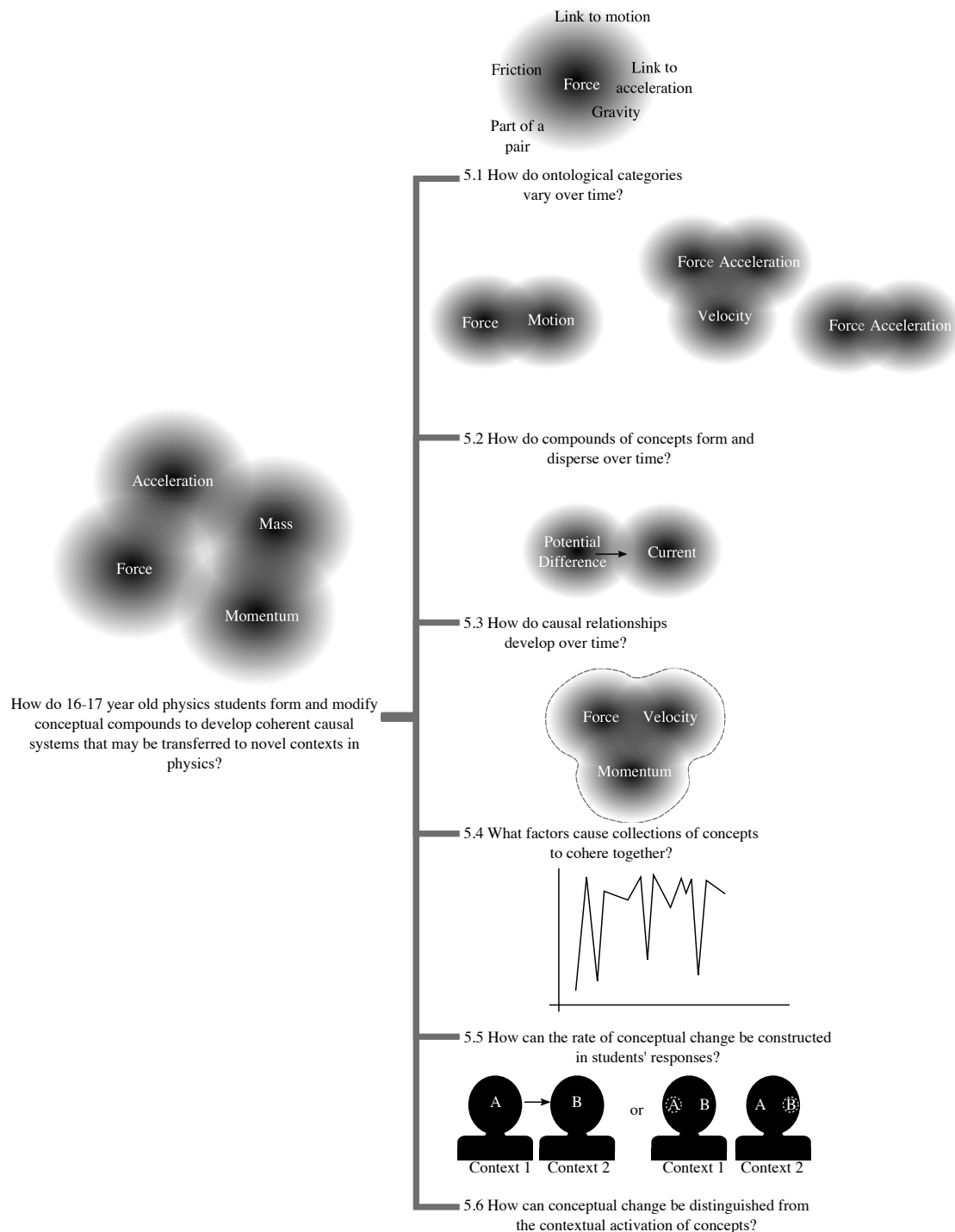


Figure 5.0: A representation of the six themes of analysis

In this section, all quotations from students' transcripts, both those quoted verbatim and those paraphrased, will be labelled with the number of the session in which they occurred, then with an utterance number. For example, (Ben, Session 1, 17), refers to utterance number 17 in the transcript of session one.

5.1 Methods of analysis

There is no single correct way of analysing qualitative data: multiple approaches exist (Coffey & Atkinson, 1996; Marton & Säljö, 1997; Onwuegbuzie & Leech, 2007); though, typically, analysis will focus on theory building rather than theory testing (Eisenhardt & Graebner, 2007). It is expected that different researchers would develop individual interpretations of the same data (Frost et al., 2010), and that a single researcher could construct multiple understandings of the same information (Taber, 2008c). Therefore, a researcher has a duty to explicate the choices and principles underlying their analysis of data (Mays & Pope, 1995; Patton, 1990). This requirement is challenging, as the development of themes will, to some extent, depend on 'hunches' or a 'felt sense' (Cutcliffe & McKenna, 1999, p. 377), which the researcher must explicate. Lincoln and Guba (1985, p. 319) argue researchers should produce an 'audit trail' that explains how analyses were developed in order that readers may argue with the conclusions (Ryan & Bernard, 2003). The adoption of a particular approach to analysis carries with it epistemological, ontological and theoretical assumptions (Mauthner & Doucet, 2003), and a researcher must make a case for the fit between these assumptions and the rest of the work.

Within constructivist research, qualitative data analysis can be seen as a method of making sense of data (Caudle, 2004; Elo & Kyngäs, 2008). Data are not inherently organised or meaningful (LeCompte, 2000); therefore, the process of data analysis is an active process of meaning development (Hatch, 2002). It is interesting to note the parallels between some of the suggested processes of qualitative data analysis, for example, 'synthesis, evaluation, interpretation, categorization, hypothesizing, comparison, and pattern finding' (Hatch, 2002, p. 148), and those suggested for the process of making sense (see Figure 1.1). Just as with making sense, analysis is described as a search for patterns (Yin, 2009), or a construction of 'meaningful' groupings (LeCompte, 2000, p. 150) with the aim of developing 'coherence' (Miles & Huberman, 1994, p. 62). Though the processes of making sense of data may be, to

some extent, opaque in the context of discovery (Reichenbach, 1938), the researcher should present a transparent case for their analysis in order that readers may evaluate the route taken to the conclusions reached.

In this research, it would be incorrect to suggest that no conceptualisation occurred before analysing the data (Strauss & Corbin, 2008), or that the categories of analysis entirely pre-existed data collection, as might occur in the positivist tradition, which favours hypothesis testing (Punch & Oancea, 2014; Taber, 2007). Rather, the categories developed were channeled both by the researcher's interpretation of the data and by his reading of the literature. In some models, analysis is conceptualised as occurring at two levels: First, the data is sifted, and meaningful units are labelled or given 'codes' (LeCompte, 2000, p. 418; Leech & Onwuegbuzie, 2007, p. 565; Strauss & Corbin, 2008, p. 101). Codes 'are tags or labels for assigning units of meaning to the descriptive or inferential information compiled during the study' (Miles & Huberman, 1994, p. 56), which may be attached to 'chunks' of data of varying sizes, from single words to larger collections of utterances. In the second stage of analysis, the coded units are themselves organised into groups (LeCompte, 2000; Strauss & Corbin, 2008). The transcripts were subject to a preliminary analysis each week in the interval between interviews. This allowed the researcher to respond to emerging themes in subsequent interviews. This initial analysis occurred across two dimensions: a) students' use of major concepts such as force and potential difference; and b) emerging themes, for example, 'understanding of causality' (see Table 5.0).

Table 5.0: Illustration of process of analysis of changes in students' concepts and emerging themes (numbers refer to the session and utterance).

Amy				
Concept of force	Session 1; 56 Argues heavier ball takes less time to fall due to greater force	Session 1; 80 Links zero resultant force with constant velocity for parachutist	Session 1; 80 Links acceleration with action of resultant force	Session 1; 56 Argues lorry exerts more force on car than vice-versa in crash
Concept of acceleration				

Amy				
Rate of conceptual change	Session 1; 34-40 Describes moment of sudden conceptual change	Session 2; 229 Appears to have moment of sudden conceptual connection	Session 2; 261 Connecting force and acceleration leads to clarity	Session 2; 271 Noticing period is independent of mass for pendulum leads to clarity
Causality	Session 2; 126 Describes a causal link between energy and motion	Session 2; 130 Describes weight as causing motion	Session 2; 130 Changing tension is seen as causing changing velocity	

Once all the interviews were completed, the second phase of analysis began. For each of the six emergent themes (the development of conceptual categories, the formation of conceptual compounds, understanding of causality, the development of coherence, the rate of conceptual change, and the relationship between conceptual change and transfer), I returned to the transcripts and re-coded the data to describe change over the course of the sessions and to examine commonalities between students. This process typically took several iterations and continued until a perception of theoretical saturation was reached. This process reflects the two stages of analysis described by a number of authors (Miles & Huberman, 1994; Mills, 1959; Saldana, 2009): a process of coding followed by categorisation of codes into groups. Further details of the codes used are given in the relevant subsections of the analysis chapter.

Qualitative data analysis could go on indefinitely (Merriam & Tisdell, 2016) and some indicator of completeness is required. In this work, the condition of theoretical saturation, that is when ‘no additional data are being found [to] . . . develop properties of the category’ (Glaser & Strauss, 1967, p. 61) was taken as the goal. A similar concept was described by Lincoln and Guba (1985, p. 202), who proposed ‘selection to the point of redundancy’, in which ‘sampling is terminated when no new information is forthcoming from newly sampled units’. However, determining when saturation or redundancy has occurred is subjective: as Bowen (2008, p. 138) observes, ‘Explicit guidelines for determining saturation are almost non-existent’. As the end point of research is subjective, a researcher might be expected to hold their conclusions ‘lightly, maintaining openness and scepticism’ (Miles & Huberman, 1994, p. 11), but the onus rests on the researcher to provide justification for claims of theoretical saturation (Bowen, 2008).

5.2 Themes arising from the data

5.2.1 The formation and modification of conceptual categories

The concept of force and its relationships to other concepts was chosen as the focus of ontological analysis as it is a concept which has been reported as causing ontological challenges for students (Brookes & Etkina, 2009; Dykstra et al., 1992; Hestenes et al., 1992); and, in the students' transcripts, the concept was invoked in a large number of utterances coded for ontology. In order to develop a valid picture of students' changing understandings of ontology, the eleven sessions covering forces and dynamics were divided into two blocks of five consecutive sessions- sessions 1-5 sessions 11-16; and session 22- the final interview. It is expected that a representation of a students' ontology will require assessment through multiple probes, as ontologies are multi-faceted and contextually sensitive (Gupta et al., 2010). Therefore, change will be constructed between two blocks of five sessions and a final interview, considered to be static intervals (see section 4.3.2.3). It is reported that changing the ontology of a concept is challenging (Chi, 1992, 2013); therefore, it is assumed that ontologies change gradually and that a static interval covering several weeks will be a suitable match for the rate of ontological change. Approximately two months elapsed between the end of first and start of the second static interval, and just under two months between the second and third intervals. Any utterance in the students' transcripts that referred to their understanding of the nature of concepts was labelled with an ontological code. These codes were subsequently sorted into the three themes: differentiation, clustering and instance/abstraction.

The next two subsections present two case studies of the development of ontology in students who were selected as extreme cases: I judged Ben's categorisation to have shown the greatest variation out of the students, whereas Daniel's ontology displayed the least change over the period of observation. A significant assumption of this analysis is that students' ontologies may be understood through their use of language. This is a common assumption for research into ontology: Brookes and Etkina (2007, 2009) argue grammatical structures can give insight into categorization, and Chi and colleagues (Chi, 1992; Chi et al., 1994; Slotta et al., 1995) argue students' use of predicates, for example, the verb applied to a concept (e.g., force 'flows' or 'moves') can indicate ontological assumptions. This approach is adopted in this thesis, and

inferences about the nature of students' ontologies are made from their responses to probes. Note that, in the discussion below, the descriptions of students' ontology are conceptualised as representations constructed by the researcher.

5.2.1.1 Changes to Ben's ontology

The next subsections consider the development of Ben's ontology across the three themes of development proposed in the literature review: differentiation of categories, clustering of conceptual members and the transition from situated to abstracted representations.

5.2.1.1.1 Changes to Ben's differentiation of concepts

In his first session, Ben displayed evidence of a relatively undifferentiated motion category linked to the concept of force. On two occasions, in the context of a lift and a ball falling after being projected horizontally, he linked force to the idea of motion:

Therefore for the lift to move up the force pulling on it must be greater. (Ben, Session 1, 128)

...the only force acting on the ball when the ball is dropped is a downwards force so it would just move downward. (Ben, Session 1, 106)

However, as Gupta and colleagues' (2010) model suggests, Ben possesses multiple versions of the concept of motion. In the same interview, in a discussion of an object in free fall, Ben displays evidence of two distinct motion categories: acceleration and velocity.

...it will accelerate by 10 meters per second squared, um, however, as it increases in its velocity, the air resistance will increase, and because the air resistance will increase, eventually the air resistance will cancel out the gravitational force, and so due to Newton's, I think it's first law, the ball will carry on at a constant speed, and reach its terminal velocity. (Ben, Session 1, 76)

The case of a free-falling object was covered in the curriculum Ben studied in the previous year; therefore, as Gupta and colleagues (2010, p. 286) suggest, Ben's use of ontology may be contextually triggered: in the case of vertically free-falling objects, he can access scientific ontologies; but in the contexts of the lift and the ball with horizontal and vertical components of velocity, a less differentiated ontology is triggered.

In Ben's fifth session, there is further evidence of blurred boundaries between categories. In describing the oscillating motion of a ball in a bowl, Ben argues: 'because the, er, velocity and the, um, force of the gravity will be equal so it won't be going anywhere' (Ben, Session 5, 88), implying some sense of equivalence between the categories of force and velocity. This perhaps relates to the compound Ben has used on a number of occasions, that force and velocity are linked; for example, 'so you change its velocity you change its resultant force' (Ben, Session 5, 86). In a later series of utterances, this blurring reoccurs; though Ben, when prompted, makes a clear distinction between force and velocity. In the excerpt below, Ben is describing the resultant force acting on a ball when it is displaced to one side of a concave bowl:

- I: Which way would you expect the resultant force to be?
- B: Er this way [adds diagonal line down to the right] so...
- I: Yeah?
- B: Forty-five degrees below the horizontal.
- I: Where does that come from?
- B: Um [pause] um [pause] is it the ball's velocity.
- I: Is velocity the same as force?
- B: No. I was just thinking about vectors.
- (Ben, Session 5, 113-120)

In the second static interval, Ben shows a more consistent activation of clearly defined concepts of force, acceleration and velocity, for example:

I think force is something that causes something to accelerate. (Ben, Session 13, 30)

Force causes objects to move I would, um, I would there, write, I would add accelerates here because to differentiate between force and velocity. (Ben, Session 14, 387)

However, Ben displays a weak discrimination of force from other concepts. When asked to draw a Venn diagram representing the overlap of the concepts of force, momentum and energy (Figure 5.1), he constructs the concepts as almost entirely overlapping arguing: ‘they all essentially boil down to the concept of energy’ (Ben, Session 13, 247).

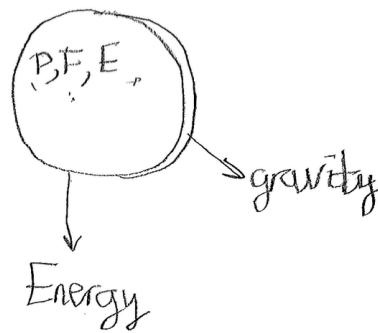


Figure 5.1: Venn diagram of the overlap between momentum (P), force (F) and energy (E) (Ben, Session 13, 239).

In the next session, Ben (Session 14, 349) suggests that ‘force pushing objects’ and momentum are ‘almost exactly’ the same thing. He argues forces are agents that ‘...tend to cause some form of order or regularity’ (Session 14, 76) because, for example, the electromagnetic force tends to cause a uniform distribution of electrons and gravity causes objects to sink to the same point. He draws a clear distinction between the object a force acts upon and the force itself (Session 14, 301-303), and argues forces emanate from objects but objects are not required for the existence of forces. Though there is evidence of development of the differentiation of Ben’s category of motion, there remain blurred boundaries between force and the concepts of energy and momentum.

5.2.1.1.2 Changes to Ben's conceptual clustering

Ben, in early sessions, had a tendency to group types of force together by the contexts in which he has encountered them. In session five, he drew the concept map shown below (Figure 5.2)

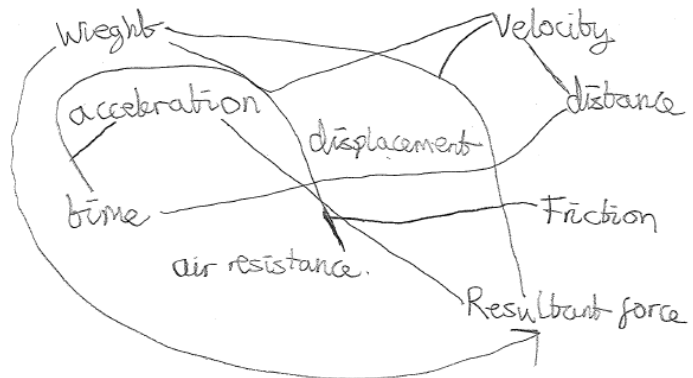


Figure 5.2: Ben's first concept map related to forces and motion (Session 5).

Ben constructed a cluster consisting of weight and air resistance, because he perceived them as opposing each other:

I would probably link air resistance and friction to gravity, weight, because sometimes they oppose or at least acting in different directions. (Ben, Session 5, 86).

Though Ben linked weight with resultant force, neither air resistance nor friction are seen as related to net force. This may be because, in the case of a falling object, weight acts in the same direction as the resultant force and air resistance does not. Ben described that, in free fall, as air resistance increases, '...so the resultant force with the weight is less' (Ben, Session 5, 86), indicating an association between weight and resultant force. Ben's concept of force seems to be relatively fragmented due to an implicit understanding that different types of forces fulfil different roles.

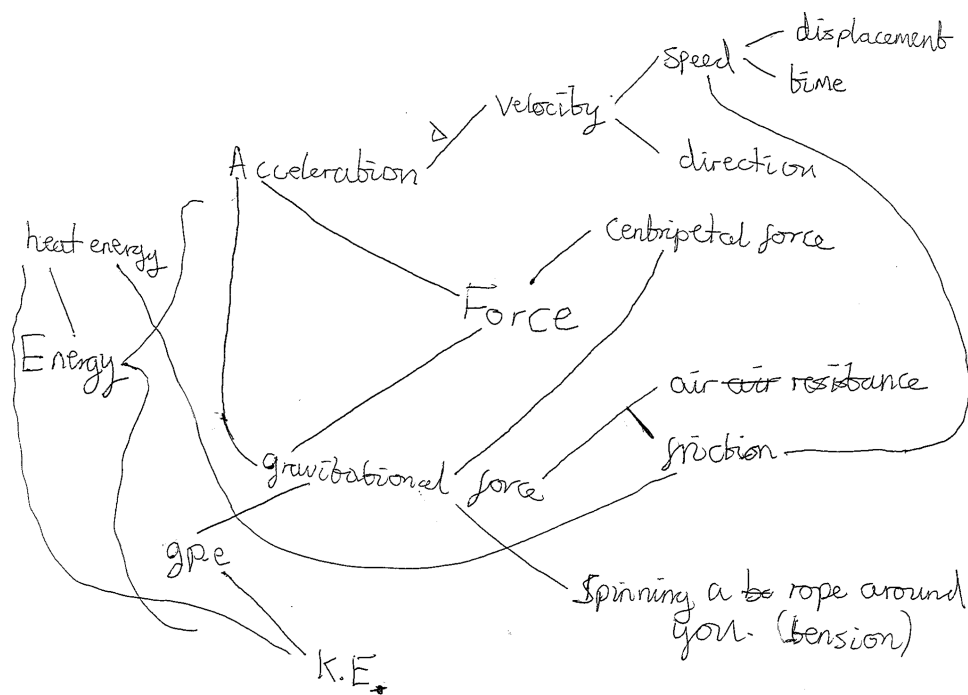


Figure 5.3: Ben's second concept map related to forces and motion (Session 15).

In later sessions, there seemed to be some tendency towards greater integration of the concepts of force under a single unifying category. In Figure 5.3, gravitational force and centripetal force are linked directly to the concept of force. However, perhaps due to the contextual nature of Ben's understanding, as he explained below, tension, friction and air resistance are linked to gravitational force. Ben argued that the common occurrence of certain forces in the classroom can make them appear more typical than others:

Um, and then I think acceleration, probably, because I'm most used to acceleration being linked to gravity, the gravitational force, because again acceleration mainly occurs in, at least for physics we're doing, where things are falling...So we're mainly concerned with gravitational force, we're very, very rarely concerned with air resistance apart from terminal velocity. (Ben, Session 15, 40-46)

Ben went on to comment that both air resistance and friction are often deliberately ignored in questions, which might explain his perception that the two forces are more weakly linked to acceleration than the gravitational force.

In session 16, Ben was asked to reflect on and annotate the concept map he had drawn in session 5 (the annotated version is shown in Figure 5.4). Ben indicated some increase in the clustering of his concept of force.

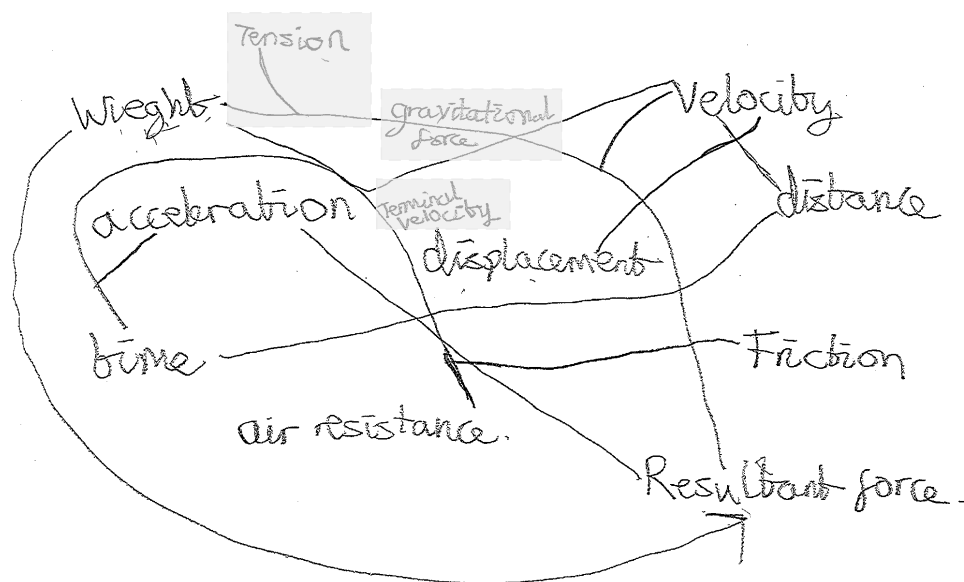


Figure 5.4: Ben's annotated concept map (Session 16). Annotated entries are shown in light grey rectangles.

Ben argued he 'was quite hasty to link weight with resultant force', because resultant force links to other ideas as well' (Ben, Session 16, 122). However, he appeared to retain some sense of differentiation between the actions of different types of forces:

- I: So you'd still link weight to resultant force?
- B: Yes, but via the gravitational force, in the sense that, that is, almost saying the resultant force is directly determined by the weight or vice-versa... Rather the weight is determined by the gravitational force, and then the weight causes the resultant force. (Ben, Session 16, 122-128)

In addition, Ben saw tension as an effect of force; therefore, tension appears more peripherally on the map: 'I think on a separate branch to weight I think I would put tension [writes] because tension at least in general scenarios is caused by weight

exerting a force on something and it having to produce a reaction force' (Session 16, 142). Nevertheless, Ben argued he would now 'start with more general concepts and I would group it separately so I would begin with the force...And then link the forces to, um, the effect of forces so acceleration types of forces' (Session 16,152). Ben's development of a more abstract ontological categorisation will be examined in the next section.

Ben began his final concept map (Figure 5.5) by showing an awareness of the challenge of balancing the generality of the concept of force with the nature of particular types of force: 'I'll begin with the, um, major forces acting that, seems to me, actually, no, because the problem is the, all the forces are linked to particular ideas' (Session 22, 4).

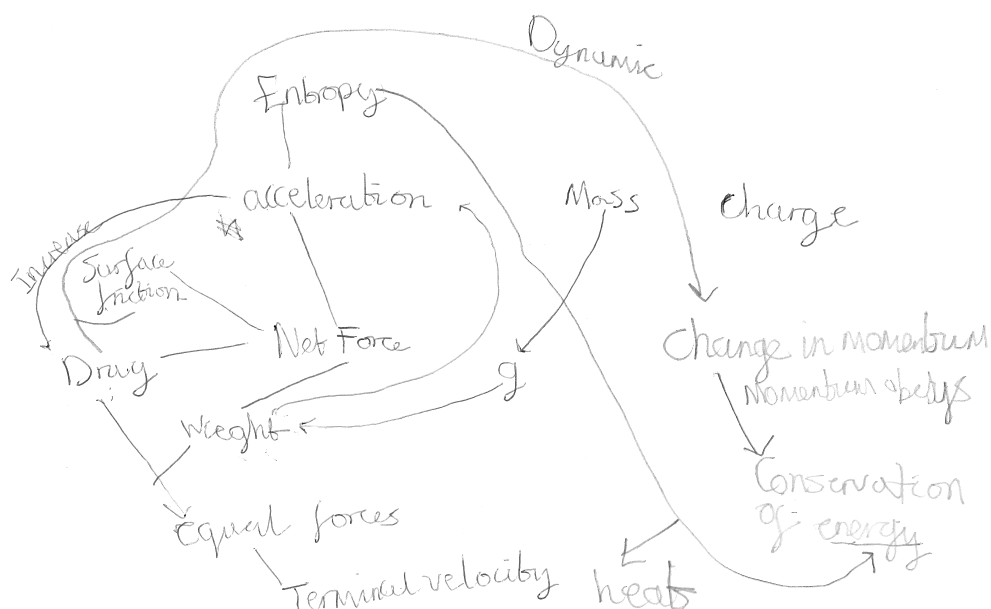


Figure 5.5: Ben's final concept map related to forces and motion (Session 22).

In Figure 5.5, Ben showed a clearer understanding that all the forces listed, surface friction, drag and weight, may act as a net force, a change from his earlier concept map (Figure 5.2). In that sense, there appears to be a growing understanding of the similarity between different types of force. However, Ben maintained some distinctions between different types of force. He proposed a distinction between forces which do not 'necessarily change momentum', such as weight, from forces which are linked to changing momentum: for example, drag and friction (Session 22,

78). This distinction appears to arise from a misunderstanding of the concept of resultant force, as Ben commented: ‘...because you can still have a gravitational force acting on you...Even if your momentum isn’t changing’ (Ben, Session 22, 82); for example, in the case of sitting in a chair. By contrast, ‘with surface friction and drag it there has to be a change in momentum’ (Ben, Session 22, 88).

5.2.1.1.3 Changes to Ben’s categorisation by instances and abstractions

Some of Ben’s initial applications of concepts were grounded in specific contexts in which they had been learned. For example, in the excerpt below, he was considering the forces on a ball travelling round a looped track, and developed a situated notion of reaction force as a force that acts upwards:

Yes, but I’m not, I wouldn’t be sure why the reaction force would be acting when it’s up here [top of track], I can understand when it is sitting on here [bottom of loop], but I am not sure whether there would be any reaction force when it is all the way up at the top, because then it’s not resting on anything. (Ben, Session 4, 98)

In the next session, when asked to draw a concept map of his understanding of forces and motion, Ben began by describing a link between friction and centripetal force that arises from a particular context:

Um, so friction, um, acts as a centripetal force...I’m thinking of the last time when we did the experiments of the marble going into the tube...and then circling around it... And also I was thinking of in my revision guide, at one point, it has a picture of a car circling around and, um, I’m not sure what’s it called but, um, and the friction was always acting to the centre of it [pause to write] when an object is moving in a circle. (Ben, Session 5, 68-74)

Ben’s situated understandings led to erroneous predictions. He conceptualised tension as a reaction to weight and therefore argued the tension in the string of a pendulum remains constant during its motion (Ben, Session 5, 76). He proposed that ‘the force acting on an object will have a particular direction depending on the weight of the

object' (Ben, Session 5, 86), a claim that may arise from frequent encounters with situations in which objects travel in the direction of the gravitational force.

In the second static interval, Ben was asked to complete the card sorting activity shown in Figure 5.6, below (see Appendix 8.7.3.1). He was shown a set of cards displaying situations and asked to sort them into categories of similar forms of motion.

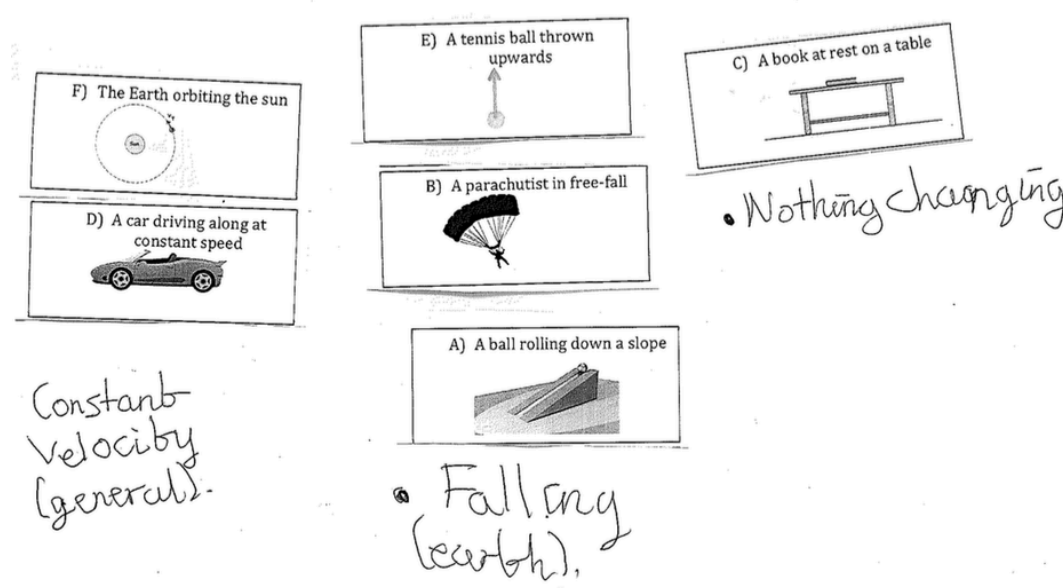


Figure 5.6: Ben's categorisation of situations in Session 11 (See Appendix 8.7.3.1).

Ben tended to categorise the situations by the perceivable features nature of motion, such as falling or change, rather than using abstracted notions related to scientific concepts. In the next session, when Ben was asked to group a set of problems (Appendix 8.7.3.2) he displayed some ability to look beyond the surface features of the problems to their 'deep structures': for example, he grouped one set of problems by their relation to accelerating objects; and another group involved problems with 'no forces acting' (see Figure 5.7). Ben chose to group motion in two dimensions as distinct from the other categories.

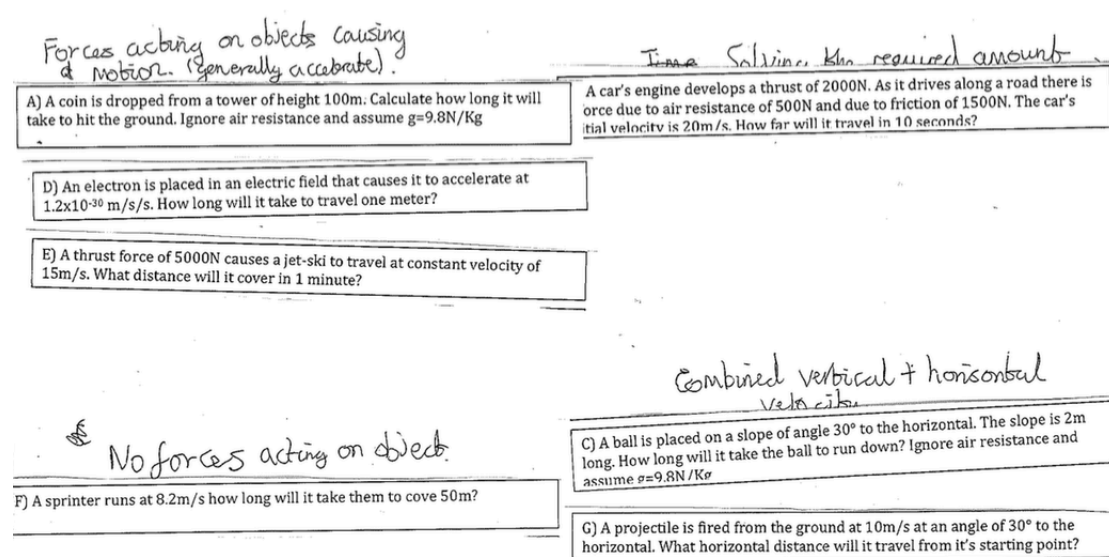


Figure 5.7: Ben's Categorisation of problems in Session 12 (See Appendix 8.7.3.2).

In session 13, Ben argued force was an abstract entity:

I don't think, um, I don't think it's something that this is necessarily confined, as in, it doesn't occupy a region of space, we say the force is here... but we really mean the force is acting here.

(Ben, Session 13, 60-62)

He classified forces as non-physical entities (see Figure 5.8) that cause acceleration and change.



Figure 5.8: Ben's understanding of the nature of force (Session 13).

Despite his growing sense of the abstract nature of force, Ben's use of the concept implied he perceived differences between certain types of force. He argued that two pairs of forces, weight and air resistance, and 'gravity' and centripetal force, have particular kinds of relationships that arise from the contexts in which they are used:

[Referring to weight and air resistance] I'm not sure if it's inversely proportional but definitely the reverse [pause] at least in the Earth. (Session 15, 28)

...centripetal force I link it with gravity, because gravity causes things to circulate around something. It very rarely causes something to actually just directly come towards it, at least in the astronomical sense. (Session 15, 78)

In general, however, in the second static interval, Ben displayed a commitment to an abstracted ontology of force. He claimed that forces emanate from objects, and therefore that forces may exist in the absence of objects (Ben, Session 14, 301-303). He argued that, whilst energy has a reality in the universe, force is 'just a concept' (Ben, Session 15, 144) and described force as '...an invisible thing that makes certain things happen' (Ben, Session 16, 245). This increasing sense of the abstract nature of forces eventually led Ben to query the existence of forces:

...so we can only really find acceleration and I, I'm not sure whether really forces actually exist. I think acceleration has to exist...But there's there doesn't seem to me to be any need for forces. (Ben, Session 22, 32-34)

Ben suggested that force is simply a name for that which causes acceleration (Session 22, 12). In drawing his final concept map (see Figure 5.5, above), Ben described how he now saw the link between force and acceleration as being the defining relationship for the concept of force, and that different types of force were incidences of an

abstracted notion: ‘So we tend to link up with force with acceleration before we link it up with individual things that we call forces like weight etc.’ (Ben, Session 22, 18).

5.2.1.2 Changes to Daniel’s Ontology

5.2.1.2.1 Changes to Daniel’s differentiation of concepts

Daniel’s early sessions were marked by an ambiguous usage of the concepts of velocity and acceleration. Daniel described acceleration as: ‘...like the time to speed up, is it like the speeding up of something’ (Session 3, 40); and, when asked how velocity changes under constant acceleration, he responded that velocity would remain constant (Session 3, 42). This lack of a clear distinction between the concepts was highlighted by two comments in the fifth session:

Um, acceleration is [pause] acceleration is, um, is it movement in a direction or is that velocity? (Daniel, 5,48)

Oh, acceleration is just [pause] is it like something that moves at a constant, no ‘cos something always has constant acceleration, is it something moving [pause] it’s accelerating, oh, it’s like something with a force acting on it to make it move. (Daniel, 5,64)

In addition, Daniel demonstrated some blurring between the concepts of gravity and free fall and had some sense that they are the same concept: ‘you say gravity and free fall is the same thing?’ (Session 5, 36).

In the second static interval, the lack of demarcation between velocity and acceleration remained. Daniel explicitly admitted to confusing the terms (Session 11, 42), before suggesting that acceleration is the rate of change of displacement (Session 11, 46). In the final session, when Daniel was asked to explain the link he had drawn between velocity and acceleration on his concept map, he responded: ‘Er because the area under the graph is displacement and velocity is a vector so it’s given a direction’ (Session 22, 68). Daniel admitted to confusion between the concepts of mass and

weight (Session 11, 98), and he described his perception of the similarity between the terms:

D: Yeah, definitely this is just one of my personal... it's a personal thing, 'cos there's the way, the way, I think I always get certain things mixed up, like weight and mass gets mixed up, and velocity and acceleration gets mixed up.

I: Why do think they are so easy to mix up?

D: Um, because they have the same, they have they take into account the same things, if you think about 'cos weight and mass, one's measured in kilograms.

(Session 11, 138-140)

When asked whether there was possibility for confusion between the concepts of energy and momentum, Daniel replied:

Possibly, but I think I think I'd be able to tell the difference between them... More than I would the others, because they're so proper, like, they're really really closely linked together... Whereas energy is, in it's way, it's own little topic and momentum is its own little topic... When you're learning this stuff you learn it together. (Session 11, 154-160)

However, despite his perception that momentum is ontologically distinct from energy, there is a greater overlap in Daniel's concepts of force and momentum than one would expect in an expert. In session thirteen, he argued: 'Um, momentum is like a force ... the force that something has on something else creates momentum' (Session 13, 56). He went on to describe the overlap between the concepts of force and energy as 'not that much, because, there, there's they link together in ways, it's not like completely linked together' (Session 13, 76) and he drew the diagram below (Figure 5.9).

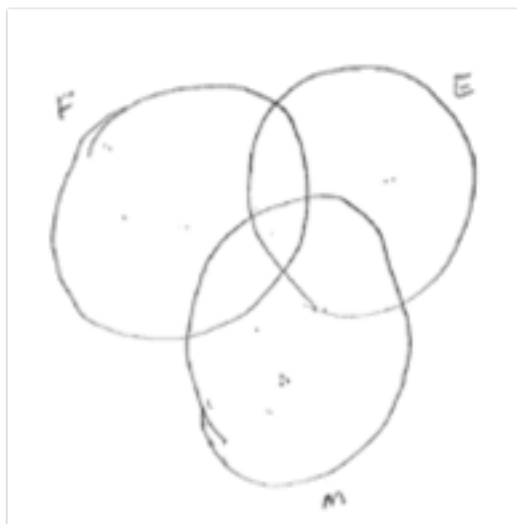


Figure 5.9: Daniel's representation of the overlap between force (F), energy (E) and momentum (m).

He argued that the reason they link together is because energy can create momentum, which can create a force (Session 13, 86-88). The notion that energy 'creates' a force reoccurs in the next session: Daniel described how a person could use 'chemical energy to create a force on the door' (Session 14, 84). In later sessions, Daniel's earlier ambiguities over terms related to gravitational force remained: he described drag as balancing 'free fall' (Session 11, 178), and then argued '...the gravity er gravitational energy er is trying to er equal with the would you say this is thrust?' (Session 11, 180). This categorisation was persistent, and in the final session, Daniel commented that gravity was the same as free fall (Session 22, 32), and that 'g is the gravity is nine point eight' (Session 22, 42). In one scenario, Daniel's intuitive understanding of motion appeared to have caused him to develop two distinct categorisations of deceleration. Daniel was asked to predict what would happen to a shopping bag on a car seat when the car brakes, and he argued that the bag would move backwards relative to the seat. On being shown a demonstration of a weight moving forwards relative to a tray during a collision, he argued the two situations were distinct:

- I: Do you think the car is different?
- D: Yeah, because it's only braking, and it's not hitting something really... Yeah there's no collision force, so it's

like, how can I explain it, um [pause]. Is it because when you're braking, you brake over a certain amount of time...But when you hit something you stop like immediately. (Session 12, 195-201)

Daniel appears to retain blurred distinctions between different concepts over the course of the sessions.

5.2.1.2.2 Changes to Daniel's conceptual clustering

In his initial concept map, Daniel referred to two types of force: friction and 'gravity' (see Figure 5.10).



Figure 5.10: Daniel's first concept map related to forces and motion (Session 5).

Daniel perceived 'gravity' and friction as having different relationships with other concepts. Daniel linked 'gravity' with force and velocity, but friction with acceleration and velocity:

... force would it be more connected with velocity than acceleration...Because say if a car is moving in a direction

there's always going to be the friction acting on the tyres and the road. (Session 5, 78-80)

...gravity and velocity go together 'cos velocity is a vector movement because it's something in a direction...And gravity pulls something down so that's basically movement in a direction. (Session 5, 86-88)

In the second static interval, Daniel maintained a loosely grouped understanding of force. In his next concept map, in session 11 (Figure 5.11), he conceptualised two distinct clusters of types of force.

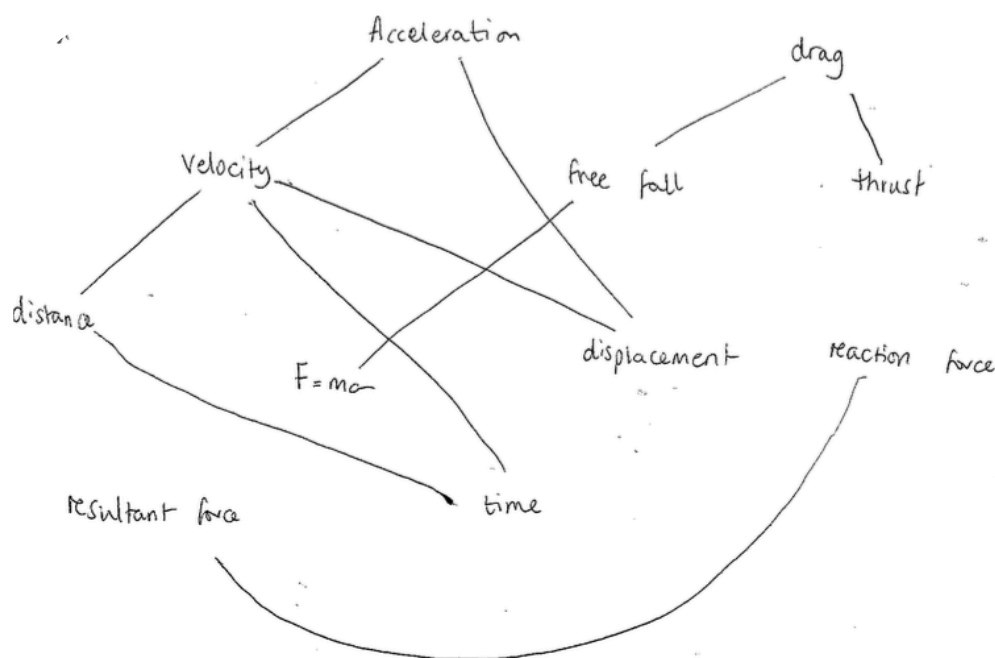


Figure 5.11: Daniel's second concept map related to forces and motion (Session 11).

Daniel developed a set of forces, in the upper right portion of the map, which related to the context of a parachutist: drag, thrust and 'free fall'. The relationships between the forces are described in that context (see the following section for a discussion of the situated nature of Daniel's concepts); hence, drag and 'free fall' were seen as acting in opposition:

Linking back to the parachutist, as well, um, there's drag acting on the parachutist...When it's open up, when you open up the

parachute, the drag force starts to get bigger until it balances out with the free fall or gravity, gravitational force acting on it...Um drag and thrust link together, 'cos, they are, can I say they are like opposite forces in the air? (Daniel, Session 11, 30-34)

Daniel developed a second group of forces grouped by their relation to the context of a person sat in a chair (reaction and resultant force). He argued that:

Um, the reaction force links with the resultant force [pause]
Because in, like, for example, the earth chair scenario, if I'm sitting on a chair, there's a force acting on...Gravity is attracting downwards and the reaction force from the chair...
To me is balancing it out so that I am sitting on the chair not falling through it or going up. (Daniel, Session 11, 36-40)

The notion that pairs of force exist in opposition appears in a number of other places in the transcripts of Daniel's sessions. In the first session, he explained the circular motion of an object occurred because '... there's more force coming from behind it than it is in front' (Session 1, 76); when analysing the motion of a pendulum, he commented that: 'it's because there's the force going in one direction is more than the force going in the other' (Session 2, 58); in accounting for the motion of a marble at the top of a loop, he argued that the reaction and gravitational forces act against each other to keep the ball from falling (Session 4, 136).

Daniel's final concept map (Figure 5.12) suggests that his fragmented ontology of force remained unchanged over the sequence of sessions.

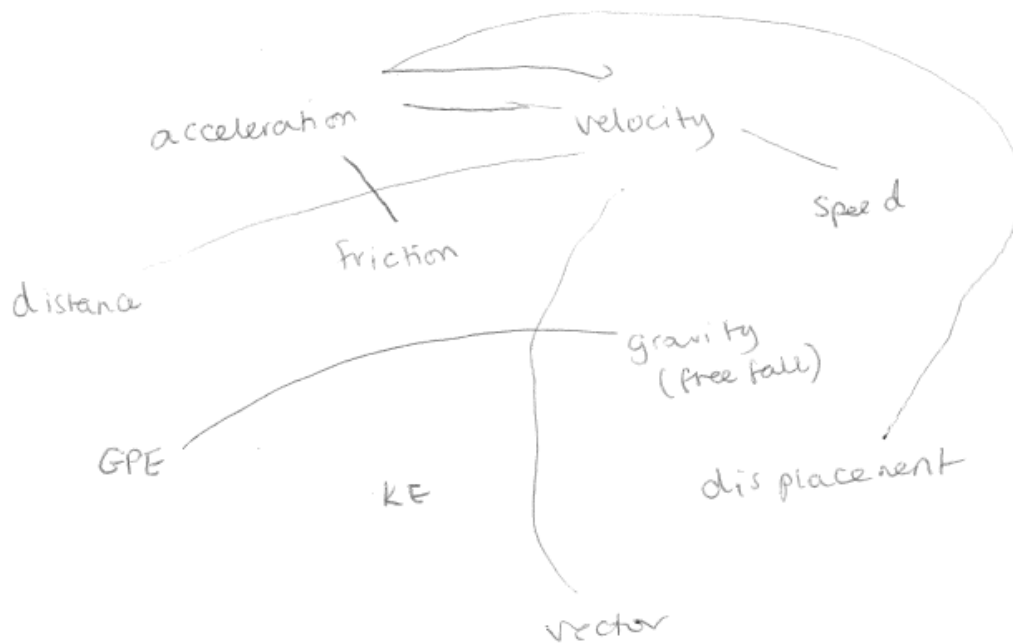


Figure 5.12: Daniel's final concept map related to forces and motion (Session 22).

As in his second concept map, Daniel did not include a general concept of force on his third map, but listed two types of force: friction and 'gravity (free fall)'. These two constructions appear to have significantly different properties. Friction is linked to acceleration, because 'if there's a high friction then acceleration won't be like maximum' (Session 22, 60) but gravity is not. The concept of 'gravity' is linked to 'GPE' because 'gravitational potential energy links to gravity and free fall 'cos GPE equals $m \times g \times \Delta h$ ' (Session 22, 40). Daniel's concept of force seems to remain weakly clustered: his perception of differences in the nature of different types of forces has been maintained over the six-month duration of the interviews.

5.2.1.2.3 Changes to Daniel's categorisation by instances and abstractions

The fragmented nature of Daniel's concept of force is related to the contextual nature of his understandings. In constructing explanations, links to particular contexts constrained Daniel's explanations. For example, when drawing his first concept map, Daniel's understanding of the relationship between force, acceleration and velocity seems to be situated in the context of the motion of a car.

... acceleration is something moving with a force acting on it, so,
and a force can be something that's acting on something else, so,
say if you was pushing a car, its acceleration would be the force

of the push that you're putting on the car, basically, so that links together um [pause] Er could friction link with it as well? ...On, yeah, say, if you was in a car and, er, there's always friction between the, the, tyres and the road so, um [pause] I don't, I just want to know how, that something to do with force. Would it be more connected with velocity than acceleration? (Session 5, 76-78)

In another example, gravity is seen specifically as the force of the Earth pulling objects into its core (Session 5, 68).

In the second static interval there was some evidence that Daniel could look beyond surface features of a context to perceive shared abstractions, for example in his categorisation of motion situations (Figure 5.13).

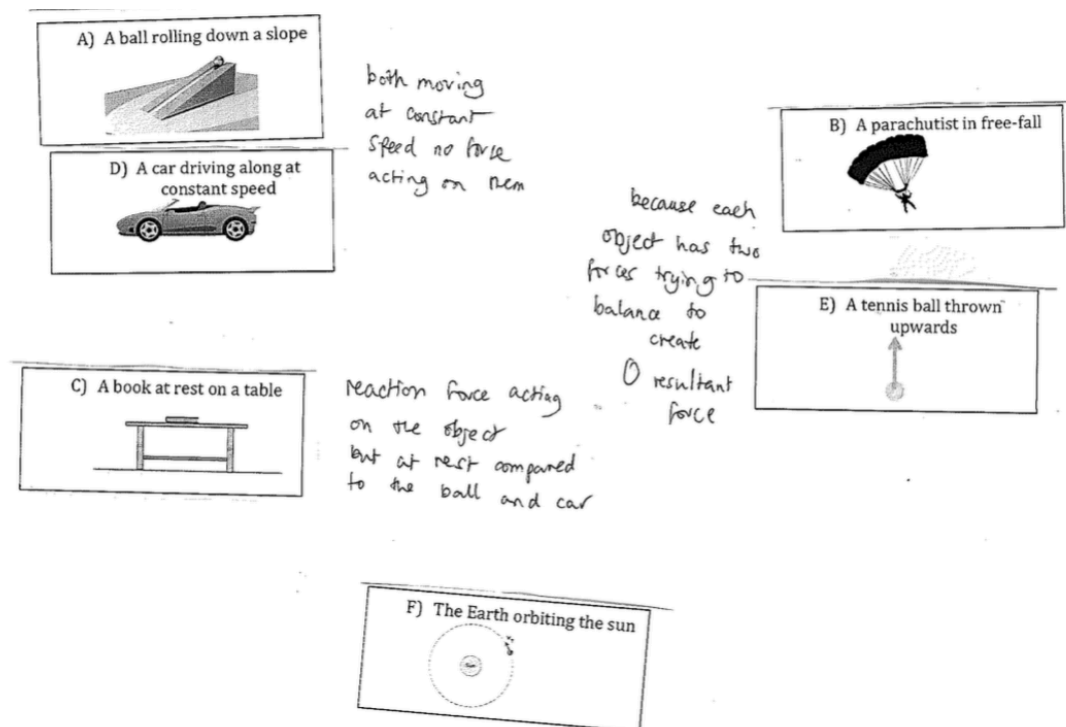


Figure 5.13: Daniel's categorisation of motion situations in Session 11 (See Appendix 8.7.3.1).

Daniel made use of the concept of force to justify his classifications, and there appears to be an activation of the notion, discussed above, that forces act in opposing

pairs. He argued that, when a tennis ball was thrown, and in the case of the parachutist: 'The drag is trying to, like, um, equal out with the free fall' (Session 11, 178). He assumed that the ball rolling down the slope would travel at constant speed, and therefore classified it as a case of motion at constant velocity. Daniel argued that, for the ball on the slope, 'there's no force acting on it except from the downwards force but no force like behind it pushing it forward to go faster' (Session 11, 184), which was similar to the situation with the car, because 'there's no force acting on it for it to accelerate further' (Session 11, 186). He argued the book and the Earth orbiting the sun cards are in their own categories because the book is at rest (Session, 11, 211), and the Earth is travelling in a 'circular orbit or not a perfectly circular orbit' (Session, 11, 221). Daniel's categorisations indicated some tendency to see abstract commonalities between apparently different contexts. However, when he was asked to categorise the problem cards in the next session (Figure 5.14), Daniel based his categorisation largely on the variable that is the target in the problem rather than deeper structural similarities in the questions.

Figure 5.14 displays several physics problem cards with handwritten notes indicating Daniel's categorisation based on the target variable.

Card 1: A) A coin is dropped from a tower of height 100m. Calculate how long it will take to hit the ground. Ignore air resistance and assume $g=9.8\text{N/Kg}$.
Handwritten note: asking you to find a time of how long something takes
 $s = \frac{d}{t}$

Card 2: F) A sprinter runs at 8.2m/s how long will it take them to cover 50m?
Handwritten note: asking you to find a time of how long something takes
 $s = \frac{d}{t}$

Card 3: C) A ball is placed on a slope of angle 30° to the horizontal. The slope is 2m long. How long will it take the ball to run down? Ignore air resistance and assume $g=9.8\text{N/Kg}$.
Handwritten note: asking you to find a time of how long something takes
 $s = \frac{d}{t}$

Card 4: B) A car's engine develops a thrust of 2000N. As it drives along a road there is a force due to air resistance of 500N and due to friction of 1500N. The car's initial velocity is 20m/s. How far will it travel in 10 seconds?
Handwritten note: how far something will travel

Card 5: G) A projectile is fired from the ground at 10m/s at an angle of 30° to the horizontal. What horizontal distance will it travel from its starting point?
Handwritten note: how far something will travel

Card 6: E) A thrust force of 5000N causes a jet-ski to travel at constant velocity of 15m/s. What distance will it cover in 1 minute?
Handwritten note: how far something will travel

Card 7: D) An electron is placed in an electric field that causes it to accelerate at $1.2 \times 10^{-30} \text{ m/s}^2$. How long will it take to travel one meter?
Handwritten note: asking how long but it's on electron

Figure 5.14: Daniel's categorisation of physics problems in Session 12 (See Appendix 8.7.3.2).

Some of Daniel's situated notion of the concept of force may stem from his belief that force is a relatively physical entity:

I'd say force is more on the concrete side...Because you can feel a force when you're acting on it, when it's acting on you, you can create a force um you can [pause] It's just something you can actually feel, you can actually, you know, it's going on around you (Session 16, 86-88)

It is perhaps unsurprising, given this ontological commitment, that Daniel struggled to overcome apparent surface differences in the nature of different types of force to develop a single abstracted notion of the concept.

5.2.1.3 Discussion of general trends in ontological development

From a reading of the literature, it was suggested that three processes might be useful in thinking about how ontological change occurs: differentiation, clustering and the transition from instances to abstraction (see Figure 5.15, below). These processes are not seen as distinct: for example, an increased understanding of the similarity between types of forces (increased clustering) is likely to increase the differentiation of force from other concepts. As a concept becomes increasingly defined by abstract concepts rather than specific instances it is likely to become increasingly clustered. The evidence from the two case studies suggests that the development of ontology is not a straightforward process. In Ben's case there appears to be some progression from a weakly differentiated, loosely clustered and contextualised concept of force towards a more clearly differentiated category that made use of abstract principles as a guide to membership. However, the process appears to proceed gradually; indeed, over the course of the six months of the case study, Daniel's fragmented and situated notion of the concept of force appears to have remained relatively static.

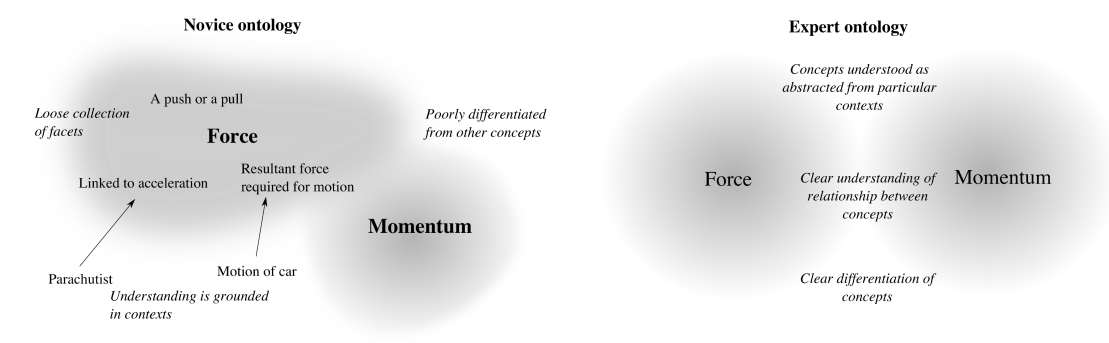


Figure 5.15: A representation of ontological development suggested by the literature review

In general, the more nuanced model of Gupta and colleagues (2010) seems a better fit for the changes observed than Chi's (1992, 2013) notion of parallel evolution of ontology (see section 2.1.4.1), as the students displayed evidence of making use of ad hoc and idiosyncratic ontological categories rather than the finite number of stable ontologies proposed by Chi and her colleagues. For example, in an incident discussed above, Daniel developed two distinct categories of collision in response to a particular prompt. Similarly, Daniel's category that subsumed the notions of gravity, weight and 'free fall' was not constructed in Ben's transcripts. The two cases described above provide evidence to suggest that ontological developmental paths may be individual. There is no evidence in the reports above that indicate students constructed novel ontological categories before assigning concepts to them, as suggested by Chi and colleagues (Chi, 1992, p. 136; Slotta et al., 1995, p. 378). Rather, Ben appears to have undergone a gradual and complex process in which his existing concepts, which had multiple contextually-triggered facets, were adjusted to match a target of expert ontological categorisation that is rarely explicitly stated in the classroom.

Daniel struggled to acquire the scientific concept partly because of his fragmented and situated concept of force. As he did not possess a single concept of force, Daniel faced the challenging task of encountering multiple contexts in which the concepts that operated were, to his perception, subtly different. Explaining the motion of an object is difficult if you perceive that friction and the gravitational force have different properties. In making an argument about the ontology of mythical entities, such as Pegasus, Quine (1980, p. 4) argued that philosophers should carry out an

ontological slum clearance to rid the universe of ‘disorderly elements’ such as mistaken categories. However, developing an expert ontology is not as simple as simply discarding alternative ontologies: students must work with their existing categories to develop ontologies that differ from everyday categories and are difficult to describe explicitly. Indeed, it has been suggested that initial categories may be useful stepping stones to developing expert ontologies. For example, a substance-based ontology for gravity may be productive at some stages of learning (Gupta et al., 2014); or, an intermediate atomic model, electronium, which treats electrons as a continuously distributed liquid, may provide a bridge between material and probabilistic electronic ontologies (Budde, Niedderer, Scott, & Leach, 2002). Conceptual categories might be thought of as being defined by the manner in which concepts are related to other concepts (Chalmers, 1999, p. 98); consequently the next section examines the formation of groups of concepts, conceptual compounds.

5.2.2 The formation and modification of conceptual compounds

The earlier discussion of conceptual compounds (Section 2.2) suggested that some types of conceptual compounds may form and disperse over short timescales. Therefore, in this section, static intervals (see Section 4.3.2.3) are defined at the scale of utterances or groups of utterances so that short timescale change may be constructed. When reading through the transcripts, utterances or sequences of utterances in which students constructed compounds relating two or more concepts together were initially given the same code. These instances were then differentiated into the categories shown below: the stability of compounds (5.2.2.1), the extent of compounds (5.2.2.2), and the interaction of conceptual elements (5.2.2.3).

5.2.2.1 The stability of conceptual compounds

A number of conceptual compounds, with differing stabilities, were constructed in the students' responses.

5.2.2.1.1 Relatively unstable conceptual compounds

In some circumstances, a student developed a temporary conceptual compound that only occurred once in the cannon of their utterances. Listed below are three reports of students' ad hoc conceptual compounds:

- *Ben's construct that force 'takes over' from energy as a cause of motion*

Ben was asked to predict the most likely trajectory of an object dropped from a plane moving with constant horizontal velocity.

Projectile from a plane, interview 1, 15, 22
(Adapted from Epstein, 2009, p. 133)

An aeroplane is travelling with constant velocity when it drops a ball. Which path best describes how the trajectory of the ball would look to an observer on the ground? Explain your answer.

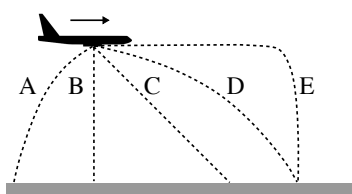


Figure 5.16: Projectile from a plane question (See Appendix 8.7.2 (m)).

B: Um, I think if it was a gentle roll, but if it was a strong force then it would follow path E.

I: Say it was like a gun that fired it outwards.

B: I think then it would be E.

I: If it was a gun it follow path E.

B: Yes sir.

I: Why path E if it was a gun?

B: Because, I think, it would probably, the force acting on it would be slightly sideways, but, if it was a gun, then I think the force acting on it would be much stronger than the force of gravity at first, so it would be practically vertical, well practically horizontal.

I: Yes.

B: But, then, eventually it would lose its kinetic energy gained from the push, and then the gravitational force would take over and it would just drop to the ground. (Ben, Session 1, 114-122)

It appears that the particular context of the question causes Ben to develop an explanation in which force can take over from kinetic energy as a cause of motion. This construct is not seen elsewhere in his explanations, and does not reoccur when the question is asked again in session 22: on that occasion, Ben chose option D.

• *Edward argues weight decreases with upward motion*

Edward was asked to discuss the forces acting on a lift as it moved upwards at constant velocity (adapted from Pople (1982, p. 27)). He was asked if the forces would be different from those in a stationary lift:

Er, well, it would be different, 'cos it's a change in its velocity, so it would be higher upwards, the reading, i.e. the reaction force, would be higher, erm, and yeah I suppose the reading

would be different, ‘cos there’d be less weight acting downwards on the scales. (Edward, Session 4, 229)

In the next utterance, Edward is asked if he believes the passenger’s weight changes during the motion of the lift. He replies: ‘No, not technically’. Again, it can be argued that the particular constraints of the question context caused the formation of a temporary conceptual compound that contradicted a more stable belief. Edward was asked the same question in sessions 1 and 22 and, in both cases, argued that in the case of constant velocity the upward and downward forces were equal and opposite.

• *Amy, Ben and Edward’s development of multiple temporary models*

The route to developing understanding may pass through several relatively short-lived moments of coherence. Clement (2013, pp. 334–338) described a cycle of model construction and testing in problem-solving and Parnafes (2012, p. 362) proposed a progression through a series of ‘plateau[s] of coherence’. It should be noted that the pattern reported here is stimulated by the interview prompts, and therefore represents an ‘accelerated’ version rather than a ‘natural’ process (Kuhn & Phelps, 1979). In session seven, Amy was asked to consider the problem shown in Figure 5.17.

What happens to the brightness of bulbs A and B when the switch is closed?

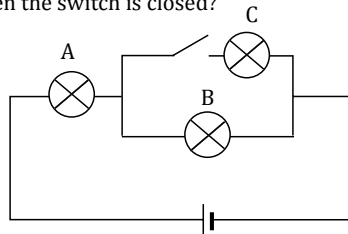


Figure 5.17: Question 29 on Determining and Interpreting Resistive Electrical Circuits Concepts Test (Engelhardt & Beichner, 2004). See Appendix 8.7.1 (v).

Amy’s response is shown below:

Erm, B would [pause]. Would B [pause]. No, B brighten and A would be dimmer...I’m thinking because [pause]. Wait no it would just stay the same....No it would dim they would, no, I’d say stay the same, because when the electrons they go into, so branch off...They’ve got the same amount of energy, I assume B

and C have the same resistance...But the electrons are still each going through, no. A would be brighter than B [pause]...Because, so the electrons go through B and C, so they use up the same amount of energy, but when they go through A, you would [pause]. You'd still have, you'd, the electrons still have, I don't know how to explain it. (Amy, Session 7, 180-190)

Amy appears to pass through two overlapping temporary compounds in attempting to find a solution to the problem. First, she related the brightness of the bulbs to the flow of current and their resistance, before using energy considerations in order to make sense. This process of developing a construct to explain a situation, evaluating the solution and altering it to create a better fit to the context, has been described as 'sense-making' or 'satisficing' by Nokes-Malach and Mestre (2013, p190).

A second example of this process was seen in Ben's thinking around how an increase in mass will affect the time period of a pendulum (Session 2, 201-225). Ben's initial argument proposed that greater weight on a pendulum leads to greater tension in the string, therefore greater accelerating force and acceleration, causing a shorter time period. When Ben is confronted with data showing the time period remains constant, he argues that tension will be unaffected by the change in weight:

...because the force of tension is acting in the opposite direction to the force, in a different direction to the force of gravity, so I don't think the force of gravity affects the tension very much does it? (Ben, Session 2, 211)

Ben had previously demonstrated the ability to construct an argument, in the case of free-fall (Session 1), that acceleration is independent of mass, but he fails to activate that knowledge in this context. Finally, Ben developed a third argument in which he suggested that, because the weight had increased, the time for the bob to move from maximum displacement to the equilibrium position is reduced, whilst the time to travel in the opposite direction is increased. This compound disperses when Ben is asked to consider the symmetry of the situation. This kind of reasoning supports

Sloman's (2009, p. 138) claim that: 'Causal models aren't necessarily waiting like ripe cherries to be picked from memory; they have to be constructed for a particular purpose'. It appears that Ben was capable of developing a number of different models to explain the motion in this context.

A third example of the development of temporary compounds was constructed in Edward's transcripts. This example related to making sense of the changes to the potential difference across an electric motor when the load it is lifting is increased:

First iteration: Edward initially proposed a link between a perception of increased 'physical resistance,' due to the decreased speed of lifting, and electrical resistance but quickly discarded the argument:

'its pulling it up slightly slower? And mm that means there's more resistance...I'd say physical resistance in this case...I was going to say it would decrease the voltage but that wouldn't make sense 'cos more resistance would just mean more voltage overall' (Edward, Session 7, 114-120)

Second iteration: Noting that the potential difference across the motor had decreased when the load was increased, Edward argued that: 'So, for some reason, the resistance [of the motor] must have gone down by quite a lot, so, ...mmm perhaps more of it's transferred into stuff waste products such as like heat or sound' (Edward, Session 7, 126-128).

Third Iteration: Finally, he moved towards a compound that links the potential difference across the motor to the distribution of resistance in the circuit: 'Because the potential difference dropped across the wire increases... 'Cos the current increases, and that causes the, um, is it the, a particles or something, that are, that um, sort of like, it's a vibrate more and stop the current coming through' (Edward, Session 7, 188-190).

5.2.2.1.2 Relatively stable conceptual compounds

Though some conceptual compounds were relatively short-lived, others may have had longer existences. For example, Charlie, in session 13, implied that gravity and weight are separate concepts: 'Er [pause] gravity's and weight's always going to be down' (Session 13, 124). This compound reappeared later in the interview when asked the cause of the acceleration of a pendulum he responded: 'Er the gravity... And er weight pulling it down' (Charlie, Session 13, 139-142). This relatively stable compound is evident in a force diagram drawn in the session, Figure 5.18.

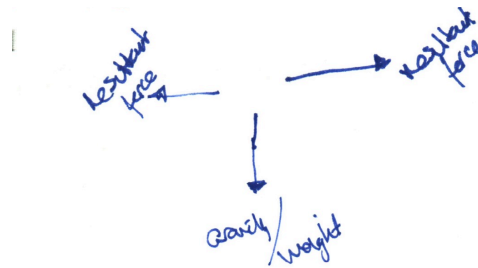


Figure 5.18: Charlie's representation of the forces on a pendulum (Session 13, 146).

This construction of a compound of weight and gravity appeared to be stable across a number of sessions over a period of at least two months:

Um, 'cos there's a heavier ball, and they both go same speed 'cos one ball's lighter, um, the weight and gravity have a less effect.
(Charlie, Session 15, 106)

Erm, gravity always acts downwards... So that contributes along with its, er, weight. (Charlie, Session 15, 168)

Because it's er going down, and it's weight and gravity would give a resultant force above zero. (Charlie, Session 15, 172)

... it's mass would be down wouldn't it... There's gravity as well [pause] mass. (Charlie, Session 16, 192-194)

In his final session, when questioned about the construct, Charlie indicated that he conceptualised weight and gravity as two distinct concepts, but used them as a stable compound:

C: So there's still er weight and gravity.

I: Are those two separate things?

C: Yeah or yeah and...

I: How are they separate?

C: Gravity is the [pause] or the field strength.

I: Mmmh.

C: Acting on everything and then an object can have an individual weight.

(Charlie, Session 22, 339-345)

A particular compound Ben developed, that all forms of energy are related to motion, seems stable across a number of sessions. This construct arose first in session thirteen, and appeared on a number of other occasions, including the final session, over a period of approximately two months:

...it only causes movement in the sense that we say there are different kinds of energy, but in a way they are all, in some way, kinetic, because, light we have oscillating magnetic and electric fields...So it's kinetic. Heat we have molecules moving so its kinetic...So it actually all energy is kinetic. (Ben, Session 13, 148-152)

I again I go back to saying that all energies are manifestation of kinetic. (Ben, Session 14, 333)

I think I'll just link energy with heat energy and then, as we've said, all energy is a manifestation of kinetic energy. (Ben, Session 15, 126)

I think even when we say something has so much heat energy, so much kinetic energy, um, as I've said before, I think they're all just kinetic energy. (Ben, Session 22, 473)

This compound appears to arise from an understanding that all forms of energy are in some ways associated with motion.

5.2.2.2 The extent of conceptual compounds

Over the course of the sessions, some of the students developed conceptual compounds that linked a growing number of elements. In early sessions, Charlie typically produced explanations that linked a small number of concepts to form an argument. For example, in describing the pendulum, he linked energy to height and motion:

So when we let go it will convert some into, er, would it be kinetic energy? So it's got an energy so it can keep moving, plus every time it goes back to a bit more height, it gets a bit more GPE, so that's how it gets energy to move, so that's how the pendulum works. (Charlie, Session 2, 124)

To account for the ability of a ball to travel round a loop-the-loop, Charlie developed a compound relating 'g-force' to acceleration:

...because, where it starts, as it goes down, er, it accelerates so its getting faster and, as its, er, a tight loop as it goes round, I dunno if it would be right, there's g-force. (Charlie, Session 4, 72)

In the context of a ball moving in a concave bowl, Charlie accounted for the motion by linking the shape of the bowl to loss of momentum and deceleration:

So it's all the same shape, wherever you go on the bowl, so by dropping the ball at one point, directly through the middle, it would keep its path going, er, up and down the sides, of the two different sides of the bowl, and, er, as time goes on, I think it loses

momentum every roll, I put on the side, so it would gradually start decelerating and end up in the bottom of the bowl. (Charlie, Session 5, 74)

In general, his early explanations link a small number of concepts to create an argument. When Charlie re-encountered the context of the ball in the bowl, in his fifteenth session, he activated a greater number of conceptual resources, but he seemed to struggle to form links between the separate components to develop a coherent argument.

At the top, and, er, when it's released it gets converted to kinetic...Erm, gravity always acts downwards...So that contributes along with its er weight...Um [pause] as it er at the top it would start to accelerate [sound of marble]...Because it's, er, going down and its weight and gravity would give a resultant force above zero. (Charlie, Session 15, 164-172)

In his final session, in comparison to his first encounter with the motion of the ball in the bowl, a greater number of concepts were activated, but the relationships between the concepts remain poorly defined:

There's GPE, and when it's released it's converted into kinetic [here Charlie rolls the ball]...Energy which helps it move [pause] it has, er, a weight and an amount of gravitational field strength...Pulling it down and erm [pause] its weight would, as it bends, there would be a weight acting down, so if it's at the top [pause] er [pause] there, there'd be a reaction force inwards...Weight downwards [pause] but the reaction force's [draws arrows perpendicular to track]. (Charlie, Session 22, 289-295)

A similar pattern can be constructed in Edward's attempts to make sense of the oscillations of a ball in a concave bowl. In his first engagement with the context, like

Charlie, Edward activated a limited number of conceptual elements related to the physical features of the situation:

Isn't it something to do with the gradient, er [pause] and the gradient's like zero at the bottom, I think, yeah, yeah it's completely flat, it's zero at the bottom. It's like a large, it's a larger number at the side so it sort of moves down to the centre. It's a word you said last week that I think has something to do with it but I can't remember what it was. (Edward, Session 5, 80)

After some discussion, he recalled a link to the centripetal force, which he used to explain the motion of an object swung on a string in the previous session. His subsequent explanations showed development in the sense that there was an attempt to make use of scientific concepts such as momentum and force, though, see below, these concepts may be conflated, to explain the motion:

Erm, as it gets higher up, the ball up the slope...It gains more gravitational potential energy...And so it would, it would, sort of, wanna go back down towards the middle, in a sort of centripetal motion, so, and as it does momentum builds, so it goes back up the other slope. (Edward, Session 15, 204-213)

E: Erm [pause] we draw a ball here then um the forces acting on it would be parallel to the platform it's on so the two forces would sort of both be going that way [draws ball in centre with two horizontal arrows, see Figure 5.19].

I: What are the two forces there?

E: In this case it'd be the forward momentum of the ball and the drag on it I think. (Edward, Session 22, 243-245)



Figure 5.19: Edward's representation of the motion of a ball in a bowl
(See Appendix 8.7.2(m))

In Daniel's case, his first encounter with the situation led to a conceptual compound that was largely related to the physical features of the bowl, rather than abstract explanatory ideas:

Is it because the shape of the bowl has a part to play in it, so when it's going down, it's accelerating and then, this is it's, 'cos it's flat here [indicating lowest point of surface], that's when it's going at constant speed, then goes up, which slows down the speed, then it's coming back down accelerating again. (Daniel, session 5, 102)

During his second attempt at explaining the situation, in session 15, he made use of abstract concepts, describing the ball as 'accelerating because the force of gravity's acting downwards'. He produced an argument based around three concepts: gravitational force, velocity and acceleration. Unfortunately, due to a scheduling mistake, Daniel's final interview was cut short, and there was insufficient time to revisit the situation in his 22nd session.

In his first encounter with the context, Ben activated a conceptualisation of gravitational force resolved into components: '...because the force is gravitational field strength times by sine theta I think for the acceleration and so as the angle becomes flatter it should the acceleration should be less'. To explain the ball's instantaneous moment of rest at maximum displacement, he developed a compound

that assumed that velocity and force could be balanced: ‘because the er velocity and the um force of the gravity will be equal, so it won’t be going anywhere’. This first engagement with the context triggered the concepts of velocity, acceleration and gravitational force, but Ben fails to activate his understanding of the reaction force - in Session 4, Ben had demonstrated an awareness of the existence of the reaction force in the context of a book at rest on a surface.

When Ben reencountered the situation, in Session 15, he added the concept of frictional force into the conceptual compound he developed and argued the constant velocity motion at the bottom of the bowl occurs, ‘...because the friction and weight cancel’. The activation of the concept of friction led to the development of an explanation that accounts for change in the ball’s direction:

Because it’s slowing, its friction must, I would suppose, in well, it’d be as if the friction increased and the friction is becoming more and more diagonal (Ben, Session 15, 245)

In the final session, Ben’s conceptual compound included the concept of a reaction force that changes direction depending on the position of the ball as well as the gravitational and frictional forces to produce a coherent account of the oscillations of the ball. Ben was able to activate increasingly complex conceptual compounds over the sessions; his initial encounter triggered a relationship between gravitational force, acceleration and velocity only, his final version is sensitive to the action of friction and a reaction force.

5.2.2.3 The interaction of conceptual compounds

It is possible for a learner to develop multiple conceptual compounds that make sense of a given context. As discussed above, these compounds can occur as a sequence of increasingly refined conceptual compounds. However, there are cases in which a student reported possessing two co-existing coherences for making sense of a single context. Amy was asked to consider how potential difference might vary across a capacitor; a situation that she was encountering for the first time. She reported being aware of two different ways to interpret the situation with her conceptual resources:

Hmmm, well, I am thinking of two different things in my head 'cos part of me is thinking, well, if the electrons can't move from one plate to the other, then there can't be a potential difference. However, if there's a build up of electrons, then, on the plate, then maybe, is, energy, electrons still transfer energy. So the potential difference increases. So I'm stuck between the two. I think it'd probably be [pause]. Would it increase? [pause] I'm stuck between that and staying the same. (Amy, Session 9, 140).

Amy believed her two models of electricity, a model of electron flow and a construct involving transfer of energy, were incompatible in this context. A similar case occurred when Ben was asked to consider a lift travelling at constant velocity.

B: Um [pause] I would like to say that the reaction force is bigger.

I: Why would you like to say...

B: Because, he has to, at some point, accelerated, because he's not stationary, but at the same time, he's not accelerating any more, and so they should be equal, and so I am not sure whether the resultant force is greater or the same. (Ben, Session 4, 196-198)

Ben struggled to decide between a compound in which motion requires a resultant force or one in which constant velocity is linked to the absence of a resultant force. This conflict reasserted itself in session 13 when Ben was asked to make sense of the forces acting on a boy jumping from a crouched position. When considering the instant of leaving the ground, he struggled to reconcile his belief that there must be a resultant force on the boy with his assumption that, because of Newton's third law, the forces acting on the jumper must be equal and opposite. This conflict led to the construction of a novel compound of concepts through which Ben argued that the forces (referring to the reaction force and the weight of the boy) did not occur simultaneously:

I'm just not sure whether they're... occur instantly after each other, and not after, instantly at the same time as each other, or whether there's a gap between them. (Ben, Session 13, 337)

In this case, Ben developed a model that allowed the retention of two compounds: one linking force with acceleration, and another which constructed the reaction force and weight as a set of paired forces. When he was prompted that the forces would act simultaneously, he developed an explanation in which the resultant force on the jumper was 'zero but she moves at constant velocity'. Ben's next attempt started from the claim that 'she's putting less weight on the floorboards when she lifts her legs up'. He argued that the floorboards move down, reducing the weight acting on the surface. Ben claimed that the jumper's weight reduced because the area of contact with the floor decreased; hence the strain decreased. The subsequent compound was formed around the notion that the jumper 'herself puts some force into jumping'. When the interviewer directed Ben to develop an explanation at the sub-microscopic level, he proposed that:

Um [pause] Is it because when she crouches down she's putting pressure so the electrons at the bottom come closer to the electrons at the surface and so there will be not only a reaction force but there will be a force causing the electrons in her feet to accelerate from the electrons in the um floor. (Ben, Session 13, 435)

With some additional prompting, Ben managed to develop a coherent explanation of the situation. When asked to reflect on his route to reaching his final explanation, Ben reported that he has just come from a chemistry lesson, which prompted his thinking about forces between particles.

5.2.2.4 Discussion of general patterns in the formation of conceptual compounds

Though the possession of certain conceptual elements may be necessary to make sense of a given situation, possessing appropriate conceptual resources is insufficient for understanding (Bransford, Brown, & Cocking, 2000, p. 9; Kosso, 2002). For example, Ben, in making sense of the forces acting on a mass on a spring (Session 3), displayed many of the elements required to provide an explanation of the situation. He described Newton's first law and the link between force and displacement and he understood, in some contexts, the relationship between force, acceleration and velocity. However, he struggled to use these elements to construct an appropriate conceptual compound in this context. This difficulty may arise from the presence of some misconceived conceptual elements that disrupted his construction. In particular, Ben's belief that the resultant force acting on the oscillating mass was zero at maximum displacement, which appears to have arisen from an awareness that the instantaneous velocity is zero at this point, interfered with his making sense.

Ben seemed to be aware of the difference between knowledge and the ability to develop an appropriate explanation in a given context. He reported that:

I think my knowledge in itself is fine. I think I will slightly improve...But I think I'm quite weak in terms of when given a situation, thinking and considering every single thing that is happening within that model...Because, at the moment I'm not linking everything, so I might only notice two things.... Instead of the whole range. (Ben, Session 16, 100-106)

The ability to activate appropriate conceptual resources in novel contexts is an important skill in learning about science and has been linked with understanding (de Regt, 2004). Therefore, understanding cannot be evaluated by assessing the presence or absence of particular conceptual elements; rather, assessment should focus on the manner in which conceptual constructs are developed across a range of contexts.

Learning might be modelled as consisting of three phases (see Figure 5.20). When students initially acquire expert scientific concepts, they may be triggered in a limited range of contexts (Tao & Gunstone, 1999) and coexist with alternative concepts (diSessa, 1988, 1993). For example, Ben was able to develop a conceptual compound that explained the independence of time to fall with mass for falling objects in a vacuum, a context he was familiar with, but struggled to organise the same elements into a compound in the context of the effect of mass on the time period of the simple pendulum. A facet of expertise is the ability to consistently apply expert concepts across a range of appropriate contexts (diSessa, 2002; diSessa & Wagner, 2005; Parnafes, 2012). An intermediate stage exists between these two phases (illustrated in the central section of Figure 5.20, below) in which a learner may possess similar concepts to an expert, but fail to activate them in appropriate contexts to form coherent conceptual compounds.

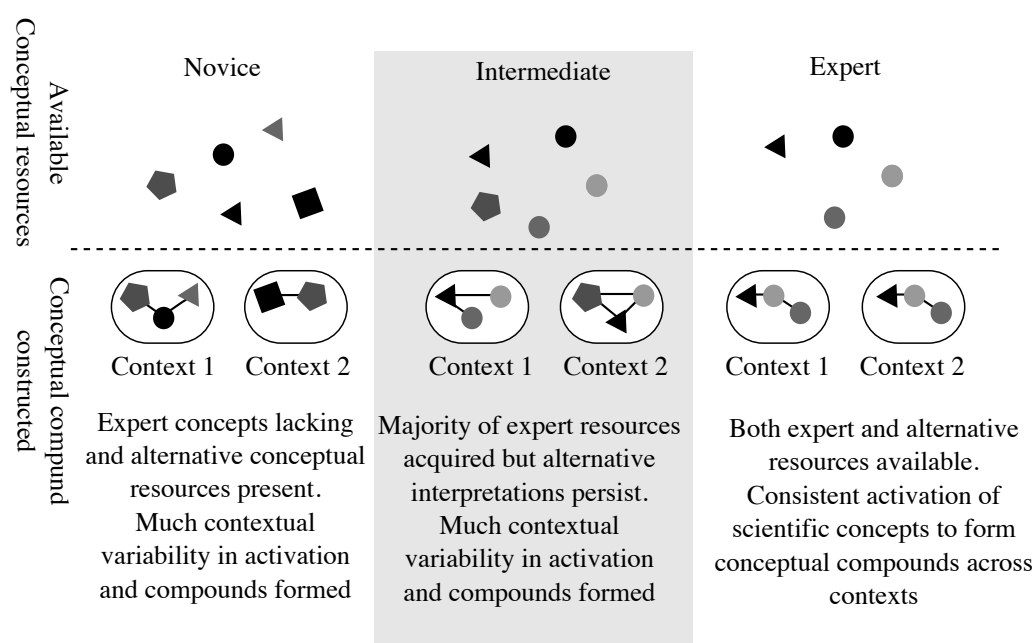


Figure 5.20: An illustration of the contextual activation of conceptual resources

It is important to distinguish the conceptual resources available to a learner from the particular conceptual compound they activate in a given context. Making judgements regarding the presence and stability of underlying resources when a learner is in the intermediate phase may be challenging, as only a subset of available resources may be elicited by a set of probes (Taber, 2013). Even in the expert phase of learning, experienced scientists may activate alternative concepts when forced to make choices at speed that are not characteristic of their responses under normal conditions

(Kelemen et al., 2013). The intermediate stage can be particularly challenging for learners and teachers, as the student does not need to be taught more propositional knowledge, but, rather, requires support to develop appropriate activation and organisation of conceptual compounds. During the intermediate phase, a student may display a high degree of variability in the kinds of conceptual compounds they can construct (for a discussion of the contextual variability of students' application of concepts see Section 5.6, below). It has been reported that high variability in approach to problem-solving contexts may precede an advance in learning (Adolph et al., 2008; Siegler & Chen, 1998); therefore, the production of a range of conceptual compounds in a given context (as described in Section 5.2.1.1, above) might be seen as an important feature of the intermediate phase of learning.

The discussion of different kinds of conceptual compounds in the literature review (see section 2.2) indicated the variety of conceptualisations of this construct in the science education research literature. To prompt a discussion of the nature of these aggregate entities, a taxonomy is proposed in Figure 5.21, across two axes of variation: stability and extent.

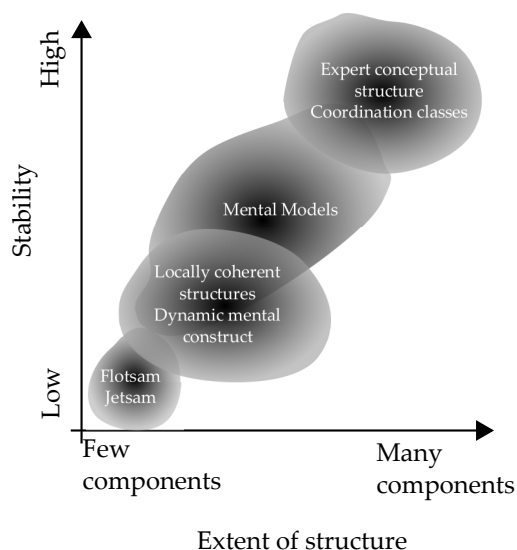


Figure 5.21: A taxonomy of different conceptual compounds

The differentiation of models of conceptual compounds shown in Figure 5.21 is not intended to indicate clear differentiations between different constructs but, rather, to indicate that the manner in which students relate conceptual elements can be constructed as differing across two axes. Initially, some of the students in this

research developed constructs of relatively few elements that were activated for relatively short periods of time. By contrast, it is expected experts might, if asked to make sense of the contexts present in this study, activate compounds that make use of multiple elements consistently over time and appropriate contexts. One factor that may drive the organisation of categories is perceptions of causality: it is reported that cause features are typically seen as more central to categories than effect features (Ahn et al., 2000). The next section examines changes in understanding of causality represented in the data.

5.2.3 Learning about causality

5.2.3.1 Students' understanding of causality in the context of electricity

A topic, which scientists model as a complex set of multiple causal relationships (Barbas & Psillos, 1997), direct current electrical circuits, was chosen to allow sufficient scope for investigating students' changing understandings of causality. In addition, a body of research exists describing students' causal understanding of electrical circuits at particular moments during development. Students tend to interpret the world through a framework involving a single agent and an acted-upon object: a causal Gestalt (Andersson, 1986). This Gestalt leads to misconceptions across topics in science; for example, in the context of electrical circuits, students may argue physical distance to the battery, or adding batteries in parallel, will affect the brightness of bulbs (Andersson, 1986). Students tend to assume linear, unidirectional causal relationships between variables (Green, 1997; White, 1995). A single variable may be assumed to be the only causal agent (Piaget & Inhelder, 1941/1997; Rozier & Viennot, 1991). For example, current may be perceived to be the only variable affecting the brightness of a bulb (Psillos & Koumaras, 1993) because, it is suggested, students may perceive current to be more concrete and intuitive than potential difference (Cohen et al., 1983).

As the causal relationships between electrical variables are complex, novice learners often develop simplified mental models. Tina Grotzer (2003, 2012, 2015) argues students often misclassify causality in science as a simple linear relationship when other more complex forms, such as mutual or relational causality would be more appropriate. It has been argued that the transition from applying linear to circular causality appropriately is a 'decisive' transition in learning about electrical circuits (Barbas & Psillos, 1997, p. 447). Students tend to apply models involving sequential causation to circuits (Closset, 1983; Reiner, Slotta, Chi, & Resnick, 2000; Shipstone, 1984) and struggle to appreciate the simultaneous causality that physicists construct (Grotzer & Sudbury, 2000; Perkins & Grotzer, 2005; White & Frederiksen, 1989). Novice learners are likely to analyse circuits, therefore, in terms of causes and effects localised to individual components, and to neglect systemic relationships (Cohen et al., 1983).

5.2.3.2 Categorising students' statements about causes

In order to develop a coarse-grained representation of changes in models of causality, students' utterances that related to causality, that is those that linked causes with effects, were categorised. A preliminary analysis of the data revealed students cited macroscopic objects, sub-microscopic entities and abstract rules as causes.

Consequently, a categorisation based on Gilbert and Treagust's (2009) taxonomy of models (after Johnstone, 1982) was felt to be relevant (see Table 5.1).

Table 5.1: Gilbert and Treagust's classification system of models applied to causes represented in Ben's transcript (see Appendix 8.8.1 for complete table of codes for all participants)

Category of cause	Description	Example response in Ben's transcripts
Macroscopic	Objects that are perceptible in everyday life are cited as causes (c.f. Gilbert & Treagust, 2009, p. 4).	I would link the resistance to the internal resistance caused by the battery. (Session 10, 66)
Sub-microscopic	Entities that are too small to be seen with optical microscopes are described as causes (c.f. Gilbert & Treagust, 2009, p. 4).	I think they will stay the same because you've got the same you're pushing the electrons by the same amount you're going to have more electrons through point one and two but they're not necessarily going to be travelling any faster than they were originally. (Session 6, 94)
Symbolic	Causes are linked to abstractions, symbols or algebraic constructions (c.f. Gilbert & Treagust, 2009, p. 4).	Current would increase um as I think one amp is actually one coulomb over one coulomb per second. (Session 6, 32)

A similar distinction between models in the context of electric circuits was proposed by Frederiksen, White and Gutwill (1999), who argued students could develop understanding based on models at the particle, aggregate charge or algebraic level. A key assumption of the classification scheme proposed here is that no category of cause is superior to another; rather, expert physicists might be expected to make use of all three types of causal entity in different circumstances. The probes used in the interviews asked students to explain an effect such as ‘Why is one bulb brighter than the other?’ or ‘Why does the current increase over time?’ The contexts the students were questioned about allowed causal explanations in any of the three categories. It may be that the selection of contexts contained some cues that triggered certain kinds of causal explanation; for example, it is possible that contexts in which practical apparatus was used may have triggered macroscopic causal explanations that were not triggered when paper based questions were presented. However, as a large number of different contexts were used in each of the static intervals (see Section 4.3.2.4), effects due to particular probes are minimised, and the aggregation of results can be seen as developing a cross-contextual representation of the availability of different understandings. The quantitative representations of data in Table 5.2 and Figure 5.22 are not intended to stand as completely valid or generalisable representations of change; rather, they are intended to act as a tool for selecting case studies for more detailed examination. It is assumed that changes to understanding of causality happen gradually; therefore, sessions 6-10 and sessions 17-21 were therefore considered to be static intervals. The categorisation in Table 5.1 was used to code students’ responses and the percentage of utterances in each category over the two static intervals was calculated (see Table 5.2).

Table 5.2: The frequency of occurrence of different types of cause over two static intervals (Amy's data is omitted as she left the process after session 10).

Student	Category of cause	Sessions 6-10	Sessions 17-21
Ben	Macroscopic	10 (25%)	5 (21%)
	Sub-microscopic	12 (35%)	10 (42%)
	Symbolic	18 (45%)	9 (38%)
Charlie	Macroscopic	11 (52%)	9 (39%)
	Sub-microscopic	1 (5%)	6 (26%)
	Symbolic	9 (43%)	8 (35%)
Daniel	Macroscopic	10 (37%)	13 (39%)
	Sub-microscopic	5 (19%)	5 (15%)
	Symbolic	12 (44%)	15 (45%)
Edward	Macroscopic	14 (38%)	12 (32%)
	Sub-microscopic	6 (16%)	9 (24%)
	Symbolic	17 (46%)	16 (43%)

The data in Table 5.2 were plotted in the graphs shown in Figure 5.22 below:

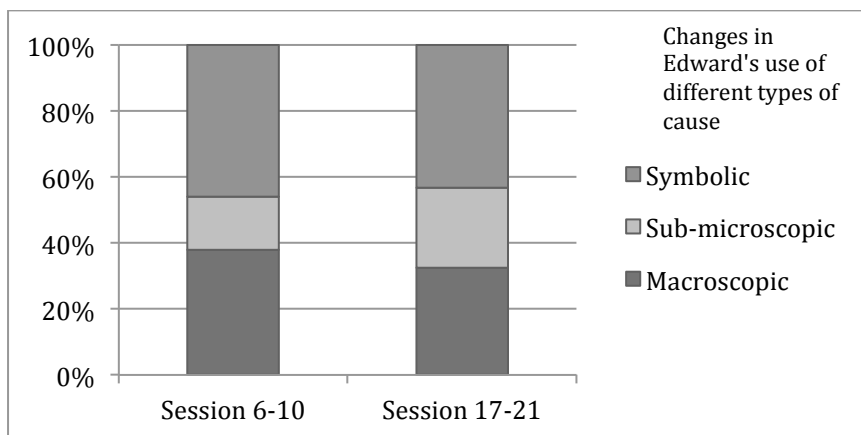
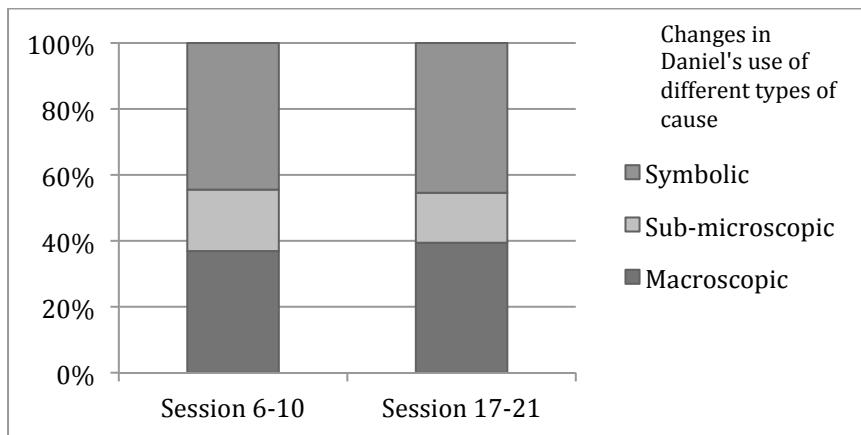
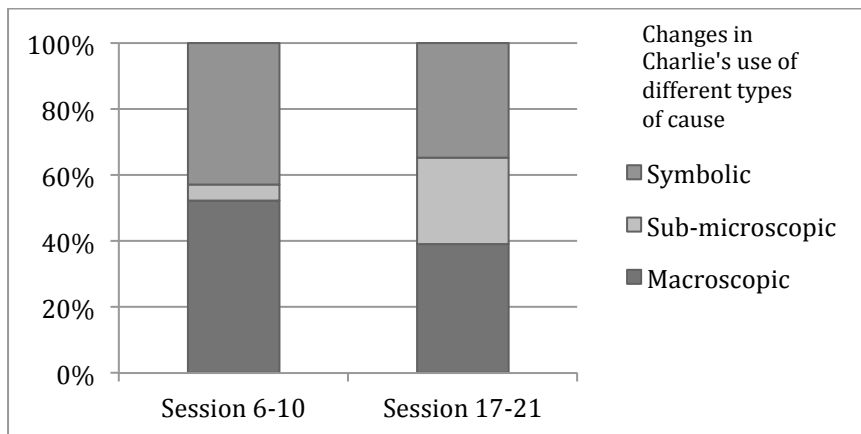
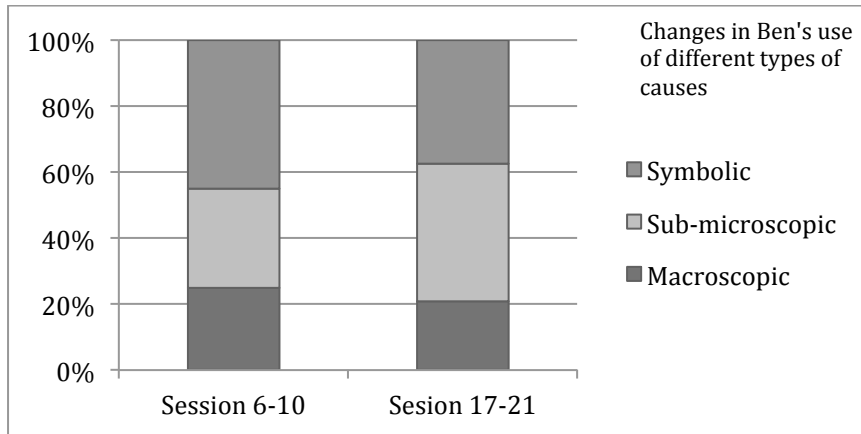


Figure 5.22: Patterns of change in students' use of different categories of cause.

The graphs in Figure 5.22 suggest that the changes in the use of causes between the two static intervals were relatively small for two of the students (Daniel and Edward), but larger for Charlie and Ben. In order to understand this change in more detail, the next section presents case studies of Ben's and Charlie's development.

5.2.3.3 Ben's learning related to causality

In his early sessions, Ben was generally comfortable using causal explanations involving abstract concepts: 'if the resistance of the wires is equal [current] will halve at that route and so effectively you've got the same current going to points' (Session 6, 140). He was also able to link abstract electrical concepts to physical entities: 'I think bulb C will be brightest um I think less because you've got more current so in a fixed amount of them you've got more electrons passing through the filament at point C and because of that you'll have more collisions and more energy will be transferred to the ions' (Session 6, 130). Ben's language sometimes suggested a direct link between physical objects and electrical concepts, for example, when discussing an electric motor lifting a load: 'Because um is it because the same amount of electricity has to pull up more weight so it's going to so the turn's going to be turning less fast and so the current's going to be less' (Session 7, 80).

Ben tended to think of variables in causal pairs that act in opposition to each other but, on one occasion, he displayed some early sensitivity to the existence of a wider causal network:

I think that they oppose each other, because if you have the same amount of potential difference, but more resistance then it would be harder for the current to get through. But if you've got the same current, and you increase the potential, then you decrease the resistance, providing the temperature isn't changing um [pause]. I think I would link current with potential difference because of Ohm's law that the current is directly proportional to the voltage across a conductor, provided the temperature remains constant, um [pause]. I think in the same way that potential difference and resistance oppose each other, current and resistance oppose each

other, 'cos if you have more resistance, then the electrons are going to have a lower average drift velocity so the current is going to be less. (Ben, Session 6, 38)

In general, however, in the first static interval, Ben tended to attribute effects to single causes, for example, 'it's the potential difference that causes things to get hot and emit light' (Session 8, 32). The explanations Ben gave in response to stimuli generally involved a fairly linear causal chain, for example: 'A [a bulb] will be less bright because you've slowed down the electrons so less electrons is reaching the bulb second so there'll be less collisions, less light energy emitted' (Session 6, 152).

As Ben's understanding of electricity developed, in the second static interval, his reasoning became dominated by abstract or algebraic arguments with little reference to macroscopic causality. For example, in calculating the potential differences across the bulbs in the circuit below (Figure 5.23), he ignored the physical structure of the circuit and simply divided the EMF between the four bulbs:

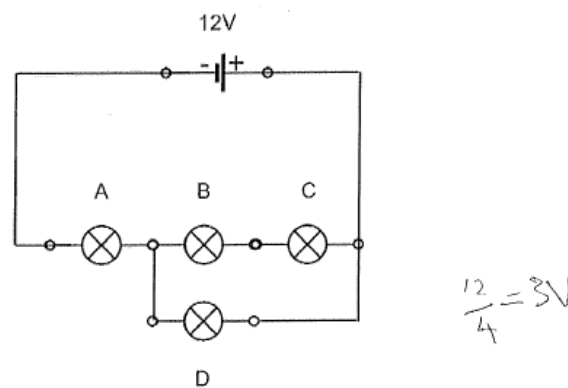


Figure 5.23: Circuit problem used in session 18 (See Appendix 8.7.2 (am)).

Yes, well one two three and four [pause]. So the [pause]. We've got four, four resistances to get through once, that's nearly. Three plus three which is six. So it'd be three so six minus three that'd three volts...Because this is going to use three joules per coulomb this is going to use three...Because if they're equal resistances then the voltage will be split evenly across all the resistors. (Session 18, 201-209)

Ben justified his commitment to abstract notions explicitly in a later session arguing: ‘it was much easier to work out things mathematically with potential difference’ (Session 21, 6). He reported that he found reasoning at the abstract level easier than working with sub-microscopic models:

I think because potential difference it’s easier to um I think picture and also decide on the values because it is just literally out of the EMF how much energy’s transferred to each component... Which I think is much more um easier to picture than a whole random collection of electrons moving along a wire. (Session 21, 72-74)

As Ben’s understanding developed he was able to explicitly comment on the mutual causality that exists: ‘Rather with electricity all the variables affect all the other variables’ (Session 21, 172). The complexity of his understanding of causality can be seen in Figure 5.24, below.

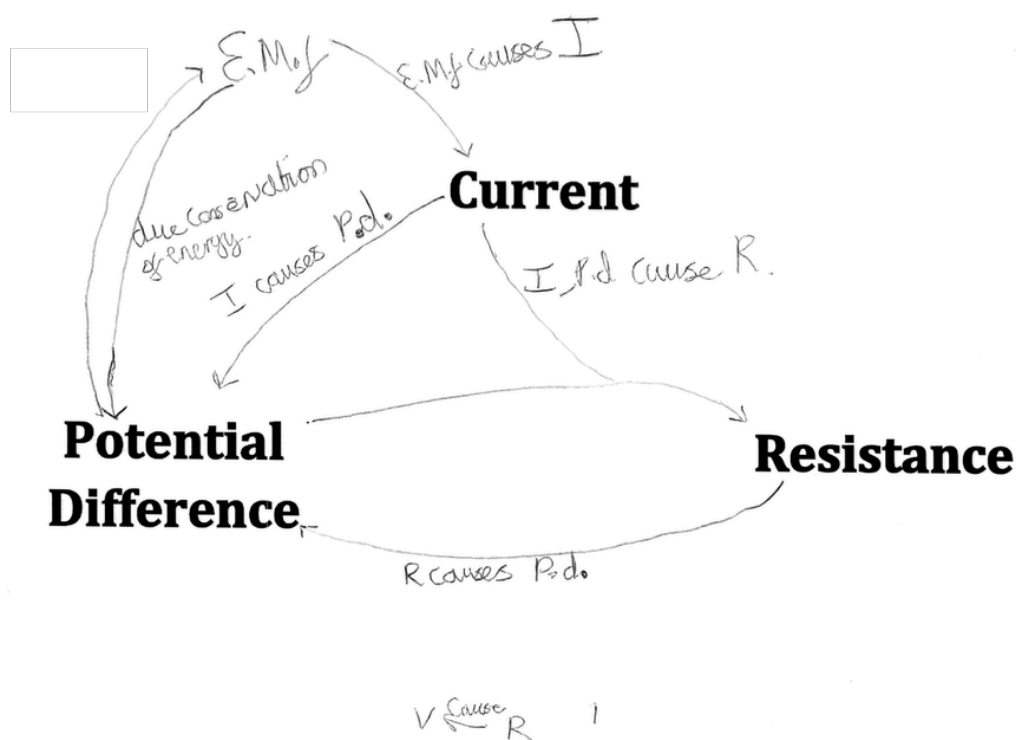


Figure 5.24: A representation of Ben’s understanding of causal relationships between electrical variables drawn in session 20 (See Appendix 8.7.7). The arrows point from cause to effect.

Ben displayed awareness that some electrical variables might be perceived as both causes and effects. For example, he argued current caused potential difference:

I think current [pause] causes the potential difference because, you, the electrons have to be moving through something...And if they're not moving through something, similar to the idea of something having a resistance, they're not going to have any potential difference. (Session 20, 58-60)

In addition, current was seen as an effect of the electromotive force: 'I think [pause] EMF [pause] causes current because it's the initial that provides the energy' (Session 20, 82). The increased sophistication of his causal understanding is demonstrated in his explanations, which take an increasing number of causal factors, at a range of different levels, into account:

Because, the, I think the main idea is if you're going to, if you're going to have more current, you're going to have more electrons passing, and if you've got, um, and so the voltage would then increase if R remains constant. (Session 17, 225)

5.2.3.4 Charlie's learning related to causality

Charlie's early arguments had a tendency to use macroscopic properties as causes in his explanations. For example, in explaining the division of current in different sections of a circuit he argued that distance will affect the flow of current: 'Cos it's in series and that's parallel so more er coulombs would go through the shorter route' (Session 6, 94). In his discussion of how the current drawn by a motor would alter if the load were changed, Charlie constructed a causal link between a physical object and current: 'Er because this [indicating masses being lifted by the motor] is against the current more current is going to have to be needed so it can pull up the weights' (Session 7, 130). The direct influence of macroscopic entities on electrical variables was also seen in a discussion of a capacitor circuit, as Charlie argued 'the current would decrease as time goes on 'cos of the gap' (Session 9, 90-92). Charlie's early

explanations suggested an understanding of current and resistance as opposing causal forces, in which: ‘potential difference has got to be more than the resistance’ (Session 6, 42) in order for current to flow. In a later session, asked why the potential difference between two points in a circuit is zero, Charlie argued: ‘Cos there’s more it’s a bigger er resistance than the voltage going in’ (Session 8, 126). Charlie tended to describe the causal links between pairs of variables, and rarely referred to more than one cause leading to an effect. His understanding of the relationship between current, potential difference and resistance appeared to exist as discrete pairs of relationships between variables, rather than as a network of interlinked causes and effects.

In the second static interval, macroscopic objects are still a common type of cause; in Session 17, Charlie reuses his earlier argument that the length of a wire affects the magnitude of a current. There are several instances in which physical objects are seen as the dominant causal agents, for example: ‘Because resistors are made to slow down or act against...a current’ (Session 21, 124-126). However there is a growing tendency to include sub-microscopic justifications, such as the repulsive forces between electrons: ‘‘Cos they’re negatively charged and they come yeah so they have repulsion between each other and they have a general direction where they flow’ (Session 20, 217). This kind of explanation was almost completely absent from his arguments in early sessions. Additionally, there seems to have been some development towards an understanding of the causal networks in electricity:

Mmm, can I put like tri... these three are all linked because in
V equals I R, the equation, er, changing one of these would
have an effect on the others as well, so they would all link
(Session 17, 162)

In an activity during session twenty, Charlie was asked to draw arrows, running from cause to effect, to describe the causal relationships between variables (shown in Figure 5.25).

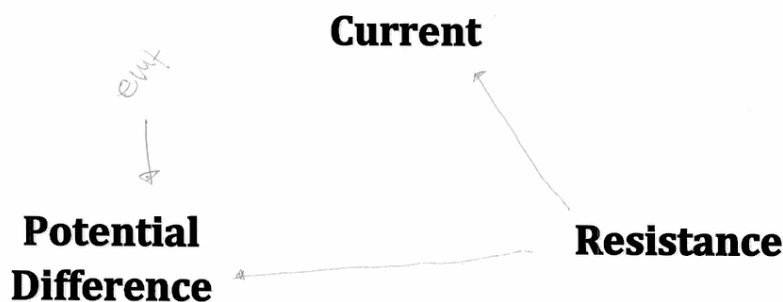


Figure 5.25: Charlie's understanding of causal relationships in electricity in session twenty; arrows run from cause to effect (See Appendix 8.7.7).

Despite the apparent awareness of the interrelatedness of causality shown in session 17, this diagram hints that Charlie's model of causality, at this time, consisted of a chain of uni-directional causes and effects.

5.2.3.5 Discussion of general patterns in learning about causality

The general pattern shown in Figure 5.22 suggested that the students, when they began the interview process, were typically more likely to make use of causes at the macroscopic and symbolic levels. Students' extensive use of macroscopic causes contrasts with Piaget's (1930/1970) claim that only children at early stages of their development will ascribe causality to physical objects, whereas older learners tend to use abstract causality. The case studies presented here suggest the pattern of development may be more complex than a simple transition between stages and, as will be argued in the conclusion (see Section 6.1.3), the ability to develop explanations at all levels of causality is a useful scientific skill. The prevalence of macroscopic causality in the students' initial responses might be accounted for by reference to the students' ontologies. In the discussion of the development of students' ontology above (Section 2.1.4.4), it was suggested that learners' initial categorisations tend to be linked to concrete examples of a category, rather than by abstract rules (Keil & Batterman, 1984; Rehder, 2007; Vygotsky, 1962/2012) and it has been observed that novice learners tend to categorise electrical variables as having a material ontology (Reiner et al., 2000). To take Daniel as an example, there are several instances that suggest, at times, he activated a substance-like model of electrical current:

Is it because its already gone through A and there's nothing like blocking nothing like resisting the current through A? (Daniel, Session 6, 138)

...like it [referring to a motor] used up more in the beginning. (Daniel, Session 7, 146)

Because [pause] it hasn't like been used by the bulb. (Daniel, Session 17, 136)

Um, it gets used up as it's coming in...Then it's dropped all of its current and it picks up here [the battery]. (Daniel, Session 20, 134-136)

Daniel's physical ontology of current may have led to his frequent selection of macroscopic causes in his first static interval. It has been suggested (see Section 5.1.3) that Gupta and colleagues' (Gupta et al., 2010) dynamic model of ontologies may be more fruitful than a model in which individual concepts are categorised in a single ontology (Chi, 1992; Chi et al., 1994); hence, Daniel's substance-like ontology of current is seen as one possible categorisation that is activated in certain contexts. A model in which ontologies are contextually triggered and which allows for the combination of features of different categories ('ontological blending' (Gupta et al., 2010, p. 304)), suggests that the sequential stage-like model of development of causality proposed by Piaget (1930/1970, pp. 258–273) is unlikely to occur; rather, Figure 5.22 suggests the development of causality proceeds through gradual changes in the likelihood of activation of different categories of cause.

In addition to macroscopic causes, symbolic entities, such as the concepts of resistance or potential difference, were often cited as causal factors in the students' early arguments. Such symbolic causes are likely to have been acquired from formal education. The dominance of macroscopic and symbolic causes might be likened to the initial position in Vygotsky's (1962/2012) metaphor of the direction of conceptual acquisition. Vygotsky (1962/2012, pp. 193–194) argued that development might be imagined as involving the 'upward' development of spontaneous concepts which move away from the concrete situations in which they were acquired, whilst 'scientific' concepts develop 'downwards', moving away from their original

abstracted conceptualisation towards more situated and personalised understandings. Similarly, in causal thinking, students' early arguments related to electrical variables may make frequent use of macroscopic causes because they are suggested by experience of physical objects as causal agents, and symbolic causes, because they are commonly referred to in classroom discussions.

5.2.4 The coherence of conceptual compounds

Students' perceptions of coherence may differ from those of expert scientists (Driver et al., 1985, p. 3). However, it is assumed that, when students developed a construct in a particular context, they perceived some degree of coherence between the elements they related, in so far as they had the option to chose not to develop an explanation. For example, Daniel (Session 16, 183), in one encounter with the ball in the bowl situation, admitted that he had 'no clue' how to construct an explanation of the motion. Though their emic perceptions of the strength of coherence doubtless varied between contexts, any attempt to relate two or more elements into an argument suggested some perception of potential coherence between the related parts; consequently the utterances containing such structures were coded as relating to coherence. There was considerable overlap in the utterances coded as relating to conceptual compounds and coherence; however, the foci of analyses were different: for compounds, the emphasis was on the nature of the compound constructs; for coherence, the focus was on the factors that drove a perception of relatedness. The examination of the construct of coherence, above (Section 2.4), led to the construction of three factors that were seen to drive the formation of coherence: pre-existing concepts, epistemology and the nature of the context. These aspects were used to categorise codes, and are discussed in the first three sections below (5.4.1-5.4.3). Incidents in which students defended developed coherences (5.4.4) emerged as an additional category during the analysis.

5.2.4.1 Pre-existing concepts as a driver of coherence

In some cases, the activation of a particular conceptual resource could be interpreted as driving the coherence formed. Daniel displayed a belief that, for objects in motion, there exists a driving and retarding force, which determine their motion and tend to equilibrium. For example, he accounted for the motion of a ball by arguing:

...because, like, there's more force coming from behind it than it is in front, but then the force isn't going to stay constant at all times, so, it might, the force might get lower from behind
(Session 1, 76).

This conceptual compound was stable over a number of sessions. For example, it reoccurred in session 11 when Daniel described the forces affecting the motion of a ball thrown vertically, and argued: ‘...it’s trying to equal out to come back down’ (Session 11, 273). This conceptual compound appears to act as a constraint that drives the formation of coherence. In session four, Daniel made sense of the forces that acted on a ball swung round on a rope in a horizontal circle. It appears that his belief in the existence of balanced forces in this situation, led him to propose an inward and outward force (see Figure 5.26), though, when questioned, he was unable to describe the nature of the outward force.

D: [pause] um, because when this [the ball] is swinging, the tension on the rope is tight, so it’s like restricting it from flinging off, so it’s like, I dunno how to explain it, but in my head I know what it is, but I just can’t explain it properly. It’s like, it’s not the force going outwards is being like slightly overtaken by the force coming in.

I: Well why label on the forces you think um you think would be there.

D: Um this is a force coming off [draws force along radius outside circumference, perpendicular to motion], and there’s a force.

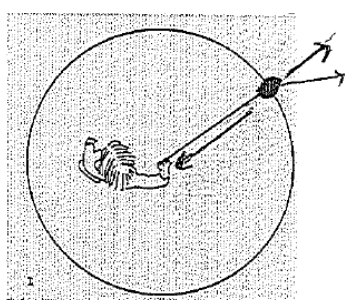


Figure 5.26: Daniel’s representation of forces on a rotating object.

I: What’s that force going outwards?

D: [pause] I don’t, I don’t know, I don’t what force it.

I: Where is there definitely a force?

D: There’s definitely a force here [indicating string].

I: Pulling which way?

D: Pulling inwards. (Daniel, Session 4, 80-88)

It appears that an organising principle, the existence of balanced forces, drove the arrangement of other conceptual elements into a compound (see Figure 5.27). As will be discussed in section 5.4.5, it appears that some of the understanding developed by the coherence, the nature of the outward force, is inexpressible or tacit.

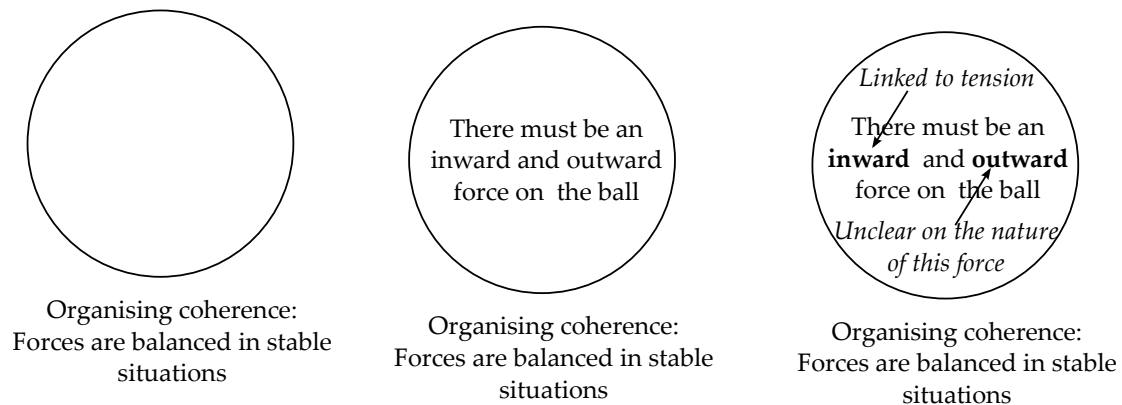


Figure 5.27: A representation of the manner in which Daniel's understanding of balanced forces drives the formation of coherence.

A different case of the manner in which prior knowledge may have affected Charlie's making sense occurs in relation to 'g-force'. Charlie first referred to this concept when making sense of the motion of a marble round the loop-the-loop:

I read in a car book when they do a wall of fate [wall of death].
I think it's called a wall of fate, and it's 'cos it is driving round
'cos its going so tight a circle it eventually gets pushed
outwards so its allowed to stick on the wall (Session 4, 100)

This piece of knowledge was used to develop a personally coherent explanation of the motion of the marble due to the interaction of the gravitational and 'g-force' (see Figure 5.28).

I think, because gravity is always going to pull it down, so it's gonna be pulled down to this [indicating bottom of loop], at this point the bottom of the loop, and it's already on the ramp so as it will go up, it will stay on path, and, I think, if you could say g-force would help it be pushed back up on the ramp, still, and it would carry on going round until it reaches the end.
(Charlie, Session 4, 86)

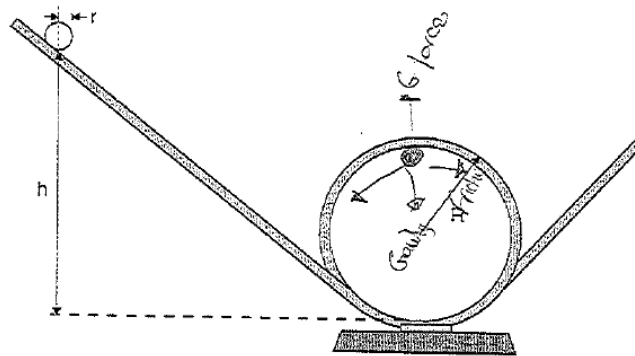


Figure 5.28: Charlie's representation of the forces acting on a marble in a loop-the-loop (See Appendix 8.7.2 (k)).

To develop this argument, Charlie drew on the assumption that, at the top of the loop, there was no resultant force acting on the marble. He proposed that: 'At that point [the apex of the loop] the forces g-force and gravity would be equal' (Session 4, 106). When asked if that construction makes sense, he changes the construct so that the 'g-force' acting radially outwards is larger than the weight.

Charlie often activated the belief that a force acts in the direction of motion. When making sense of the forces that act on a ball thrown vertically into the air, he developed a coherent argument around that belief. He described a motion force that acts upwards against a downward force, labelled as 'drag or gravity' (Charlie, 11, 136). He argued the motion force is larger than the downwards force on the upward part of the ball's motion, the forces are balanced when the ball reaches its peak, and the size of the motion force increases as the ball descends (see Figure 5.29).

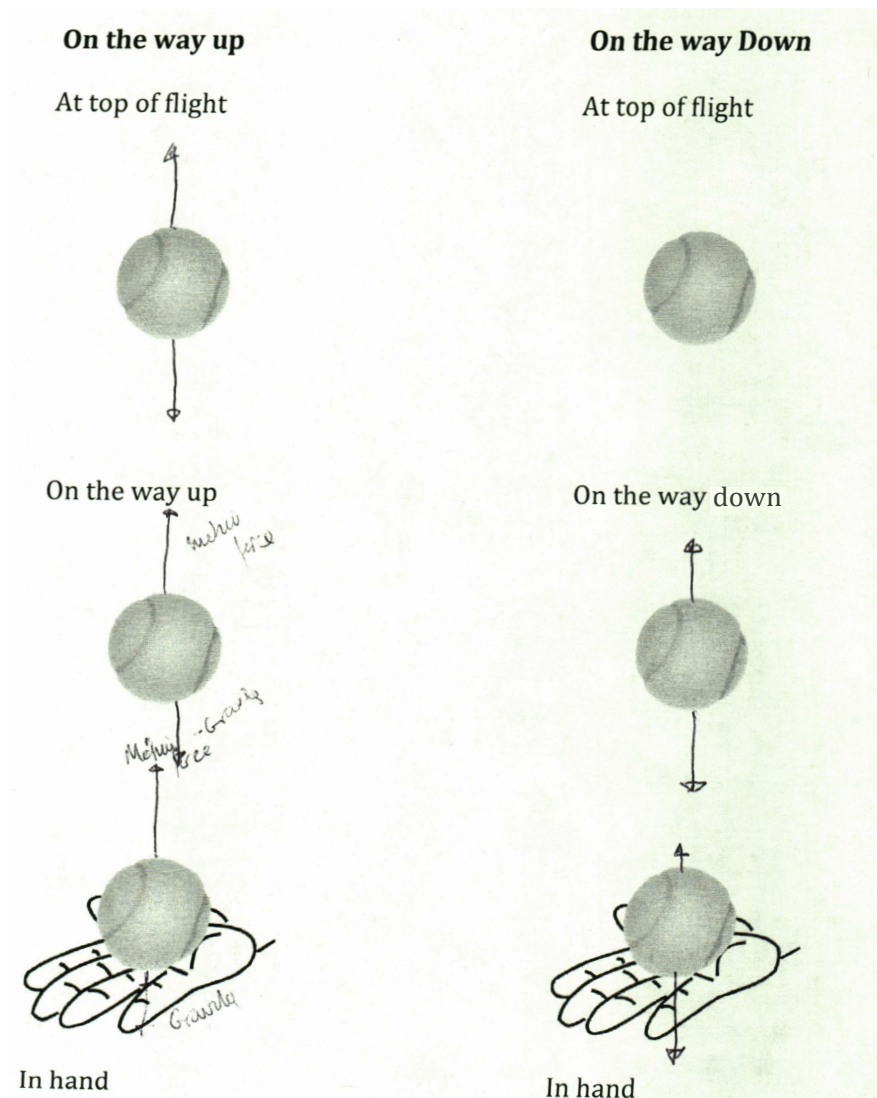


Figure 5.29: Charlie's representations of the forces acting on a ball, (See Appendix 8.7.2 (ag)).

Within his existing conceptualisation of motion, Charlie developed a coherent model of the variation of the two forces that he imagines act, in order to explain the motion of the ball.

5.2.4.1.1 The role of tacit elements in developing coherence

In addition to explicit conceptual elements, tacit elements, those that are not directly expressible in words (Polanyi, 1966, p. 4), may also channel perceptions of coherence. The noted difficulty of describing the nature of the concept of coherence (Garnham, 1997, p. 159) may stem from the partly tacit nature of constraining factors. A number of incidents in which the participants reported tacit influences playing a role in the development of coherence are discussed in this section. Daniel argued that

two balls of equal size, with different masses but dropped from the same height, will hit the ground at the same time. He proposed that ‘they have the same force acting on it, the same, like, magnitude of force’ (Session 15, 68) a claim which arose from his intuition that: ‘I know they’ll definitely hit the ground at the same time, but explaining it, I wouldn’t know how to explain it’ (Session 15, 72). Similarly, Amy was asked to predict and explain the trajectory of a ball swung in a horizontal circle when the string broke. She suggested the ball would follow a tangent to the circle, but struggled to articulate the reasons behind her prediction: ‘I just think it seems logical that’s what I’m just thinking I am not really basing it on any knowledge I’m just thinking it sounds logical’ (Session 4, 114). Daniel’s and Amy’s perceptions of the motion of objects may be based on an intuition about the manner in which physical objects move that is not expressible in words (Brock, 2015).

Ben described an awareness that some of his reasoning was based on intuitive hunches and, in the context of a collision between a car and a lorry, he was able to overrule the tacit perception with a reasoned answer:

I had a gut instinct and still have a gut instinct that they exert equal amounts of force...I could, but I couldn’t find, the, um, logical reasoning for it, so I did what I could, which was logically reason something that, that, from that perspective seemed to be correct.
(Ben, Session 16, 60-66)

This kind of cognition has been described as characteristic of ‘intuitive’ or ‘system 1’ thinking: Kahneman (2011, p. 105) argues that system 1 thought ‘creates a coherent pattern of activated ideas in associative memory’ and exaggerates consistency, neglects ambiguity and ignores absent evidence. This kind of difficult-to-express construction is also seen in Daniel’s understanding of the relationship between forces acting on a lift moving up at constant velocity:

D: As it’s going up the [pause]. The force of gravity is getting bigger [pause]. Yeah, I think the force is getting bigger as it goes up.

- I: Why does the force of gravity get bigger as it goes up?
- D: [pause] I don't really know to be honest. I just, it's just one of these things that you just know, like, 'cos higher up it is [pause]. Um the more time it takes to come down.
- (Daniel, Session 1, 94-96).

Similarly, Daniel perceives that the motion of a ball on a U-shaped track and a pendulum are similar, yet struggles to articulate the areas of coherence: 'I don't know how it would link to tension but it would have more like I don't know what you would call it here [end of track] it would just have more effect on it' (Daniel, 15, 371).

5.2.4.2 Epistemology as a driver of coherence

Epistemological resources can play a role in the formation of coherences, as a student may make assumptions about appropriate responses when they encounter a difficulty in making sense of a situation. In a discussion of his learning in physics, Ben (Session 4, 30) commented that: 'I think sometimes physics can be very detached' and '...if you are looking at the topic for the first time in which case you just have to look at it on its own'. During his first session, Ben (Session 1, 4) had remarked that he did not expect to fully understand physics; rather, he suggested that there is 'always some confusion'. In describing his process of learning about electricity, he remarked that: 'I think there are a lot of models that work and are different but we haven't been able to sort out which one is the correct' (Session 5, 44). This epistemological expectation that physics will have plural, possibly contradictory models may underlie the tendency in Ben's thinking to be accepting of the existence of multiple models rather than seeking a single unified account. Taber (2000b) describes a similar case, in which a student accepts the existence of a plurality of explanatory models of chemical bonding.

In session six, Ben was asked to consider what would happen to the potential difference across two branches of a parallel circuit, each containing a bulb, if one of the bulbs were removed. He initially argued the potential differences across the branches would increase; then he claimed the values would remain constant. Ben was aware of having developed two models, one based on '[t]he amount of coulombs per

second', and the other 'in terms of push' (Session 6, 110-116). He described a difficulty in choosing between the two models suggesting that his preference is: 'I think eighty per cent for the speed of the coulombs and twenty per cent for the voltage being pushed' (Session 6, 120).

In the context of thinking about the motion of a lift (described above in section 5.2.2.3), Ben developed two explanatory models of the situation and concluded: 'I am not sure whether the resultant force is greater or the same'. He did not attempt to reconcile the contradictory accounts and seemed to accept the state of contradiction that existed. A similar situation occurred in Ben's analysis of the forces on a boy jumping from the ground (discussed in detail in section 5.2.23). He was again unable to resolve a situation in which he could perceive two coherent accounts.

I'm just not sure whether they ...occur instantly after each other and not after instantly at the same time as each other or whether they, there's a gap between them. (Ben, Session 13, 337)

Ben may, or may not, have possessed the skills to evaluate which of the two coherences was more fruitful, however, it is interesting to note that he again made no attempt to resolve this apparently incoherent mental state.

Amy reported that if she couldn't make sense of an idea in physics '...it is always in the back of my mind. I do like to know how things work' but accepts 'there are things that I just don't get so I'll just leave it and move on'. She claimed that, rather than focusing all her energy on resolving a particular difficulty, it was best to progress onto other issues. This attitude appears to have caused Amy similar difficulties to Ben: she was aware of two interpretations of how potential difference across a charging capacitor varied (see Section 5.2.2.3, above), but was unable to choose between them: 'I'm stuck between the two' (Amy, Session 9, 140). However, in the context of discussing the forces on a lift, she made a choice to resolve two incoherent accounts, though admits the reasons for her choice may be tacit:

Well the upwards force can't be greater than the downwards force because otherwise the person would just move up to the top of the lift [pause] erm [pause]. I don't know, now I am thinking would they just be, would they just be the same, erm [pause]. I don't think it would be the same. I wouldn't be too good at explaining why though [laughs]. (Amy, Session 4, 373)

Daniel, in his first session, was asked if he believed ideas in physics cohere, and he replied: 'Yeah, yeah it should but not all of it does' (Session 1, 6). He imagined a moment when two contradictory explanations occurred: he felt he wouldn't be able to reach a resolution on his own and that he would seek help from a teacher. In comparing the current flowing into and out of a motor lifting a weight, Daniel (Session 7, 132) argued first that 'there's just more current [entering the motor] because then if the current was the same it wouldn't be able to lift it up'. Subsequently, he proposed a model in which the currents entering and leaving would be equal, though he argued that he couldn't justify that prediction: rather 'it just sounds right' (Session 7, 150). Daniel described the existence of two models as 'baffling', and, when asked to assign confidence to the two interpretations, claimed: 'It's probably the second one but I just like because of the because I can explain the first one I'd say like sixty forty for the first one because I can explain it' (Session 7, 152). It is impossible to infer a direct link between epistemological beliefs and the students' interpretive dilemmas. However, it might be assumed that a stronger commitment to the coherence of physical explanations might have encouraged greater reflection when contextual and knowledge affordances allowed the construction of two personally coherent explanations.

5.2.4.3 Context as a driver of coherence

The contexts of particular probes may drive students to develop conceptual compounds that are personally coherent, even to the extent that the compounds contradict other beliefs. For example, when Ben explained how a ball can loop-the-loop, he temporarily argued that gravitational force can have a sideways component.

- I: Why doesn't the ball drop downwards?
- B: [pause] Is it because [long pause]. Is it because gravity is causing it to, um, de- [pause] -ccelerate, well, accelerate towards the centre? But gravity is also, because it's resisted here [at top], it's almost swinging it around
- I: Which way does which way does gravity always act?
- B: Downwards.
- I: Can it provide a sideways component?
- B: Yes [pause].
- I: Explain.
- B: Yes, so, gravity acts downwards [pause]. So it can also do [pause] a horizontal component [labelling horizontal arrow H in Figure 5.30, below] and a vertical component [labelling vertical arrow V and adding diagonal line] that's with itself.
- I: Where's the horizontal component of gravity coming from?
- B: [pause]
- (Ben, Session 4, 109-118)

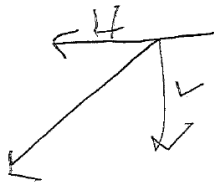


Figure 5.30: Ben's representation of the forces acting on a marble at the apex of a loop-the-loop.

It would appear that Ben required there to be some horizontal component of the force on the ball for it to be able to loop-the-loop, perhaps due to his understanding, triggered in some contexts, that a force acts in the direction of motion (see section 5.2.5.1). He assumed that the only force acting on the ball was the gravitational force; consequently he applied knowledge that a vector quantity may be resolved into two perpendicular components to argue that a horizontal component of gravity caused the ball to travel round the loop. The coherence is one to which Ben has little commitment, and it is soon discarded. In this case, the nature of the context causes

Ben to temporarily develop a local coherence that contradicts a secure knowledge element, the direction in which the gravitational force acts.

Coherence is conceptualised as a perception of fit that occurs between conceptual resources; however, such perceptions may vary across contexts. In his first session, Edward (Session 1, 58) showed awareness, in the context of the motion of a lift, that an object travels at constant velocity when no resultant force acts on it. When he came to observe the motion of a simple pendulum in the next interview, Edward perceived the motion as involving an initial acceleration from its stationary state, followed by a period of uniform motion:

I: And are there any points when it is not accelerating?

E: Yeah, almost the rest of it.

I: Because?

E: It is travelling at a constant velocity.

(Edward, Session 2, 49-52)

Despite developing an understanding that the tension in the string supporting the pendulum's bob varied with displacement, because Edward was committed to his perception that the pendulum moves with constant velocity, he argued that the 'overall force' on the bob remained constant: 'the overall force on from each individual force is always the same so the acceleration remains constant' (Edward, Session 2, 140).

In the third session, Edward was introduced to the oscillations in the vertical axis of a mass on a spring. In this context, Edward categorised the motion of the mass as involving changing acceleration with displacement: '... if there's more displacement that means there is more force acting on it therefore higher acceleration'. By linking the changing acceleration to resultant force and displacement, Edward was able to develop a coherent explanation of the motion of the mass on the spring. In the fifth session, the discussion of a practical situation focused on the oscillations of a marble released from the rim of a concave bowl. Edward's initial attempt at explaining the motion activated few resources related to abstract concepts such as force or

acceleration, rather it focused on physical features of the situation: ‘Isn’t it something to do with the gradient, er [pause], and the gradient’s like zero at the bottom ... It’s a larger number at the side, so it sort of moves down to the centre’ (Edward, Session 5, 80).

When prompted to explain in more detail, Edward proposed an argument that: ‘...the gravity acting down on it would be stronger as the further you pull it away the more force acts on it’ (Edward, 5, 96). This may be a partial reactivation of the force-linked-to-displacement resource that was used in the case of the mass on the spring; however, Edward was unable to describe a mechanism which explained the variation. This difficulty may have arisen from Edward’s weak understanding of reaction force: when asked to describe the forces acting on the ball, he replied: ‘...probably weight and something to do with lift’. Without the necessary resource, the changing direction of reaction force with displacement, Edward struggled to develop a coherent argument. In a model of making sense as the coordination of conceptual resources, Edward’s ability to form a coherent structure in each of the contexts might be summarised as shown in Table 5.3:

Table 5.3: Summary of Edward’s attempts to develop coherent accounts in three contexts.

Pendulum (Session 2)	Mass on a spring (Session 3)	Ball in bowl (Session 5)
<ul style="list-style-type: none"> • Perceived the bob as moving at constant velocity. • Was aware of link between tension and displacement. • Made sense by arguing whilst overall force didn’t change, tension did. 	<ul style="list-style-type: none"> • Perceived motion as involving varying acceleration. • Was aware of a link between the magnitudes of displacement, force and acceleration. • Made sense in a manner that matches accepted scientific explanation. 	<ul style="list-style-type: none"> • Perceived motion as involving speeding up and slowing down. • Had a weak understanding of reaction force. • Made sense by arguing gravitational force varied with displacement, but was unable to explain variation.

Edward's attempts at making sense of the different contexts demonstrate the challenge of coordinating multiple conceptual resources. Edward has many of the appropriate resources to develop coherent accounts of the situations, but an erroneous perception of motion, and missing resources related to the reaction force, led to the development of alternative accounts. The context of the mass-spring oscillator and the ball in the bowl triggered a perception of accelerated motion that drives the formation of coherence. As the claim related to a perception, it is difficult to understand the particular features of the pendulum context that led to Edward's claims that the bob: '...stops just for a second [at maximum displacement] and then it continues going at the same speed' (Edward, Session 2, 38).

Even when many appropriate resources exist, students may still develop alternative coherences. In the first session, Edward was asked which of two objects with different masses, released above the surface of the Earth, would hit the ground first. His response is shown below:

Hmmm, I would say, the one with the heavier mass, 'cos because, going back to Newton's Law, force equals mass times acceleration. If they are both going the same speed, they'd both have a similar acceleration, but if the one has a higher mass, then mass times acceleration would bring a higher force behind it than the other...The bigger one would travel further. (Edward, Session 1, 32-34)

In the excerpt above, conceptual resources that match scientific understandings, Newton's second law and the observation that the masses will accelerate at the same rate, are used to justify an intuition that the larger mass will travel further. In order to develop a personally coherent argument with these elements, Edward forms a link between force and distance travelled. Elsewhere in the first interview, in discussing a collision between a lorry and a stationary car, Edward had argued: 'the lorry doesn't just carry a greater mass but there is also more speed therefore more acceleration acting behind it so the force would be greater' (Session 1, 40). This link between force and velocity (Viennot, 1979) might be linked to a conflation of velocity and

acceleration that appears a number of times in Edward's arguments and might underlie the development of the link between force and distance travelled. In the example above, when Edward attempted to describe the motion of falling objects, despite the availability of appropriate resources to develop a coherence that matches the scientific model, intuitions regarding the nature of motion that are triggered by the context lead to the construction of an alternative coherence.

An examination of another case, Ben, demonstrates the personal nature of the development of coherences (see Table 5.4).

Table 5.4: Summary of Ben's interpretations of three contexts.

Pendulum (Session 2)	Mass on a spring (Session 3)	Ball in bowl (Session 5)
<ul style="list-style-type: none"> • Argued gravitational force causes acceleration. • Stated he didn't understand how the pendulum could move upwards. 	<ul style="list-style-type: none"> • Linked motion to changes in tension. • Argued tension decreased as displacement increased. • Suggested acceleration was zero at maximum displacement. 	<ul style="list-style-type: none"> • Argued the magnitude of gravitational force varied due to changing gradient of bowl. • Argued that, at the top of the slope, force was balanced by velocity so ball would be stationary.

Ben's attempts to make sense of the contexts differed from Edward's. He appeared to have a more stable link between the concepts of resultant force and acceleration than Edward, however he struggled to develop explanations in which several forces acted together. The differences between the coherences developed by Edward and Ben in different situations suggest that contextual factors may have had an impact on the formation of coherences.

5.2.4.4 There is a drive to maintain a developed coherence

The meaning maintenance model (Heine, Proulx & Vohs, 2006) suggests that the representations of the world people develop have some stability because disruptions to meaning frameworks are unpleasant, therefore people strive to protect developed meaning structures. An example of a coherence defended against a threat to its

stability is seen in Edward's comments related to a ball being swung round on a string.

I: Which way is the resultant force on the ball?

E: Going that way isn't it [adds clockwise arrow on Figure 5.31].

I: If there was a force going that way what would happen to the velocity of the ball?

E: It would stay constant.

(Edward, Session 4, 89-92)

In this case, Edward activates the belief that a force is required in the direction of motion. He is then prompted to consider the effect of the resultant force on the motion of the ball.

I: Um will there be a resultant force in the direction of its motion?

E: Er, not necessarily,

I: Not necessarily?

E: No, if there's a reaction force going the opposite way that's equal to it, then it will just keep it at a constant velocity rather than acceleration.

(Edward, Session 4, 101-104)

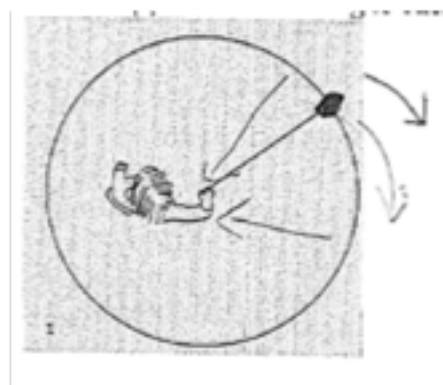


Figure 5.31: Edward's annotation on a diagram of a ball being swung on a string.

The discussion triggered Edward's belief that force causes acceleration and so, in order to defend his coexisting belief that a force acts in the direction of motion, he constructs a 'reaction force' that acts in the opposite direction to the 'driving force', in order to allow the ball to travel at constant velocity.

As described above (see Section 2.4.4), preconceptions about the outcome of an event may cause students to disregard novel information in order to maintain their existing model (Chinn & Malhotra, 2002). In such a case, Charlie was asked to predict the potential difference across two equal resistors connected in parallel to a 12V supply. He had predicted that there would be a potential difference of 6V across each resistor, because 'there's two components so it would be half' (Session 19, 265).

Subsequently, he was shown a simulation of the circuit and confronted with the contradictory data that the reading across the two resistors was 12V. In order to maintain the coherence he had developed, Charlie argued that because the parallel branches were physically linked together, the potential difference measured in either of the branches will be a measure of the total potential difference across the two resistors: 'So it's like wherever you measure on one yep if you put it [referring to the probes of the voltmeter] on any of the others it's the sum of er them both of them added up 'cos it's the front and the end of it' (Charlie, 19, 307).

The stability of coherences may be linked to their emotional resonance. Thagard (2006) has claimed that the experience of developing coherence is associated with positive emotions: reaching, even a temporary state of coherence may result in comfort and satisfaction (Parnafes, 2012). Conversely, Daniel reported strong aversive feelings in the moment of not being able to make sense:

Basically, like, I don't know, it's just the way I work, if I don't, if I understand something, I don't understand something it, it bugs me, it annoys me if I don't understand something. So that's why I like go the extra mile to know how to understand something so that my mind's at rest, literally...Urgh, it's terrible like I actually, ah, I just hate it. I hate it when I don't get something and when I

go back on it and I understand it I find out how easy it is and that is what annoys me the most. (Daniel, Session 4, 8-10)

By contrast, Daniel described the moment of reaching understanding as: 'It's relief. Like the big one of the biggest reliefs' (Daniel, Session 4, 12). Ben described how, once a 'habit of thinking' is established, it is very difficult to break from it and establish a new model. The affective associates of coherence may well be factors that promote or minimise conceptual change (Thagard, 2006, pp. 182–183).

5.2.4.5 Discussion of general patterns

Coherence is a significant concept as it defines the manner in which concepts are perceived to 'fit' together. The three factors described above seem to be a useful structure for discussing the notion. It is worth noting that students' alternative concepts acted to channel the kinds of coherences they perceived. This observation is significant as alternative concepts might be imagined to have a broader function than simply competing for application with the concepts accepted by science. As coherence has been argued to involve judgements of fit in relation to background knowledge (Patalano et al., 2006), students' idiosyncratic conceptual ecologies can be conceptualised as channelling the kind of constructs they judge as coherent. As discussed above, Daniel's belief that two competing forces act on objects in motion leads to the development of a coherent explanation of circular motion. The examples cited above suggest that the students, on a number of occasions, could perceive multiple alternative coherences, but failed to make a judgement between them. This acceptance of incoherence may have arisen from their assumptions about the unity of physics as a discipline and their expectations of sense making (Hammer, 1989). Though the failure to choose between alternatives may, be problematic in some contexts, it may be a useful approach for maintaining multiple alternative explanations in contexts where evidence is limited. Indeed, some degree of inertia to change between mental models, sometimes called the 'status quo' cognitive bias (Kahneman, 2011, pp. 304–305), may be a useful feature that prevents overly rapid switching between conceptual positions.

Students may develop a range of different coherences, in different contexts, based on factors that are challenging for an external observer to detect; judgements of

coherence are subjective acts (Hoey, 1991, p. 12). Hence, it is unsurprising that students may perceive situations in a different way to the researcher, and may perceive contexts that a researcher views as similar, as distinct. For example, Edward interpreted the motions of a pendulum and a mass on the spring as being of different kinds. The subjective perception of contexts may lead to the development of ‘locally coherent’ systems of conceptual elements (Hammer, Elby, Scherr, & Redish, 2005; Parnafes, 2012). As the examples above suggest, students attempted to defend some of their coherences, though others were short-lived and quickly abandoned. The stability of some coherent conceptual compounds is both a benefit and hindrance to students’ conceptual development: constructs that resemble, and differ from, accepted scientific arguments may be difficult to change if they are perceived to be coherent.

5.2.5 The rate of conceptual change

The rate of conceptual change was defined in Section 2.5.5 as the rate at which the oftenness of application of a concept, in a particular context, varies over time, where oftenness was taken to refer to participants' or researchers' subjective interpretation of how commonly a particular concept is triggered in a given context. The analysis occurs in four sections divided into 'emic' (as constructed by the participants) and 'etic' (as constructed by the researcher) descriptions of change (Pike, 1967, pp. 571–575). A further division is constructed between descriptions of change over long (between interviews) and short (within contexts) timescales.

5.2.5.1 Etic descriptions of long timescale conceptual change

An important facet of the definition of rate of conceptual change given above is the notion that conceptual change should be assessed in a single context. Descriptions of learning suggest different contexts may trigger the activation of different concepts (Clough & Driver, 1986; Mishler, 1979; Palmer, 1993; Taber, 2008b; White, 1985); therefore, claims to change should be made by comparisons of activation in a single context. Table 5.5 and Figure 5.32 illustrate the repeated probes that were introduced to students in the sessions related to force and motion.

Table 5.5: A representation of the repeated probes in the sessions related to force and motion. The dark grey bars indicate where sessions on electric circuits took place. Interviews with consecutive numbers occurred at intervals of 1 week. An interval of eight weeks occurred between interview 5 and 11, and an interval of seven weeks occurred between interview 16 and 22.

Probe	Session														
	1	2	3	4	5		11	12	13	14	15	16		22	
Mass on a spring			✓								✓			✓	
Simple Pendulum		✓									✓			✓	
Astronaut in Space			✓									✓		✓	
Dropped balls	✓										✓				
Projectile dropped from a plane	✓										✓			✓	
Object in free fall	✓										✓			✓	

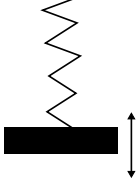
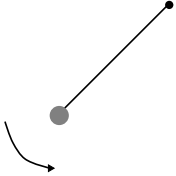

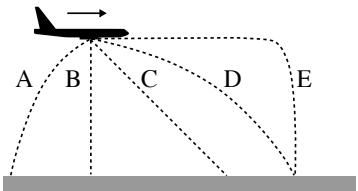

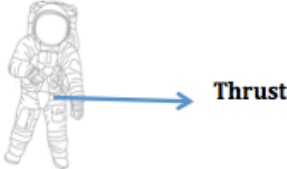
<p>Mass on a spring, interview 2, 15, 22 Student is shown a mass-and-spring oscillator</p>  <p>The student is given the following prompts:</p> <ul style="list-style-type: none"> • Describe the motion of the mass (sketch graphs of displacement, velocity and acceleration against time) • Explain the motion of the mass • Draw a force diagram to illustrate your answer • Predict what will happen when the mass on the spring is increased 	<p>Simple pendulum, interview 2, 15, 22 Student is shown a simple pendulum system</p>  <p>The student is given the following prompts:</p> <ul style="list-style-type: none"> • Describe the motion of the bob (sketch graphs of displacement, velocity and acceleration against time) • Explain the motion of the bob • Draw a force diagram to illustrate your answer • Predict what will happen when the mass of the bob is increased
<p>Dropped balls, interview 1, 15, 22 (Adapted from Epstein, 2009, p.27)</p> <p>Two balls are dropped at the same time, from the same height. The balls have the same diameter but one ball has a greater mass than the other. Which ball will hit the ground first? Explain your answer.</p> 	<p>Projectile from a plane, interview 1, 15, 22 (Adapted from Epstein, 2009, p. 133)</p> <p>An aeroplane is travelling with constant velocity when it drops a ball. Which path best describes how the trajectory of the ball would look to an observer on the ground? Explain your answer.</p> 
<p>Free fall, interview 1, 15, 22</p> <p>A ball is dropped from the top of a building. Describe and explain its subsequent motion</p> 	<p>Astronaut in space, interview 3, 16, 22</p>  <p>The astronaut below is in space, far from any planets. They have on a thruster which exerts a constant force. Describe the motion of the astronaut when the thruster is fired. Describe how their displacement, velocity and acceleration will change over time? Sketch a graph of each.</p>

Figure 5.32: Representations of repeated prompts (See Appendix 8.7.2)

The context of forces and motion was selected as a domain for the analysis of the rate of conceptual change as two concepts of force, force linked to acceleration and force linked to motion (Viennot, 1979), occurred frequently in the students' transcripts. The transcripts were coded for the occurrence of these two concepts, and the point at which they occurred within a session was noted, as shown in Table 5.6. Note that these two understandings are not conceptualised as representing the totality of interpretations of force available to Daniel.

Table 5.6: Examples of coded sections of Daniel's transcripts (See Appendix 8.7.6 for complete list of codes).

Session; utterance	Comment linking force to acceleration	Comment linking force to motion
1;52		...it's heavier when it's coming down it will be coming down quicker than a lighter ball
2;180	this is where it is accelerating here 'cos the force that's going to be acting on it	

The applications of these understandings were tracked in contexts that occurred repeatedly (see Figure 5.32) and plotted as graphs, shown in Figure 5.33, below. This representation is an adaptation of the figures found in Tao and Gunstone (1999). Daniel's and Ben's transcripts were selected for discussion because they contained the greatest number of incidents of activation of the two concepts of force in the repeated contexts. As argued above, the data are not intended to be generalisable to all students, but rather to represent the detail of conceptual change for a particular learner. Note also that, as represented in Figure 4.3, a short static interval is implied because change is constructed between individual utterances, or sections of utterances.

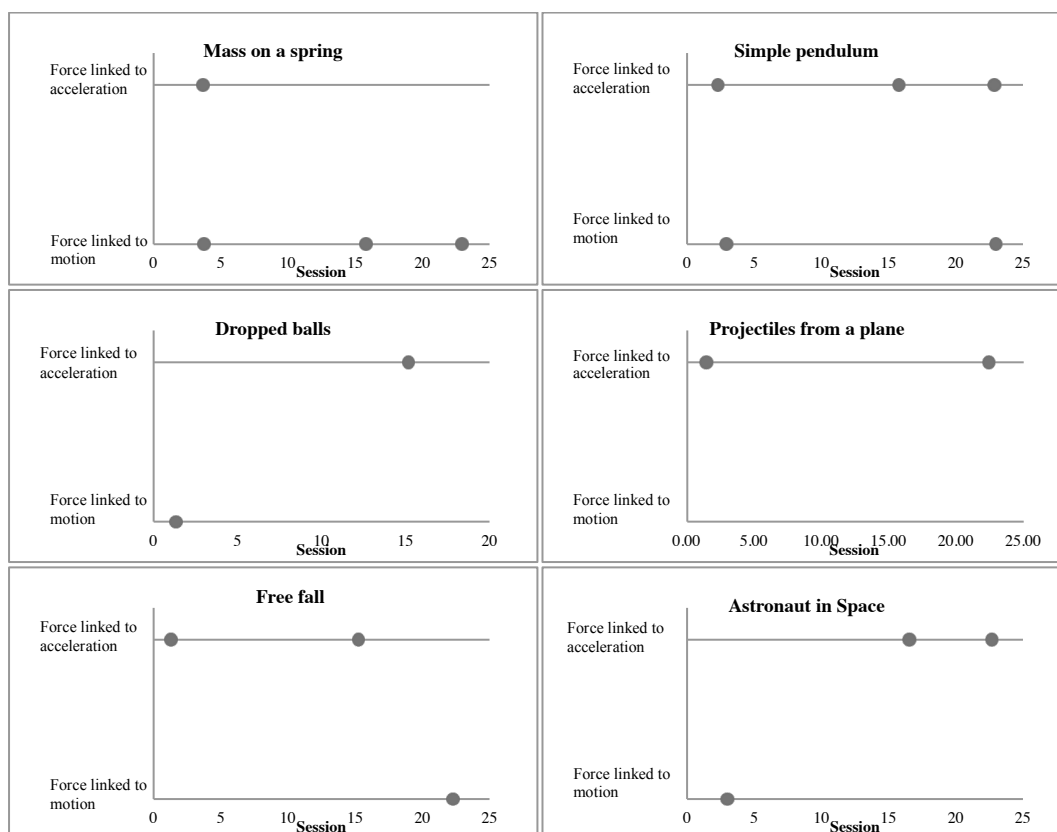


Figure 5.33: A representation of conceptual change in Daniel's application of two interpretations of the force concept across various contexts. Note that the x-axis is discontinuous in this representation, as it only represents time within sessions. The markers indicate the position of an utterance within a session. For example, Daniel's second session consisted of 210 utterances, so an activation of force linked to acceleration in utterance 105 would be plotted at the point (2.5, 1).

The representations in Figure 5.33 suggest that conceptual change may proceed at different rates in different contexts. In one context, a projectile dropped from a moving plane, Daniel seemed to make stable use of the concept of force linked to acceleration over time. It might be conjectured that this stability relates to the explicit teaching that occurs in the curriculum regarding the context of a falling parachutist. However, in the another context related to a falling object, a stone dropped from a building (labelled 'free fall' in Figure 5.33), Daniel links force to acceleration in his first two encounters with the context but reverts to an understanding linking force with motion in his final session. He suggests the ball reaches a maximum speed soon after release, and argues that: 'there was a force acting on it for the whole time like a fixed force' (Daniel, Session 22, 120).

In general, Daniel's pattern of application of the two understandings of force across the contexts appears variable. The graphs in Figure 5.33 suggest that conceptual change must be considered in a given context, as change can occur at different rates in different situations (Tao & Gunstone, 1999). In a number of contexts, for example, the mass on the spring and the pendulum, Daniel makes use of two different conceptualisations in the same context over relatively short time-spans. These graphs suggest that short timescale variability should be interpreted against a representation of change on a longer timescale, rather than simply standing as clear evidence of change. The graphs in Figure 5.33 present a complex picture of Daniel's transition in understanding between two concepts of force. There appears to be a high degree of variability in Daniel's application of the two understandings of force, both across different contexts and over time. To provide a comparison with Daniel's variation, data from Ben's sessions are plotted below, in Figure 5.34.

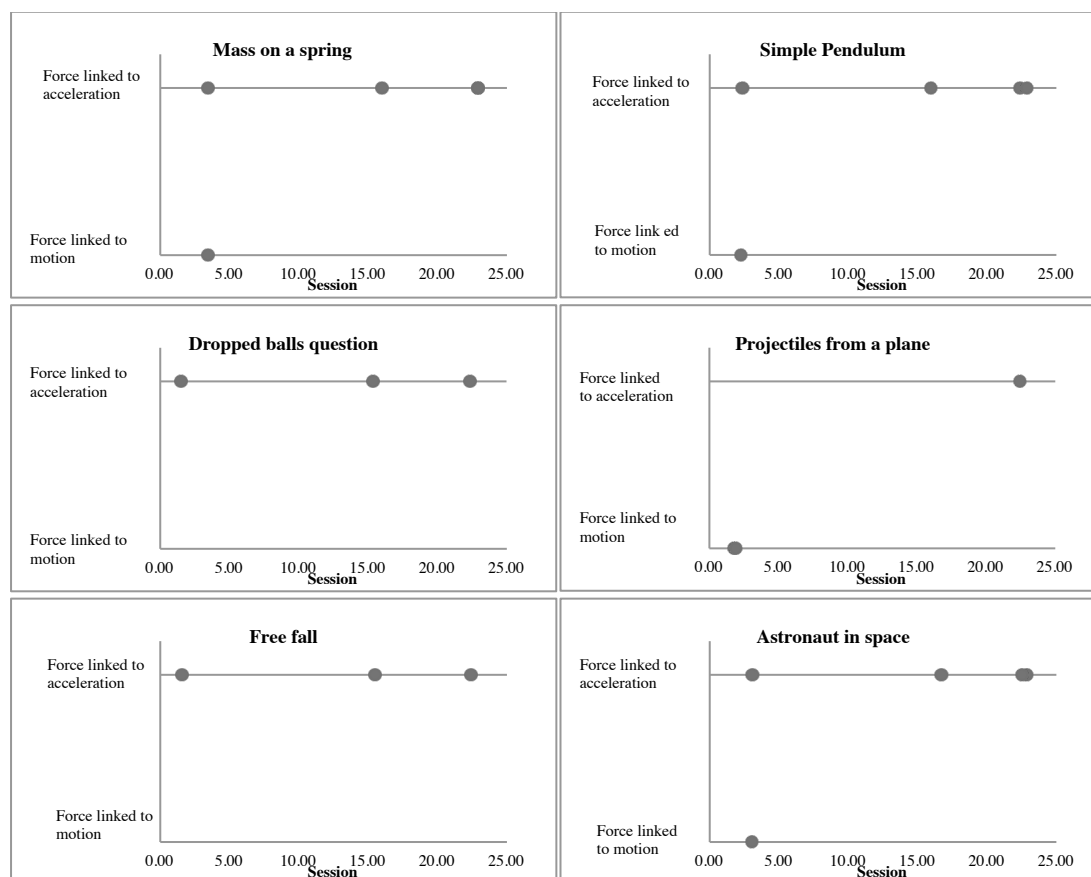
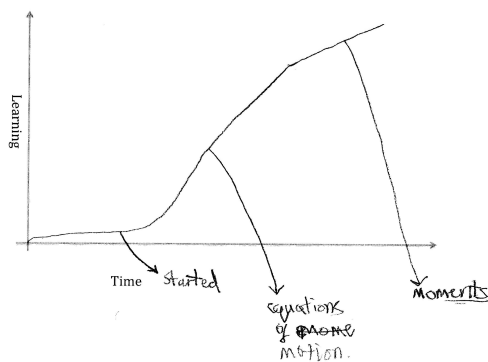


Figure 5.34: A representation of conceptual change in Ben's application of two understandings of force across various contexts.

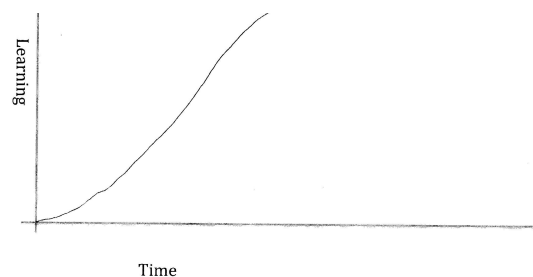
Ben appears to display greater stability in his application of the force linked to acceleration concept. In sessions 11-16 and session 22, in the contexts in Figure 5.34, he exclusively activated the force linked to acceleration concept. In general, the graphs in Figure 5.34 might be taken as representing a student who has a stable understanding of force linked to acceleration in two contexts linked to free fall, and is developing a stable application in other contexts. A change in the frequency of the application of force linked to acceleration occurs in four contexts between the first two periods of sessions and change appears to occur at a similar rate in those contexts.

5.2.5.2 Emic description of long timescale conceptual change

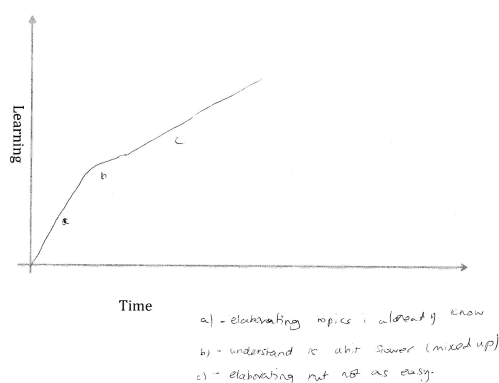
In session 14, the students were asked to draw a graph representing their learning about forces and dynamics over the course of the sessions, and to comment on the pattern of change. The term ‘learning’ was chosen as a non-technical descriptor that would be familiar to the students, and because learning is often modelled as conceptual change (E.g. Strike & Posner, 1982). The students’ representations are shown below (see Figure 5.35). When asked to describe the rate at which their learning progressed, three of the students described periods of different rates of acquisition.



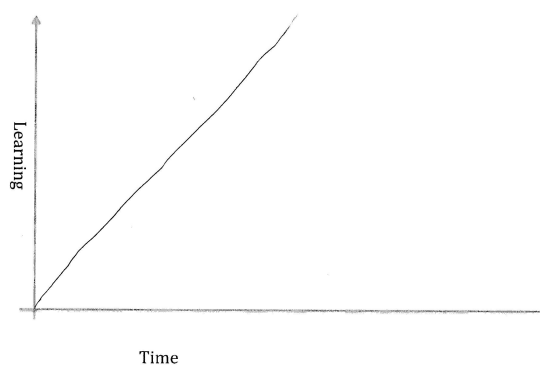
(i) Ben's representation



(ii) Charlie's representation



(iii) Daniel's representation



(iv) Edward's representation

Figure 5.35: Students' representations of changes in their learning about forces and motion over time, produced in interview 14.

Ben described his learning about dynamics as initially occurring at a low rate, as his classroom lessons recapped material he had previously encountered (labelled 'a' on section i of Figure 5.35). He reported that he learned more rapidly when encountering the novel topic of equations of motion (labelled 'b'); but the topic of moments, which he perceived as counter-intuitive, caused a dip in the rate of his learning (labelled 'c'). Charlie argued that acquiring new concepts initially 'took a bit of time', followed by a period of consolidation, in which the concepts were applied to new contexts (indicated by the plateau on the right hand side of section ii, above). Daniel reported that he initially found learning about dynamics easy, so he progressed rapidly

(labelled a in section iii); then he became confused between the concepts of velocity and acceleration, causing a decrease in his rate of learning ('b' in section iii) before a final period ('c' in section iii) in which elaboration on previously-learned concepts led to an increased rate of learning. Edward (Session 14, 4) conceptualised his learning as occurring 'continually at one level', without any changes in rate. Though the students tended to perceive their learning as occurring relatively continuously, a close examination of the students' application of concepts indicates that moments of sudden change over short timescales can be constructed in their transcripts.

5.2.5.3 Etic descriptions of short timescale conceptual change

When conceptual change is conceptualised as an alteration in the frequency with which a concept is applied in a given context, the period over which change is constructed becomes significant. An alteration in the manner in which a concept is used may occur on a single instance but not lead to longer-term change in the application of that understanding. Such unstable shifts have been conceptualised in a number of ways (see section 2.2.4): for example, Piaget's (1979, pp. 16–17) notion of 'romancing' and Taber's (1995, p. 95) construction of mental 'flotsam and jetsam'. Moments of short timescale change are worthy of study for a number of reasons: it has been suggested that constructions that are apparently constructed in the moment may develop into conceptual elements with longer timescale stability (Barsalou, 1983; Taber, 1995). In addition, even if an apparent switch in application of a concept does not lead to a more permanent change, examining moments in which students' application of concepts varies in a given context may lead to an understanding of the processes that prompt change. Utterances in which a student appeared to switch their conceptualisation over a short timescale were coded and are discussed below.

Clement (2008, p. 99) has linked insight with the rapid formation of a novel set of relationships between concepts and this process also seems to have occurred in Amy's understanding of oscillating motion. Amy initially considered the oscillations of a pendulum and a mass on a spring to be unrelated situations but experienced an abrupt transition:

A: I wouldn't say they are that similar, no, because [pause].

I: What makes them different?

A: Because [pause]. This one with the pendulum, when the pendulum moves to the side, it's the [pause]. I am thinking now that they would be similar because, it's there, because the resultant force decreases as the pendulum moves to the side, which causes it to slow down and with this um [mass on spring] when it's moving upwards [pause] the resultant force [pause] when it's moving up to the equilibrium point from here to there the resultant force acting on it upwards decreases as well. (Amy, Session 3, 235)

One feature that has been proposed as marking the difference between novice and expert physicists is an ability to focus on the 'deep structure', the underlying commonalities of situations, rather than surface details (Chi et al., 1981). Amy's perception of the two simple harmonic oscillators appeared to change in a short space of time through the perception of a common pattern in the variation of force with displacement. In this case, the change seems to be relatively long lasting. In session five, Amy considered the oscillations of a marble released within a large concave bowl, and was asked if it reminds her of anything. She replies it reminds her of the pendulum 'because there's the resultant force changes as it goes along' (Session 5, 255). Amy's understanding that certain kinds of motion are related, because of a similar pattern of variation in force with displacement, may have had some stability over time and transfers to at least one novel context.

Not all changes are as stable as Amy's: in the example below, Daniel was making sense of the distribution of potential difference in an electric circuit (Figure 5.36). He displayed a rapid change in his understanding of potential difference towards the end of session 8, as he became able to correctly analyse the distribution of potential difference in the circuit problem with switch A and B closed. He reported that the situation 'makes sense':

I: So what potential difference...[is there across bulb two]?

D: Er, twelve.

I: Twelve. Bulb three? Between two and three is..
D: Zero [pause] Twelve!
I: So on the right hand side.
D: OK, that makes sense now.
I: So they'd all light up and how bright would they be?
D: The same.

(Daniel, Session 8, 220-231)

Switch Circuit

(Adapted from Grimvall, 2007, p. 32)

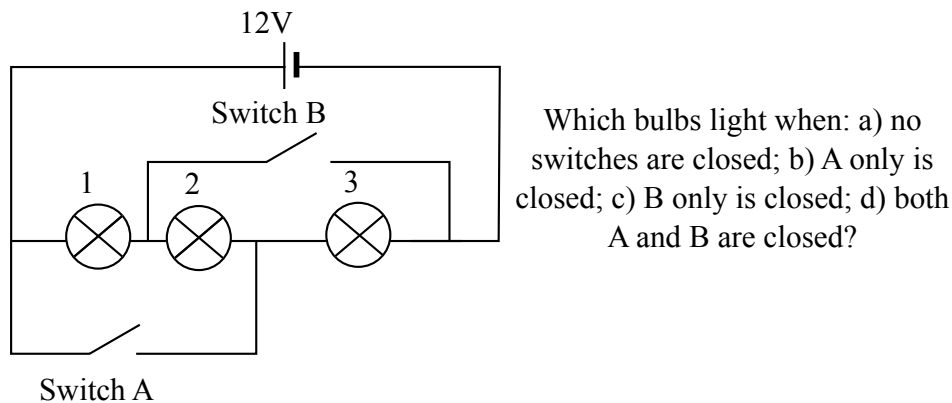


Figure 5.36: Circuit problem set in session eight (adapted from (Grimvall, 2007, p. 32) see Appendix 8.7.2 (ab)).

In a later session, he reported that he felt that potential difference is an area in which he had undergone change: ‘Yeah in potential difference yeah right when I first when I got it then I just knew how to do the rest of it and everything’ (Daniel, Session 10, 26). However, later in session ten, he reverted to his initial model of potential difference, in which he treated potential difference as a substance which flows: ‘Because ten’s coming out this way... Then it has to split here’ (Daniel, Session 10, 118-122). This sequence illustrates the importance of probing cognition at multiple points in time. Though it appeared from Daniel’s answers, that he was capable of calculating potential differences at various points in simple circuits and expressed a feeling of understanding, in later sessions, in a similar context, he reverted to his former understanding. Daniel’s perception of change to his available conceptual resources may not be reflected in their application at a particular time or in a particular context. As illustrated in Figure 5.33, Daniel may possess appropriate

conceptual resources to understand a situation, but their application may not be stable over time.

Not all conceptual change leads to scientifically accepted concepts: students' perceptions that their novel understanding of the world is 'correct' may contrast with experts' assessment (Ylikoski, 2009). Irvine (2015, p. 226) has described the category of 'false aha moments', which appear to be 'a genuine insight' but 'fail the verification process'. As Irvine's construct conflates two issues, the outcome of the insight and the nature of reflection on the insightful product, here, 'false insights' refer to sudden transitions that lead to alternative conceptions. An example of a 'false' insight can be constructed in a moment of change in Ben's transcripts. During an extended process of making sense of the forces acting on a person jumping from a crouched position, Ben drew a diagram which led to a first insight which largely resembles the canonical account of the jump: 'Oh yes, oh, now I understand, um, so this is a person, um, and they push downwards with a certain force that causes a reaction force upwards and so then they can jump up'. However, in response to a question about whether the jumper experiences a resultant force at the moment of leaping, Ben appears to undergo a sudden shift.

I: Is there a resultant force on her?

B: Yeah [pause] Oh is it zero but she moves at constant velocity...

(Ben, Session 13, 348-349)

This construction is productive for Ben as it allowed him to develop a model that explained the motion of the jumper that was consistent with his belief that the forces on the jumper should remain balanced at all times - e.g., 'there's going to be zero Newton's overall' (Session 13, 343). It might therefore be classified as a moment of sudden transition in Ben's explanation that led to a construct that did not match the accepted scientific model - a false insight. The attractiveness of developing a coherent account was compelling, and seemed to override Ben's stable understanding that acceleration requires a resultant force.

A sudden change in conceptualisation may occur when a concept that a student possesses, but has not previously activated in a given context, is triggered. Working memory has a limited capacity (Miller, 1956), so students can activate a finite number of conceptual resources in a given context. Therefore, the development of expertise depends not only on the acquisition of appropriate conceptual elements, but also on selecting and linking suitable concepts in a given context (Sabella & Redish, 2007). In reflecting on the motion of a marble round a loop-the-loop, Ben initially attempted to make sense of the situation by focusing on the relationship between gravitational force and the velocity of the marble.

...It's at the top, the only force well, its velocity is that way, but then at the top its, um, gravity is pulling it downwards so its velocity is gradually going to become less and less sideways. It's going to become more and more steep and so it will, maybe in average, approximately this direction, and as it moves down the [pause]. It's um horizontal, it's what horizontal component of its velocity will decrease and so it will [inaudible] downwards (Ben, Session 4, 166)

When asked to reflect on the forces acting on the marble at various points, the concept of reaction force, which Ben had applied in other contexts, was brought to mind, and appeared to trigger a sudden transition to a novel argument based around the resultant of reaction and gravitational force.

[Referring to the resultant force on the marble] Zero Newtons, so it wouldn't accelerate. Oh so [pause]. Is it the reaction force bigger? (Ben, Session 4, 174)

Ben repeatedly struggled to appreciate that the velocity of an object may be instantaneously zero whilst a resultant force acts on the object when explaining contexts related to simple harmonic motion. In the following excerpt, Ben was considering the motion of a pendulum and initially argued that the resultant force was

zero when the pendulum was at maximum displacement. However, examining his force diagram prompted a rapid transition to a novel understanding:

Because I want to get for it to, stationary, I want to, tension to completely cancel out the weight [pause], and yet my arrows don't. Ah I think I might know, um, here. I think what's happening is there is a force acting on it but it's acting completely opposite to the direction of motion. (Ben, Session 22, 591)

A related incident of the activation of an existing understanding occurred when Ben was reflecting on the motion of a box on a car seat when the car brakes. He had initially presented an argument that a resultant force acted on the box during braking, causing it to move. Subsequently, he transitions to a different interpretation:

Um oh! Is it because if the the box is also moving with the car at constant velocity, and if the car stops then the box will carry on, supposedly moving at that constant velocity, and so it will move forward because the car isn't moving but the box is? (Ben, Session 12, 259)

When questioned as to why he felt he was able to make the connection, he reported that he had been reading a book that referred to relative motion:

...it talked about it looking like you're not moving at all if you're moving at the same rate as another object...And so that made me think well what would happen if you were not moving at the same rate as the other object (Ben, Session 12, 265-267)

A failure to activate a concept in a context does not indicate that a student does not possess that understanding (Taber, 2008b). Conceptual change is constructed not simply as the development of a novel concept but as an alteration to the likelihood with which a concept is activated in a context (Mortimer, 1995). Following the descriptions of short timescale conceptual changes as constructed by the researcher in

the students' transcripts, the next section examines student's reports of change over short timescales.

5.2.5.4 Emic descriptions of short timescale conceptual change

At the start of each session, the interviewer asked the students to reflect on their recent learning experiences and to describe any changes they had experienced. A number of these reflections contained reports of apparently sudden changes in understanding. For example, Charlie described how, in learning about dimensional analysis, '...something's just snapped in it's oh yeah it's got to be that' (Session 12, 12). In an earlier session, he had used the notion of 'snapping' to refer to a sudden change in his understanding of electronic configuration:

Well, it's, we're, s p d f notation... It kind of snapped really 'cos, I thought, I thought 'cos, when I first done it, I couldn't remember it all, actually do it, 'cos it took a while to think about before I could do it, but then I think it was a homework, we were just we'd just done it, and I could just do it, it just made sense so I could do it... It's hard to explain because I kind of looked at it differently when I done it, 'cos I saw it as like, I kind of mind blocked it as something that's really hard (Charlie, 3, 205-211)

Charlie's description refers to being 'mind blocked' before a change in interpretation that led to the development of understanding. Researchers in science education have described how 'functional fixedness', an adherence to a particular strategy or interpretation of a situation, may precede a reconceptualisation of a problem resulting in an insight (Bing & Redish, 2009; Clement, 1989; Furió, Calatayud, Bárcenas, & Padilla, 2000). Ben reported a similar change in perspective:

I was given a question which was why can nitrogen only form three covalent bonds... But phosphorous can form five and I think the problem was in GCSE I was taught that elements in the same group can form the same number of bonds... Nitrogen and phosphorous are in the same group so

I wrote out their actual configuration and then I stared at it for about ten minutes... And then suddenly I realised for nitrogen the next sub shell would be a completely different shell and for phosphorus it [sic] a completely empty subshell on the exact same shell... And so it can move its electrons to that subshell for phosphorus but nitrogen doesn't have anywhere to move its electrons. (Ben, 3, 269-277)

Ben attributed the difficulty of reaching an insight to his commitment to the belief that elements in the same group form the same number of bonds, an alternative interpretation channelled by teaching (Taber, 2001b). As argued above, reconceptualisation might occur through the activation of some prior knowledge, as in Edward's thinking about the gradient of current-voltage graphs:

E: ...I think what we were doing the other lesson for instance, I was looking is looking [sic] at where a high temp would equal a low resistance, and low temp would equal a high resistance etc.

I: Yes.

E: At first I didn't understand how the steeper the graph would like be lower resistance, but then, when I remembered the equation $U = V \cdot I$ what was it

I: So, Ohm's Law [pause] so R equals V over I

E: Yeah, basically I suddenly realised why it would work
(Edward, Session 3, 116-120)

Moments of conceptual change over short timescales may be stimulated by an external prompt. Amy described struggling to make sense of a question about horizontal projectile motion, which led her to consult her teacher. She reported that: 'he just explained it to me in a different way and I suddenly remembered something and then I got it'. These reports suggest that students, on occasion, experience conceptual change as occurring at a relatively rapid rate. However, introspective reports of cognitions must be treated with caution, as at least some of our cognitive

processes occur beyond our awareness (Nisbett & Wilson, 1977), and an insight that appears suddenly may be the result of incremental changes in conceptual structure (Nersessian, 1999, pp. 13–14).

5.2.5.5 Discussion: developing the concept of the rate of conceptual change

Ben displays some degree of independence between the rates of conceptual change in different contexts. Ben is able to consistently apply the force linked-to-acceleration resource in two contexts in which an object drops vertically (Figure 5.34). His apparently stable-over-time application in one context, but not in others, indicates the importance of developing a description of conceptual resources over both time and across contexts. It might be assumed that expert scientists' knowledge is, to some degree, disassociated from context, as experienced learners are capable of solving problems in situations they have not previously encountered. An important issue, that can be investigated using the two dimensional model presented here, is the manner in which students transition from relatively contextually situated understandings to more abstracted knowledge. diSessa and colleagues (diSessa, 2002; diSessa & Wagner, 2005) argue that the gradual integration of contextually triggered elements into networks, known as coordination classes, explains this transition. However, there are, as yet, insufficient data that describe changes in students' application of conceptual resources over multiple contexts and over time to begin to understand the processes involved in this change.

If learning is modelled as the activation of multiple contextually-triggered resources (diSessa, 2002; diSessa & Sherin, 1998; Hammer, 2000), it may be appropriate to move away from conceptualisations of conceptual change as the simple replacement of one concept with another over a relatively short period of time. A more nuanced, novel, definition might suggest: *conceptual change is an alteration in the frequency with which a concept is applied in a given context*. A similar suggestion has been hinted at in Patrice Potvin and colleagues' prevalence model of conceptual change (Potvin, 2013; Potvin, Sauriol, & Riopel, 2015). Potvin has argued that:

If we consider conceptual prevalence instead of conceptual transformation, then the appropriate attitude toward initial misconceptions, from the moment they cease to manifest

themselves, would be to consider that they have not been defeated and are, most likely, just temporarily supplanted or masked.
(Potvin, 2013, p. 32)

However, the authors do not clearly define the term ‘conceptual prevalence’; nor do they present data displaying evidence of the patterns of change over multiple points in time. The definition above clarifies the meaning of prevalence as the oftenness with which a concept is applied in a given context. An oftenness model of conceptual change is useful as it fits with a model of cognition as contextually-triggered conceptual resources and allows for the occurrence of moments of rapid change within more gradual long-term variation. This conceptualisation highlights two issues for conceptual change researchers.

When conceptual change is considered as a change in oftenness of the application of a concept in a given context, claims of conceptual change become challenging to substantiate. For example, consider Daniel’s application of concepts in the context of the pendulum (shown in figure 5.33 above). In session 2, he links force to both acceleration and motion; in session 15, he connects force with acceleration once; and, in the final session, he applies the two concepts on one occasion each. There are at least two possible interpretations of these data: a) Daniel possesses two understandings of force which are triggered with roughly equal oftenness; or, b) he is undergoing a shift towards a more frequent application of the force linked to acceleration concept. The oftenness model of conceptual change highlights the difficulty of substantiating claims to conceptual change, and suggests reports from probes at multiple points in time would be required to substantiate change. Imagine the case of the use of one concept, followed by the application of a different concept in the same context (see top of Figure 5.37).

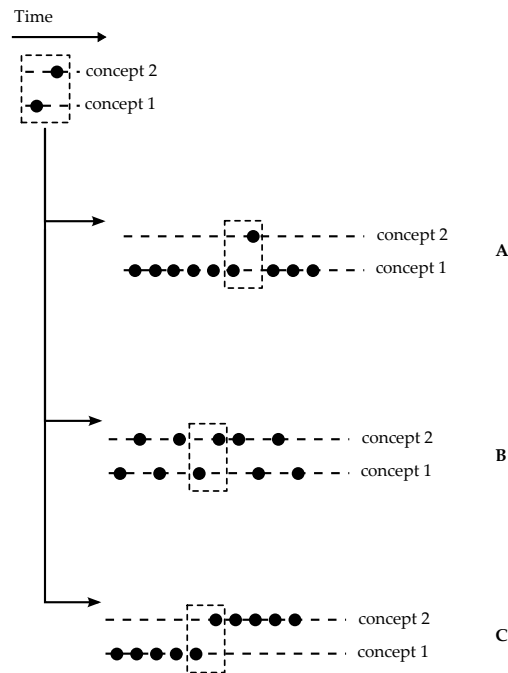


Figure 5.37: A representation of the significance of extended periods of sampling in the oftenness model of conceptual change. The black dots represent activations of a concept in a given context at one time.

Reports of the sequential application of two different concepts are insufficient to substantiate a claim for change. The data may indicate an isolated and short-lived usage ('A' in Figure 5.37) or a period in which the two concepts are applied with equal oftenness ('B' in Figure 5.37) - therefore a period in which change is not constructed as occurring. In order to substantiate a claim of change, an extended period of sampling, represented in section 'C' of Figure 5.3.7, would be required. In terms of what can be observed, conceptual change is likely to be a 'messy' process (Taber, 2013, p. 126), and is unlikely to occur in a discontinuous manner: it is suggested that moments of insight are likely to be rare occurrences (Brock, 2015). Typical change might be represented as gradual change in the oftenness with which multiple concepts are applied in a given context (see Figure 5.38).

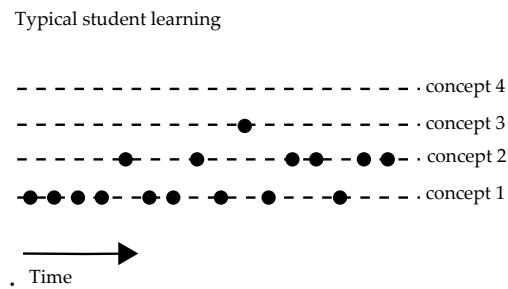


Figure 5.38: A representation of typical student conceptual change. Notice that, in this representation, it is impossible to define a moment in time when the conceptual change might be thought of as occurring.

It is best to avoid claims that conceptual change has or has not occurred based on a small number of reports of application. It is difficult to define a number of data points that would stand as sufficient evidence of stable conceptual change. However, researchers should aim to present data from multiple points in time to provide evidence for an overall trend; the concept of ‘theoretical saturation’, developed in grounded theory, may be useful in making a case (Glaser & Strauss, 1967, p. 61). With such data, it may be more appropriate to claim that the oftenness with which a student applies a concept has altered, rather than asserting that conceptual change has occurred.

A consequence of conceptual change research that has tended to sample data on students’ thinking through relatively few, widely-spaced probes is that changes to students’ ideas that occur over relatively short timescales have received insufficient attention. This section has presented evidence that students report sudden changes in their understanding and a number of potential examples of insight-like change were discussed. Though such moments may be rare (Fisher & Moody, 2002; Vosniadou, 2008b; Vosniadou & Ioannides, 1998), their emotional resonance may mean they are powerful learning experiences that are worthy of further study (Brock, 2015). It might be tempting to consider short timescale changes in understanding as ‘noise’ that has little significance for further learning, but, without an extended period of sampling, it is impossible to know whether an apparent moment of insight develops into a more permanent change. A number of authors have hypothesised that short-lived constructs may become more stable features of cognition at a later time (Barsalou, 1983; Taber,

1995). For this reason, proponents of the microgenetic method, such as Flynn, Pine and Lewis (2006) recommend that short timescale variability in data should be seen as potentially meaningful rather than simply discarded as ‘noise’.

5.2.6 Conceptual change and conceptual span

This section considers the manner in which students' application of concepts across a range of contexts, their conceptual span, may be constructed, and the relationship of this construct to the notion of conceptual change. It was argued in Section 2.6.6 that representations of conceptual change should be developed in a particular context and separated from constructions of conceptual span, which require probes in a range of contexts. Two different approaches to representing conceptual change were used in the previous section: a graphical approach (Figures 5.33 and 5.34) and representations of transcripts from interviews. The next section considers approaches to representing conceptual span.

5.2.6.1 Approaches to representing conceptual span

In order to allow comparisons with the models of conceptual change developed in the previous section, the analysis will focus on the two cases discussed above: Ben and Daniel. One way to represent Ben's activation of concepts related to force is to present extracts of his transcript in a number of contexts. To develop these representations, initially all utterances in which Ben made a claim about the concept of force were coded. For example:

In the context of two balls dropped (Appendix 8.7.2(a)):

...the gravitational force on each of the balls, although it is different because of the masses, they both accelerate by ten meters per second squared. (Ben, Session 1, 60)

In the context of two balls rolled off table velocity (Appendix 8.7.2(b)):

I think, because the heavier ball has a higher mass, the gravitational force on it would be greater, and so as the gravitational force is acting downwards, it will be pulled downwards more strongly, and therefore the force acting to the side of it will be less, and therefore it will hit nearer to the table than the lighter ball. (Ben, Session 1, 72)

In the context of a stone dropped from a building (Appendix 8.7.2(c)):

It will accelerate by 10 meters per second squared ...eventually the air resistance will cancel out the gravitational force and so due to Newton's, I think, it's first law, the ball will carry on at a constant speed. (Ben, Session 1, 78)

In two of the contexts, that of objects falling with purely vertical motion, Ben activated an understanding of force-linked-to-acceleration. The context of horizontally projected objects appears to have activated an understanding that a horizontal force would act on the ball, indicating a concept of force-linked-to-motion, and a belief that the action of one force can affect another. In the next context that involves an object falling with a horizontal component to motion, an object dropped from a moving aeroplane (Appendix 8.7.2 (d)), Ben argued that after the projectile is fired, 'the force acting on it would be slightly sideways' (Session 1, 120). These data suggest that particular features of the contexts trigger different conceptual resources.

A researcher attempting to display multiple incidences of the use of a concept encounters the challenge of retaining the detail of the data whilst carrying out necessary data reduction (Pope & Denicolo, 1986). A novel way of achieving this goal is the concept repertoire table, shown below (Table 5.7). In this representation, every reference to a concept, in this case, force, in the transcripts of Ben's first two sessions has been summarised by the researcher.

Table 5.7: The concept repertoire table. A summary of interpretations of the concept of force in Ben's first two sessions. A link to the probes in the Appendix is given in brackets.

Session; Utterance	Context	Researcher's interpretation of utterance(s)
1; 60-66	Object falling vertically (8.7.2(a))	Force linked to acceleration.
1; 72	Object falling with horizontal velocity (8.7.2(b))	Believes there is a horizontal force during projectile motion which influences vertical force.
1; 78	Object falling vertically (8.7.2(c))	Force linked to acceleration and clear understanding of Newton's First Law.
1; 88	Collision between lorry and car (8.7.2(e))	Uses scientific understanding of Newton's Third Law.
1; 106	Object falling with horizontal velocity (8.7.2(d))	Suggests that there is no horizontal force on an object dropped from moving aeroplane but argues object will fall in a straight line.
1; 120	Object falling with horizontal velocity (8.7.2(d))	Claims horizontal force acts on projectile. Argues gravitational force acts only a certain time after projectile is fired.
1; 125-128	Object in a lift (8.7.2(f))	Argues upward motion of projectile requires upward force.
2; 3-12	Forces on a car (8.7.2(h))	There must be a forward force acting on a car travelling at constant velocity.
2; 17-18	Forces on a car (8.7.2(h))	Argues resultant force is required for deceleration but then argues a stationary car has no forces acting on it.
2; 106	Forces on pendulum (8.7.2(g))	Unable to describe force that would cause the pendulum to rise- no reference to tension. Implies force is required for motion.
2; 107-108	Forces on pendulum (8.7.2(g))	Stationary implies no forces act on a pendulum.
2; 131-132	Forces on pendulum (8.7.2(g))	At maximum displacement of pendulum, argues tension drops to zero and then draws tension acting vertically.
2; 181	Forces on pendulum (8.7.2(g))	Argues, at equilibrium position, pendulum will have low velocity due to low tension
2; 201	Forces on pendulum (8.7.2(g))	Argues greater mass on pendulum will lead to greater tension, greater acceleration, greater velocity and therefore shorter time period.
2; 201	Forces on pendulum (8.7.2(g))	Argues changing string length of pendulum will affect the tension in the string.

Different understandings are triggered in different contexts, though it is difficult, from these data, to understand the contingencies that trigger a particular concept. Whilst the concept repertoire table is useful for retaining information about the context of utterances and giving a sense of the detail of a student's thinking, it is not a particularly compact representation, and it does not give a reader a sense of the patterns of change. An alternative method of representation is to plot the activation of the two concepts of force analysed above: force-linked-to-acceleration, and force-linked-to-motion; but, rather than plotting activations in particular contexts as shown in Figures 5.33 and 5.34, all activations across a range of contexts can be displayed. In Figure 5.39, below, the activation of an understanding of force linked to motion or force linked to acceleration is indicated on the y-axis. The x-axis is not continuous and displays the point at which the utterance occurred within a session- for example, a concept used at utterance 200 out of 400 in session 2 will be plotted at 2.5).

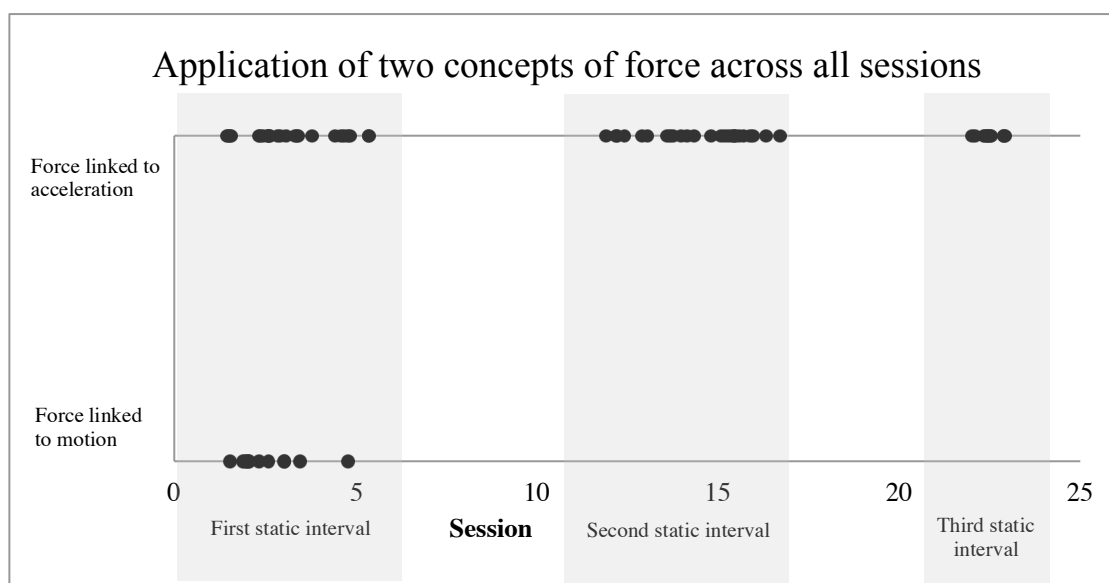


Figure 5.39: Graphical representation of Ben's application of two concepts of force over time: force linked to acceleration and force linked to motion.

In order to construct change in the application of concepts across contexts, the sequence of twenty-two sessions was divided into three static intervals, over which it is assumed that no change in activation occurs. This decision was made as the static intervals consisted of time periods containing consecutive weekly sessions, with the

exception of the final session, separated by gaps of approximately two months. Studying change in activation requires exposure to multiple contexts, both novel and familiar; therefore extended static intervals are appropriate. The representation in figure 5.39 indicates that the number of contexts in which Ben activates an understating of force linked to motion decreases over the course of the sessions; that is, his conceptual span of that understanding is decreasing. An alternative representation, shown in Figure 5.40, represents the percentage of instances in which the two conceptualisations are activated in each static interval.

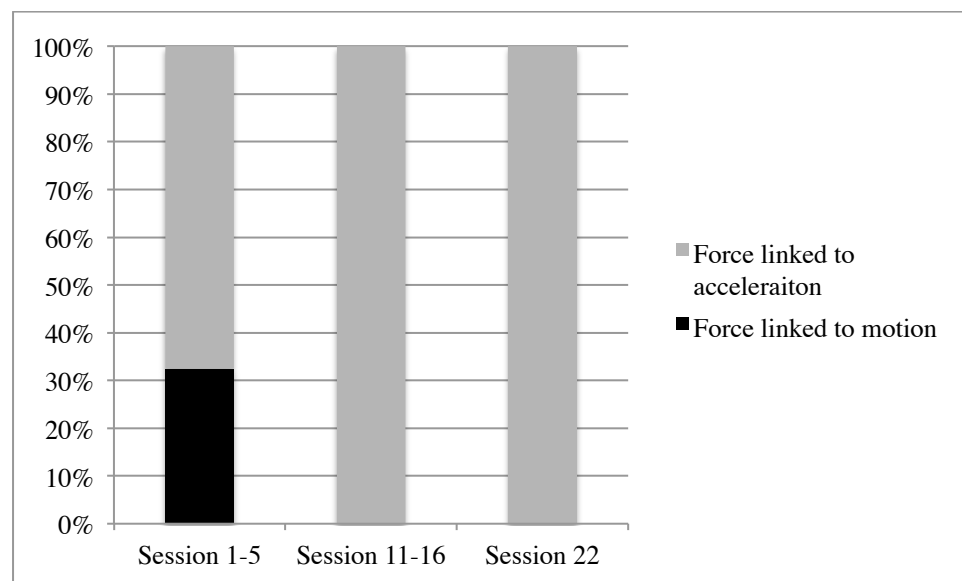


Figure 5.40: Graphical representation of the relative frequency of the two concepts of force over three static intervals in Ben's transcripts.

Figure 5.40 displays the increasing likelihood of Ben activating a concept of force linked to acceleration. In the first static interval, around a third of contexts activate an understanding of force linked to motion. In the second and third static interval, all contexts trigger the force linked to acceleration interpretation. Though the representations in Figure 5.39 and 5.40 give information on the general trend in Ben's application of concepts of force to different contexts, they do not provide information on the contexts that trigger particular understandings. An alternative representation, that displays the contexts that trigger different understandings of force, is shown in Table 5.8, below.

Table 5.8: Contexts triggering different concepts of force across the static intervals in Ben's transcripts. The letters in brackets refer to interview prompts listed in Appendix 8.7.2.

1 st Static Interval		2 nd Static Interval		3 rd Static Interval	
Contexts triggering force linked to acceleration	Contexts triggering force linked to motion	Contexts triggering force linked to acceleration	Contexts triggering force linked to motion	Contexts triggering force linked to acceleration	Contexts triggering force linked to motion
<ul style="list-style-type: none"> • Dropped balls (a) • Stone in free fall (c) • Balls rolled off table (b) • Forces on a braking car (h) • Lift (f) • Pendulum (g) • Astronaut in space (j) • Mass on a spring (i) • Swung ball (l) • Loop-the-loop (k) • Ball in a bowl (m) • Concept map 	<ul style="list-style-type: none"> • Balls rolled off table (b) • Ball dropped from a moving plane (d) • Lift (f) • Forces on a car at constant velocity (h) • Pendulum (g) • Astronaut in space (j) • Mass on a spring (i) 	<ul style="list-style-type: none"> • Dropped balls (a) • Ball in Bowl (m) • Skydiver • Bag in braking car (ah) • Describing properties of force • Concept map • Stone in free fall (c) • Balls rolled off table (b) • Mass on a spring (i) • Pendulum (g) • Astronaut in space (j) • Jumping from crouch (ai) 		<ul style="list-style-type: none"> • Dropped balls (a) • Concept Map • Describing properties of force • Stone in free fall (c) • Ball dropped from a moving plane (d) • Lift (f) • Astronaut in space (j) • Pendulum (g) • Mass on a spring (i) • Pendulum (g) • Mass on a spring (i) 	

In the first static interval, contexts that trigger a link between force and acceleration involve an object that is accelerating, whereas several of the contexts in which Ben links force to motion involve objects that are moving at constant velocity, or motion in two dimensions. The relatively rapid increase in conceptual span of the force linked to acceleration concept is reflected in the pattern of conceptual change seen in the repeated contexts Ben encounters (Figure 5.34). The frequency with which Ben uses

the concept of force linked to motion decreases greatly between the first and second static intervals in all of the contexts.

By contrast, a different pattern of change in conceptual span can be constructed in Daniel's transcripts. As shown in Figures 5.41 and 5.42, below, in the first static interval, Daniel's concept of force linked to acceleration is triggered on five occasions, compared to twelve activations of the force linked motion understanding.

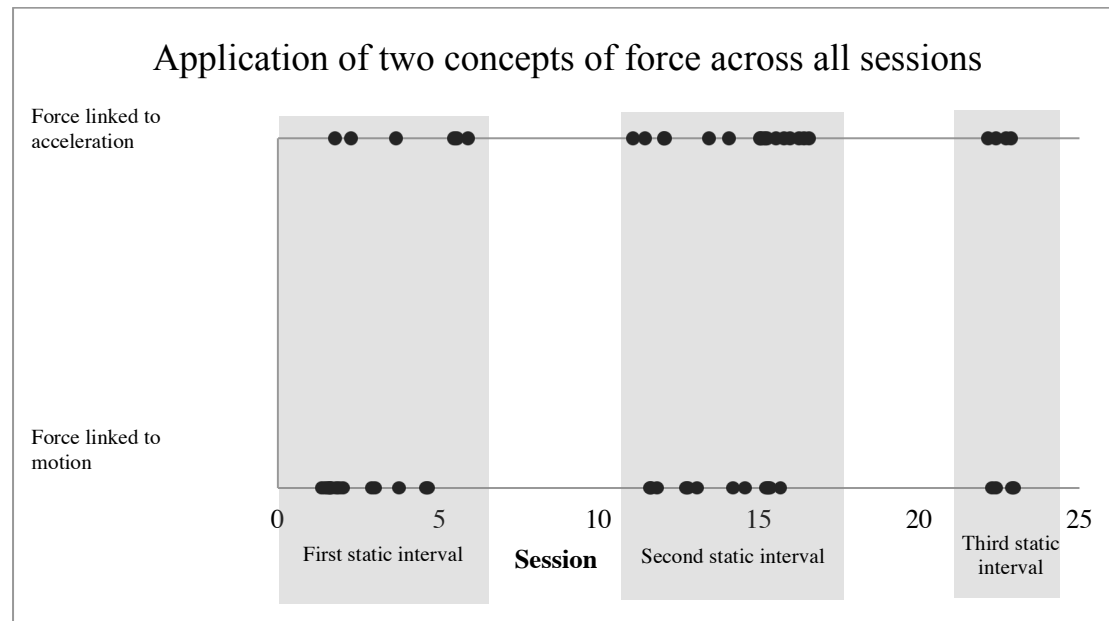


Figure 5.41: Graphical representation of Daniels's application of two concepts of force over time: force linked to acceleration and force in direction of motion.

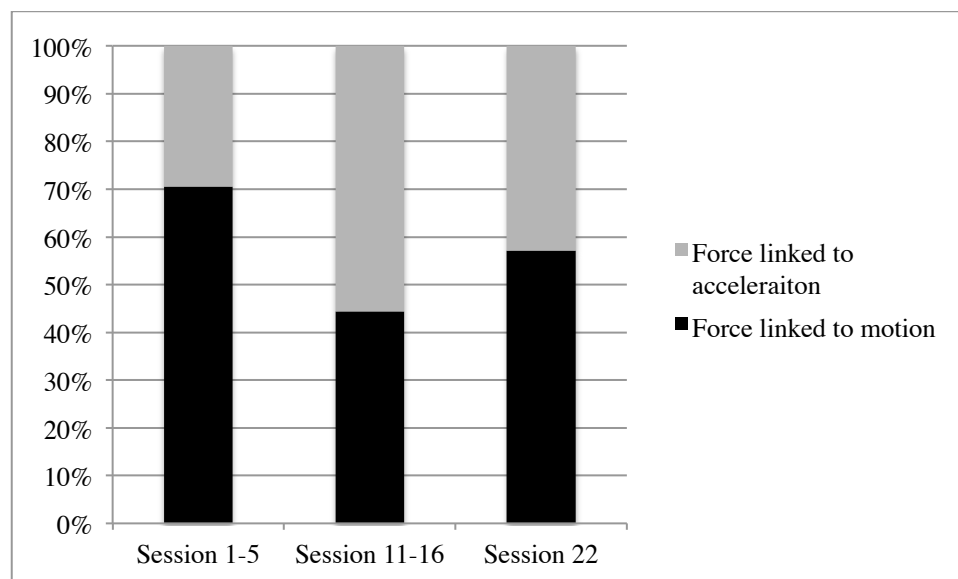


Figure 5.42: Graphical representation of the relative frequency of the two concepts of force over three static intervals in Daniel's transcripts.

In contrast to Ben, Daniel's data do not represent a simple pattern of increase in conceptual span, though, in both the second static interval and the final session, Daniel makes more frequent use of the force linked to acceleration concept than in the first five sessions. An analysis of the contexts that triggered different concepts is shown in Table 5.9, below.

Table 5.9: Contexts triggering different concepts of force across the static intervals in Daniel's transcripts.

1 st Static Interval		2 nd Static Interval		3 rd Static Interval	
Contexts triggering force linked to acceleration	Contexts triggering force linked to motion	Contexts triggering force linked to acceleration	Contexts triggering force linked to motion	Contexts triggering force linked to acceleration	Contexts triggering force linked to motion
<ul style="list-style-type: none"> • Ball dropped from a moving plane (d) • Pendulum (g) • Mass on a spring (i) • Concept map • Ball in a bowl (m) 	<ul style="list-style-type: none"> • Dropped balls (a) • Balls rolled off table (b) • Stone in free fall (c) • Collision (e) • Swung ball (l) • Lift (f) • Car at constant velocity (h) • Pendulum (g) • Astronaut in space (j) • Mass on a spring (i) • Loop the loop (k) 	<ul style="list-style-type: none"> • Concept map • Card sort • Concept discussion • Jumping from crouch (ai) • Discussion of learning • Concept map • Dropped balls (a) • Stone in free fall (c) • Ball in bowl (m) • Pendulum (g) 	<ul style="list-style-type: none"> • Ball thrown vertically (ag) • Ball on a ramp (card sort 8.7.3.1) • Bag in braking car (ah) • Jumping from crouch (ai) • Ontology table • Concept map • Stone in free fall (c) • Collision • Mass on a spring (i) • Astronaut in space (j) 	<ul style="list-style-type: none"> • Lift (f) • Astronaut in space (j) • Pendulum (g) 	<ul style="list-style-type: none"> • Stone in free fall (c) • Ball dropped from a moving plane (d) • Mass on a spring (i) • Pendulum (g)

It is not possible to know, and Daniel may not be aware, why some contexts triggered one concept in preference to another. Some contexts triggered both concepts of force, and different aspects of a context may lead to differing activations. For example, when describing the motion of the pendulum, Daniel comments that: 'when it decelerates, starts to slow down, ... the force going backwards gets greater than the force going forwards' (Session 2, 58). However, when he is asked to predict how the

time period of the pendulum will change when the mass of the bob is increased, he argues: ‘the gravitational pull will be much more so it will basically swing ten times quicker’ (Session 2, 192). It is difficult to understand the factors that cause these different activations when considering different aspects of the same context.

5.2.6.2 Patterns in the development of conceptual span

It has been reported that the activation of knowledge elements in novice thinking is less reliable than might be expected of experts (Clough & Driver, 1986; diSessa, 1993). In one conceptualisation, structures, labelled ‘coordination classes’, are imagined to guide the consistent activation of conceptual resources across contexts seen in experts (diSessa 2002; diSessa & Sherin, 1998). Over the course of the interviews, the range of contexts in which Ben activates an understanding of force related to acceleration increases and the use of the force linked to motion concept is suppressed. Despite Ben’s exclusive activation of the force linked to acceleration concept in all contexts in his later interviews, it is impossible to know whether Ben will apply the concept in all novel contexts he encounters. Some evidence suggests that even expert learners will reactivate novice knowledge elements that are generally suppressed, in certain kinds of context, for example if forced to reason rapidly (Kelemen et al., 2013). A task for teachers and researchers is to define a set of contexts in which they expect successful learners to activate scientific concepts.

It might be expected that conceptual span developed in a consistent order across contexts for different students. For example, some research has suggested that contexts related to accelerated motion with non-collinear acceleration and velocity, may trigger the force linked to motion understanding even in students with some expertise (Galili & Bar, 1992, p. 79). Viennot (1979) proposed that the force linked to motion concept was more likely to occur in contexts when motion was in a different direction to the resultant force. However, the evidence from the two case studies above suggests that the order in which contexts began to trigger the force linked to acceleration concept was idiosyncratic. It has been proposed that novices and experts perceive different features of contexts as significant (Chi et al., 1981). Such personal perceptions and pre-existing knowledge, an ‘implicit’ context, make judgements of the factors driving contextual activation subtle and hard to predict (Palmer, 1993).

5.3 Students' experience of the research process

In their final session, the participants were given the opportunity to reflect on their experiences of the research process. As Amy chose to end her involvement in the research after her tenth interview, there was not an opportunity to seek her views on the process, though she reported that her decision to finish was related to the pressure of upcoming modular examinations. The other four students reported that the research was a positive experience, and that attendance at the weekly sessions was not onerous. It may be that, because the students felt they were learning in the sessions, they felt the activity was mutually beneficial: '...it was on what we'd been learning and although it was a lot of time overall it's just one hour each week' (Ben, Session 22, 549). For Edward, the opportunity to receive one-to-one attention was attractive, and mitigated the burden of the sessions: '...in class it's sort of about twenty to thirty students and they each have different needs weaknesses strengths and all that...But with me it's just like you can just focus on me' (Edward, Session 22, 10-12). Initially, I had been concerned that students would become frustrated with a process in which they were not told the correct answers, but Ben commented that the process allowed him to 'go down routes and see where it will lead' (Ben, Session 22, 533). He argued that this was different from his experience of learning in class:

And even if it is wrong the problem is in class if you stop someone they won't see what is wrong about it...Rather the good thing with being able to go all the way with it...Is one can see what the end result is...And therefore chase the problem and not do it again
(Ben, 22, 535-541)

Similarly, Daniel reported that being allowed to detect errors in his own thinking was a useful skill:

Yeah um I think that's better because if I if I can realise that I've made a mistake then it's much better as well because I just know if I'm thinking of something in the way then I'll know how to think of it if I get the change to ask answer a question like that

again I'll know what I have to basically go like I wouldn't think
of the same as thought about the other time (Daniel, 22, 16)

In general, the students reported that the process had been a productive experience; and, although it may have been difficult for them to express criticisms of the process to the researcher, that four of the five students chose to continue to participate in the research for twenty-two sessions, despite being repeatedly reminded that they could leave the process at any time, indicates that the sessions were, indeed, experienced positively.

6.0 Conclusions

6.1 Summary of themes

The following sections (6.1.1-6.1.6) discuss the key themes that emerged from the analysis, building towards a synthesis of ideas (6.2). The final sections present a critique of the research in the thesis (6.3) and examine the consequences of the conclusions for teaching (6.4), research (6.5), and describe my personal learning development (6.6).

6.1.1 The development of ontology

The evidence from the two case studies discussed suggests that the development of ontology occurs over extended periods of time. Though Daniel showed limited ontological development, Ben displayed some evidence of a transition from poorly differentiated, loosely-clustered and contextualised concepts to more clearly differentiated, abstracted, expert-like categories. The process of development of ontology is a messy and gradual one; indeed, over the course of the six months of the case study, many aspects of Daniel's understanding of the nature of force did not progress. Therefore, the more nuanced model of Gupta and colleagues (2011) seems a better fit for the changes observed than Chi's (1992) model of change, in which novel classes are developed before transfer occurs (See Section 2.1.4). Rather, it appears that a gradual and complex process occurs in which existing facets of knowledge, which likely have plural ontological commitments, are adjusted to match a target of expert ontological categorisation that is rarely explicitly stated in the classroom. Though experienced scientists will use concepts, such as energy, in ways that imply an understanding of the properties of the concept, they may not be able to express their knowledge of ontology directly:

I incline towards a position of agnostic realism about energy: we refer to something we-know-not-what with the word "energy"...We know that energy circulates and remains constant, as well as knowing the laws of its various manifestations, but we don't know what it consists in-we have no positive descriptive conception of it... We know its abstract mathematical character, and its role in empirical theories, but our knowledge does not penetrate

to its underlying essence. We use the word “energy” to designate a theoretically useful enigma. (McGinn, 2011, p. 174)

Hence, learning and teaching about ontology is challenging, as the target knowledge is difficult to express explicitly, and students progress thorough a trial-and-error process that gradually refines different aspects of their understandings of categories.

It is also significant that students sometimes develop personal notions of ontology. For example, Ben developed the belief that force is merely a construct used to explain the occurrence of acceleration, echoing Russell’s (1925/2009, pp. 123–130) argument for the abolition of the concept. Similarly, Daniel’s conflation of gravity and ‘free-fall’ may be a construction that is found in few other learners’ ontologies. These students might be compared to the philosophers whose categorisations have been criticised for including ‘ontically undesirable objects’, thus creating an ‘ontological jungle’ (Jacquette, 1996) or ‘ontological slum’ (Haack, 1977). Haack (1977) critiqued Lewis’ ontology for allowing counterfactual entities such as Pegasus and Jacquette (1996, p. 18) argued Meinong’s work allows the existence of ‘impossible non-existent objects’. Rather than the, at least in some cases, exclusive and stable ontological categories proposed by Chi and colleagues (Chi, 1992; Chi & Slotta, 1993), the ontological landscape of the learner in science may resemble an ontological jungle. That is, there are few clearly defined categories, facets of ontological understanding are contextually triggered, distinctions are perceived within expert categories, and idiosyncratic categories exist.

The difficulties students encounter in developing appropriate categories are well-reported. However, little research has focused on developing an understanding of how novice learners’ ontologies develop towards expert understandings. A model of change over three dimensions was proposed: a) an increasing perception of similarity between the members of scientific concepts, b) an increasing differentiation between scientific concepts, c) a movement from categorisations based on instances and triggered in contexts to more abstracted notions of concepts. These processes are not seen as distinct; for example, an increased understanding of the similarity between

types of forces (increased clustering), is likely to increase the differentiation of force from other concepts. As a concept becomes increasingly understood as an abstraction, rather than a collection of special cases, it is likely to become increasingly clustered, and so on. A number of strategies to support ontological development are discussed in Section 6.4.1, below.

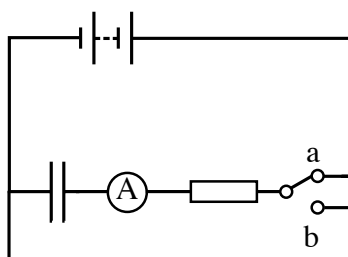
6.1.2 The formation of conceptual compounds

A trend in research into conceptual change in science education has seen a move from the cataloguing of students' alternative conceptions in various domains (Taber, 2009, p. 326) towards a perspective that seeks to understand conceptual change as variations in a system of conceptual elements (Amin et al., 2014, p. 68). However, research into the dynamics of systems of conceptual resources is currently at an early stage, and more detailed reports of the process of the formation and dispersal of conceptual compounds is required. This programme would be supported by research that can describe both short and long timescale changes in the manner in which students activate and develop compounds of concepts. It is hoped that the construct of the conceptual compound, which separates representations of a learner's activated and related conceptual resources in a particular context from underlying and inaccessible conceptual structure, will be a useful tool for researchers investigating conceptual change. Students' conceptual compounds were argued to progress from initially unstable compounds, which link small numbers of elements, towards systems in experts that are more extensive and more stable, both over time and across contexts (See Section 5.2.2.4). In particular, the data collected have drawn attention to an intermediate phase of conceptual development (Figure 5.20), during which learners possess many expert concepts but their activation and combination into compounds is contextually sensitive and variable over time. Rather than assuming conceptual change can occur at a single moment in time, teachers and researchers should be sensitive to the contingent and variable nature of conceptual activation and combination, and develop resources that allow students to develop the stability and extent of their conceptual compounds (see section 6.4.2).

6.1.3 The development of causality

Little research has examined how students' understanding of causality develops over time. In this research, the students' responses were initially dominated by causal

claims at the macroscopic and symbolic levels; and some of the students developed a greater ability to use sub-microscopic causal explanations over time. It was argued that students should be supported to become able to use causal explanations of all three types. Scientists sometimes make use of different models, at different physical scales, to construct explanations of phenomena, an approach known as ‘multiscale modelling’ (Horstemeyer, 2010). Though this approach has explanatory power, it can cause difficulties for students: in biology, students struggle to connect explanations at the molecular level to phenomena at the level of cells, organs or the organism (van Mil, Boerwinkel, & Waarlo, 2011); and in chemistry, students may develop alternative understandings of the relationships between models at different levels (Ben-Zvi, Eylon, & Silberstein, 1986; Hinton & Nakhleh, 1999; Wu, 2003). Similarly students should be supported to understand different approaches to making causal claims. For example, consider the responses students gave to the following question: ‘In the circuit below (Figure 6.0), why does the current decrease over time after the switch is moved from position a to b?’



Level	Student response
Macroscopic	‘the current would decrease as time goes on ‘cos of the gap [between the capacitor plates]’ (Charlie, 9, 90-92)
Sub-microscopic	‘...the current decreases because I’m assuming if you’re putting more electrons onto the plate then it general positive charge would decrease so there would be less pull of the electrons and so the electrons will accelerate less’ (Ben, 9, 24)
Symbolic	I think because if there’s no current and supposedly you have still resistance then the potential difference must as some point be zero due to Ohm’s Law (Ben, 9, 144)

Figure 6.0: Capacitor circuit with student responses at different levels

None of the responses is incorrect, however, they invoke different types of causality and display different facets of knowledge. The macroscopic answer allows the student to link causality with perceptions of the electrical circuit as a physical entity. The sub-microscopic answer ascribes causality at the level of the commonly used sub-microscopic model of current as a flow of electrons. The symbolic explanation displays knowledge of a causal relationship inferred from a mathematical relationship, and may allow the student to link calculations with an appreciation of causality. It has been argued that abstract explanations, that is, ones that rely on ‘formal relational features of a physical system’ (Pincock, 2007, p. 257), are the superior form of explanation because they remain valid even if some physical details of a system change. A similar case has been made for the understanding of causality: Piaget (1930/1970) argued that the most sophisticated form of causal understanding involved abstracted laws or principles. Alternatively, Noble (2013) reports that causation in science has, at certain times, been linked with the sub-microscopic level. The assumption that phenomena at lower levels determine what happens at higher levels has been described as ‘causal reductionism’ (Nelson, 2009, p. 46). However, Lewis (2013) and Noble (2013) argue that there is no privileged scale for causal arguments. Therefore, causal explanations are effective at many different levels of analysis (Fodor & Pylyshyn, 1988). Salmon (1989) describes how the forward motion of a helium balloon in an aircraft cabin during take-off can be explained via the motion of air molecules (a sub-microscopic cause) or Einstein’s principle of equivalence (a symbolic cause). He suggests both of these arguments are legitimate and illuminating in different ways. This seems to be the case with the causal claims in Figure 6.0: each is a useful expression, and fulfils a different role. The principle that there is no preferred scale for descriptions of causality is a significant caveat for teachers, especially when teaching the causally complex topic of electrical circuits. The ability to describe causality via a range of agents at different scales would seem to be a useful skill for students to develop.

6.1.4 The development of coherence

The drive towards coherence has been proposed as an explanatory mechanism for the manner in which learners develop conceptual compounds. However, the subjective nature of the concept suggests that any collection of ideas may be perceived to be

coherent; for example, the coherence of accounts of supernatural phenomena has been cited as reason for their ‘intuitive plausibility’ (Forrest, 2013, p. 269). Hence, the sense of ‘fit’ or ‘feeling of what’s right’ (Rohrlich, 1996, p. 1624), which makes coherence such an intriguing concept in science education, may be both a driver of expert understanding and create an inertia to change away from seemingly intuitive novice conceptions. Therefore, unpicking the influences that tacitly or explicitly shape perceptions of coherence is an important task for researchers. Researchers participating in the movement in science education research which models the interaction of systems of conceptual resources (Amin et al., 2014) must account for the choices students make regarding the manner in which concepts are combined. Coherence, which has been likened to a conceptual glue that binds a category together (Murphy & Medin, 1985), may therefore play a significant role in explaining conceptual dynamics. In this thesis, a triple constraint model of coherence was proposed, which may act as a starting-point for a discussion of the factors that underlie the perception of coherence. It was observed that pre-existing knowledge, epistemological assumptions and the nature of the particular context may drive perceptions of coherence. In addition, it was noted that, in some cases, the students acted to maintain coherences they had developed in the face of challenges from contradictory information. In other circumstances, it was possible to represent students’ understanding as consisting of multiple competing coherences.

6.1.5 The rate of conceptual change

It has been argued that the rate at which conceptual change occurs is a neglected feature of the extensive literature on conceptual change. This oversight may arise from a lack of studies that have collected data from multiple probes over an extended period of time in order to make claims about the shape of change. The growing trend for microgenetic studies in science education (Brock & Taber, 2017b), that is, studies that sample data at a rate that is high compared to the rate of change of the phenomenon of interest (Siegler & Crowley, 1991), may begin to remedy this deficit. A model of conceptual change as an alteration in the oftenness of the application of a concept in a particular context may be a useful construct for the analysis of data from microgenetic studies. Though studies that collect data from repeated probes over an extended period of time may be onerous for both the researcher and the participants, they offer the potential to open a novel research programme in science education that

focuses on describing the patterns of variation in the application of concepts over extended periods.

The reports from students in this study suggest they felt learning was a generally gradual progression, which also included events experienced as relatively sudden changes to understanding. A potentially fruitful direction for future research would be to examine if this perception is echoed in their responses to prompts as conceptualised by a researcher. The long-term development and consequences for future learning of apparently transient concepts remains an intriguingly open question. An alternative focus for research arises from the evidence presented in Figures 5.33 and 5.34, which suggests conceptual change may proceed at different rates in different contexts. Further research might seek to uncover how students' ability to apply ideas in individual contexts develops into more general application; and thence, to recommend an appropriate approach to the introduction of different contexts to students. These potential research directions suggest the rate of conceptual change is a novel concept that may be useful to researchers seeking to investigate learning in science.

6.1.6 Conceptual change and conceptual span

The two case studies of contextual application of concepts indicated that the pattern by which the students extended their application of concepts to novel contexts appeared to be idiosyncratic. Ben displayed a marked increase in the contexts to which he could apply an understanding of force linked to acceleration; but for Daniel, the pattern of change was less clear. In addition to measures of conceptual change (alteration in the application of a concept in a single context) the progression of learning might also be judged by increases in conceptual span, as shown in Figure 5.42. The two axes of development, conceptual change and conceptual span (i.e. change in and across contexts) should be considered as two relatively independent axes of change (see Figure 6.1).

Though the stream of consciousness may be experienced as a single stream, the underlying cognitive processes are likely to be multiple, parallel and partly tacit (Blackmore, 2002). However, research data tend to be constructed serially; that is, as a sequential report of a student's concepts (see Figure 4.0). Once a researcher has constructed a report of the use of a single concept in a particular context, they face a

methodological choice for examining change related to the concept. They might repeat the same probe in the original context to construct change, or develop probes that might activate the same concept in different contexts to develop an understanding of the contextual activation of the concept, or a combination of the two approaches (see Figure 6.1).

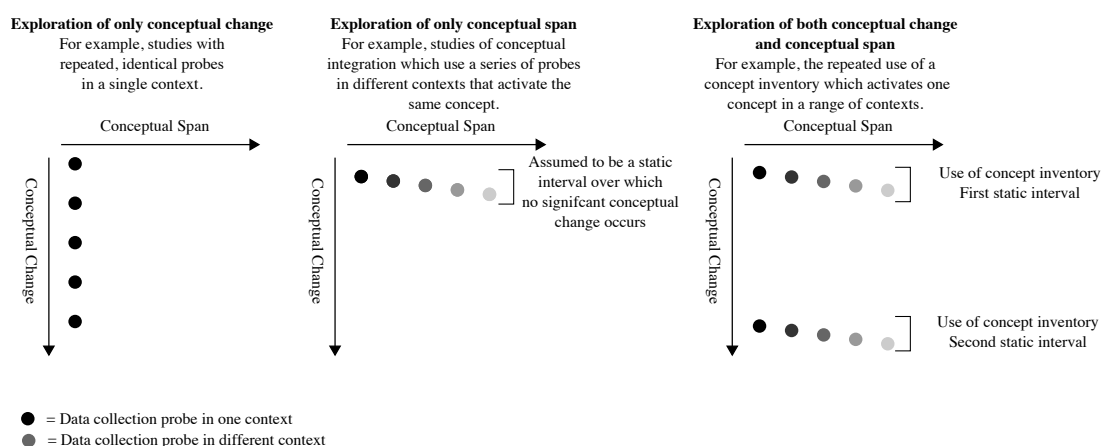


Figure 6.1: A representation of different data collection approaches across the axes of conceptual span and conceptual change.

Each of the different approaches shown in Figure 6.1 is a useful approach for understanding the extent of, and changes in, conceptual resources. However, there is an onus on researchers to discuss the assumptions behind the representation of cognition that a particular approach constructs.

- *Only conceptual change*- approaches that expose learners to identical repeated probes have the potential to develop a valid model of conceptual change, and, with sampling over extended periods of time with multiple probes, shed light on the stability of conceptual constructs. However, in this approach researchers should acknowledge that the context or contexts of focus will trigger only a subset of a student's available resources; hence, it may not model the totality of change across contexts.

- *Only conceptual span-* approaches which seek to understand how a student applies their conceptual resources across a range of contexts are useful for beginning to understand the breadth of conceptual ecology. However, as sequential probes necessarily occur over a period of time, the researcher should present justifications that no significant conceptual change occurs over the period of observation.
- *Studies of both conceptual change and span-* researchers undertaking studies in which both dimensions of change are investigated need to exercise caution in the claims they advance. Claims to conceptual change should be proposed in a single context, and claims regarding conceptual span should be developed from data collected over a period during which conceptual change is minimal, a static interval. Yet, approaches that cover both axes have the potential to develop rich models of cognition as they provide information on the contextual breadth and variation over time of conceptual resources.

It is hoped that the construction of conceptual change and conceptual span as two methodological axes of investigation will encourage researchers to clarify assumptions regarding the manner in which change is constructed in their work. This study highlighted the complex representation of students' conceptual development that can be constructed by examining change across a number of different contexts. Further research is required to better understand how conceptual understanding in particular contexts can develop into the more context-independent kind of understanding found in experts.

6.2 Synthesis of themes

As was argued in the introduction (1.3.4), making sense is perhaps most usefully conceptualised as an emergent potential that requires the possession of certain knowledge elements but, also, the ability to appropriately activate and relate conceptual resources, and is not reducible to any single fact or ability. This assumption was the basis of the epiconceptual model of conceptual change (see

Section 1.4) in that it considers factors beyond the concepts themselves such as their activation and relation in compounds. As White and Gunstone (1992, p. 5) have argued, '[i]t is doubtful even whether any particular element can be specified as essential to understanding'.

The thesis began with the discussion of a student who had memorised the facts but failed to 'make sense', and it is hoped that the six themes of this thesis might go some way to understanding the nature of the student's difficulty. The findings in each individual theme contribute to providing an answer to the research questions that arose from the definition of the concept of 'making sense' (see Figure 6.2). The concept of 'making sense' may be a useful concept in science education research as it highlights that acquiring scientific concepts is only part of a complex learning process. The six facets of the term suggest a number of strategies (discussed in Section 6.4, below) that teachers may use to support students in the challenging intermediate phase of learning, in which they possess, but do not yet appropriately combine and activate, expert concepts.

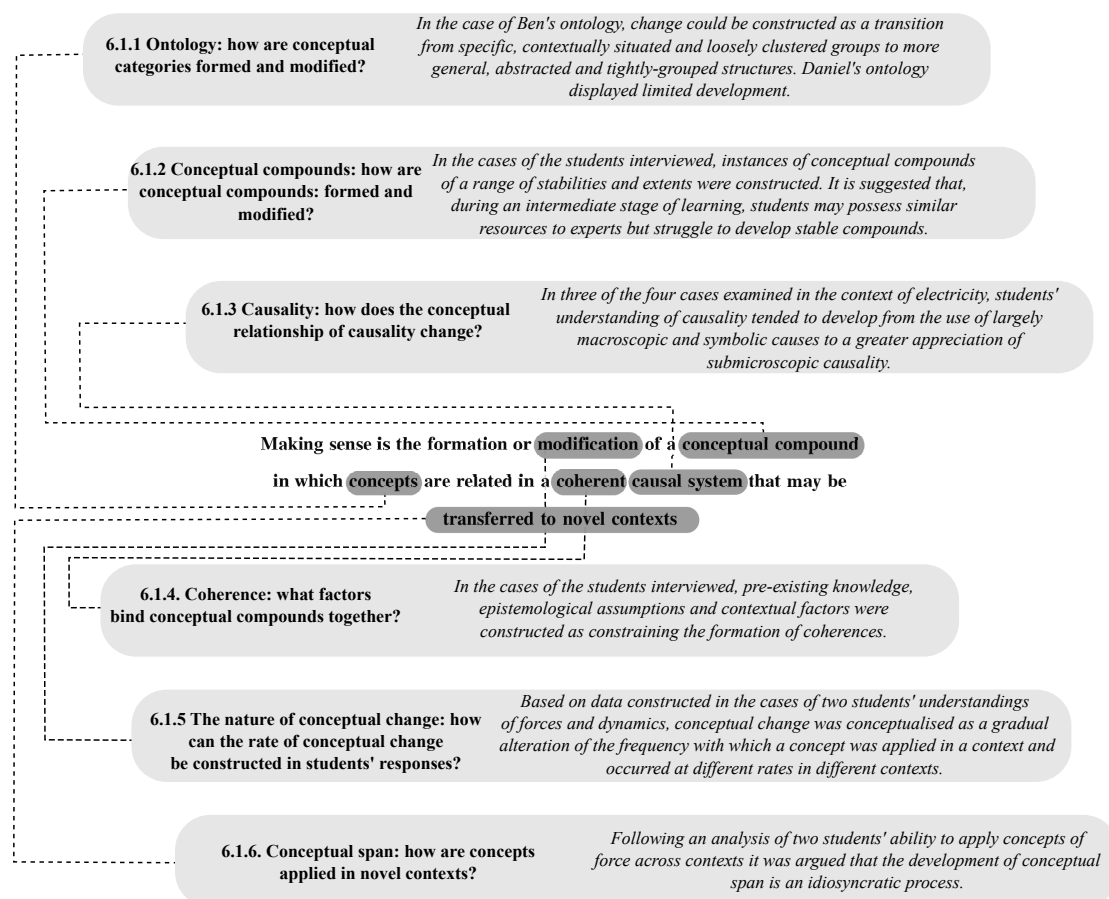


Figure 6.2: Synthesis of themes as they address the nature of making sense.

The research question asked: ‘How do students make sense?’ That is, how do learners develop coherent compounds of concepts, including causal links, which may be transferred to novel contexts? Some of the students interviewed experienced a gradual increase in the definition of their conceptual categories, which became more abstracted and increasingly removed from particular contexts over time. The ability of some students to form more extended and stable conceptual compounds developed during the sessions. In the context of electricity, some students showed an increasing ability to make use of causal models at different levels. The students’ judgements of the coherence of conceptual compounds were idiosyncratic, and depended on prior knowledge, epistemological assumptions and the nature of the context. Though moments of rapid change in the application of concepts of force were noted, conceptual change, for the students interviewed, was generally gradual and the oftenness model was suggested. Finally, a distinction between conceptual change and span was highlighted and it was noted that changes to the activation of conceptual resources across contexts occurred in different orders for different individuals.

6.3 Limitations of the research

All research has inherent limitations; thus the onus on the researcher is therefore not to remove limitations, but, rather, to make the factors which impinge on the construction of data explicit to readers (Maxwell, 2013). This section outlines aspects of this research that place boundaries on the interpretations and applications of the data collected.

6.3.1 Small sample size

Case study research has been critiqued on the basis that studies with small sample sizes are not generalisable and so of limited usefulness to researchers (Flyvbjerg, 2006; Merriam, 1995; Yin, 2009). However, as has been argued in the section on generalisability, above, this thesis did not set out to produce statistically generalisable descriptions of learning; instead, it sought to produce descriptions of the idiosyncratic processes learners use to make sense of novel stimuli, with the onus being placed on the reader to judge the applicability of the findings (Kvale, 1996; Taber, 2000a). The constructivist model of learning argues that though learning pathways will display some commonalities between learners, individuals are expected to progress on different paths and at different rates (Taber, 2009). In that case, approaches that are sensitive to both the particular and general, such as multiple case studies, are necessary to develop a full picture of learning. Taber (2009, p. 351) has suggested the progression of the science education research programme might be likened to a pendulum swinging between two extremes: in-depth studies with small sample sizes may provide fine-grained descriptions of phenomena, whilst studies with larger numbers of participants may provide complimentary data on commonalities and difference in certain populations. Both approaches are required for developing a full representation of learning. The research in this thesis is seen as having limited statistical generalisability, the findings are idiographic, rather than nomothetic, in nature (Gilbert & Watts, 1983). However the limited applicability of the claims should not be seen as a failing; rather, the detailed descriptions of students making sense are in themselves a contribution to the research programme and may compliment future larger-scale studies (see Section 6.5.2).

6.3.2 The challenge of investigating change within and across contexts

Several models of learning in science suggest that features of a context may determine the concepts a learner activates (Clough & Driver, 1986; Mishler, 1979; Palmer, 1993; White, 1985). As discussed in Section 2.4.6, a researcher may investigate conceptual change, that is, changes to the application of a concept over time in a particular context or conceptual span, the ability to apply a concept across a range of contexts. Typically, studies of conceptual change have made use of repeated identical probes applied at multiple points in time (Caballero et al., 2012; Lasry, Guillemette, & Mazur, 2014; Pearsall et al., 1997). However a number of studies have also explored how students apply concepts to a range of different contexts (Parnafes & diSessa, 2013; Taber, 2008b; Tao & Gunstone, 1999). This study attempted to explore both conceptual change and conceptual span, however, this meant examinations of each axis were limited. Studies that focused solely on conceptual change might present data from repeated identical probes at a greater number of points in time, and research into conceptual span might investigate application across a greater number of contexts than was possible in this research. It is hoped that the combination of both approaches presented a broad representation of making sense.

6.3.3 The analysis of large qualitative data sets

Pope and Denicolo (1986) described a dilemma that the researcher faces: analysis which leads to the identification of themes and commonalities in data is inherently a form of data reduction. However, qualitative researchers typically express a commitment to presenting detailed description of the phenomena they investigate. The data in this thesis was collected over 98 interviews leading to over 42 hours of audio recordings and around 360,000 words of transcribed text. When the sample size was chosen, it was expected that more students would drop out than was the case; hence, the final data set was larger than expected. A number of approaches to data reduction were developed in the analysis of the data, for example the concept repertoire table (see Table 5.7) and the graphical representations of the application of two understandings of force (see Figures 5.33, 5.34, 5.41 and 5.42). There is an ethical requirement for researchers to make use of a significant proportion of the data they collect, and all the data collected was analysed and led to the construction of the themes presented with some selection of particularly salient sections of transcripts.

6.4 Implications for teaching

The findings of the research have a number of implications for pedagogy, which are described in the sections below.

6.4.1 The development of ontology

It has been suggested that teaching approaches typically fail to describe the nature of concepts being introduced (Constantinou & Papadouris, 2012, p. 164). The nature of the entities we ask students to engage with, from relatively young ages, are complex, and expert models of concepts may be difficult to articulate directly (McGinn, 2011, p. 174). Slotta and Chi (2006) have presented some evidence that ontological training for students can provide scaffolding in coming to develop appropriate categorisations. Their approach involved explaining ‘the general properties of *emergent processes* ontology’ (Slotta & Chi, 2006, p. 271). This approach would be challenging if we admit that the ontology of categories such as force and energy are difficult to describe directly. An alternative approach may be to include in curricula multiple occasions on which the boundaries and nature of concepts can be hinted at through a range of activities. The three dimensions over which ontology develops, suggested in this thesis, may provide a useful basis to structure learning activities which could be differentiated for students at different stages in their learning (see Table 6.0).

Table 6.0: Suggested teaching approaches to support the development of ontology.

Process	Suggested activity
a) Differentiation	For a set of concepts - for example, force, energy, and momentum or current, potential difference and resistance - discuss the aspects that the concepts have in common and those that differentiate them.
b) Clustering	Introduce the members of a category - for example, types of force - and sort the elements onto a continuum by how well each member represents that category.
c) Instances to abstraction	Look at a range of contexts - for example, a set of force diagrams in different contexts - and discuss if there are any general rules that can transcend the details of each scenario.

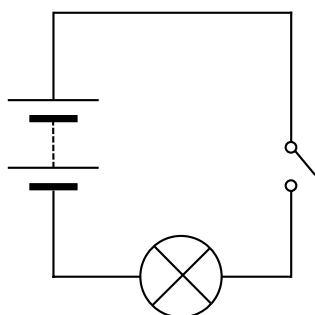
6.4.2 The formation of conceptual compounds

The conceptual compound model was proposed as it was argued (Section 2.2.5) that models of conceptual dynamics such as coordination classes (diSessa, 2002) and mental models (Johnson-Laird, 1983) carried assumptions about the stability and extent of constructs; conceptual compounds are seen as an umbrella term that encompass a range of constructs of different stabilities and extents. The term emphasises that understanding in science education is not simply a matter of acquisition of propositional knowledge; rather, it involves the appropriate coordination of conceptual resources into compounds in given contexts. This model suggests a two-phase approach to teaching: first teachers should assess whether a learner possesses the appropriate knowledge elements to understand a situation and rectify any deficits; second, teachers face the subtler task of assisting a student to trigger combinations of elements in different contexts. The ‘broaden-and-build’ approach to teaching (Fredrickson, 2001) suggests teaching the skill of generating, and then assessing, a wide range of different constructs in order to make sense of a situation. It may be beneficial if teachers modelled the skill of constructing multiple plausible conceptual compounds in a context and assessing their explanatory effectiveness before making necessary alterations to find the best possible explanation for that situation. Research into the formation of conceptual compounds is currently at an early stage, and more detailed reports of the nature and process of formation and dispersal of conceptual compounds are required in order to develop detailed teaching approaches.

6.4.3 The development of causality

Some resources have been developed to support students to develop appropriate understanding of causality in science. White (1995) argued that rather than introducing students to either mathematical abstractions (top-down teaching) or concepts in a range of contexts (bottom-up teaching), students should initially be taught a qualitative understanding of the causal mechanisms in a given context (the middle-out approach). Grotzer (2012) has proposed that students should be explicitly taught models of causality beyond simple linear causality, such as circular and sequential causality. The argument arising from the research presented in this thesis is that students need to develop fluency with causal explanations at different levels. In the case of models, Knippels (2002) devised the so-called ‘yo-yo’ strategy, which

encourages students to think up and down levels of biological organisation; a similar approach may be useful for learning about causality. A useful activity might be to support students' ability to generate explanations at different levels of causality. For example, consider two of the responses students gave, and one imagined response, to the following question: 'In the circuit below (Figure 6.3), why does the bulb light when the switch is pressed?'



Level	Student and imagined responses
Macroscopic	'...once the circuit is complete it allows the current to go through instantaneously' (Daniel, 20, 112)
Sub-microscopic	'...the electrons travel though the path and then they transfer energy...When they collide with vibrating ions' (Ben, 20, 164-170)
Symbolic	Because the resistance of the circuit is reduced and the EMF drives a current through the circuit

Figure 6.3: Circuit question: student and imagined responses

As has been argued above, there is no preferred level for causal explanations (Lewis, 2013; Noble, 2013; Salmon, 1989). None of the responses is incorrect, however, they invoke different types of causality and display different facets of knowledge. The macroscopic answer describes causality at the level of physical entities that make up the circuit, and can therefore be related to personal experiences with electrical circuits. The sub-microscopic answer links the macroscopic action of closing the switch to a sub-microscopic model of current as a flow of electrons. The symbolic explanation displays knowledge of the causal relationship between abstract concepts that are often used by physicists.

To help students develop their understanding of causality, teachers should reassure students that explanations at any level of description are equally valid, although they may not individually be considered to offer a full explanation, and allow students to practice developing different types of causal arguments. A teacher might, for example, set the type of question shown in Figure 6.3 and challenge students to develop three explanations with different levels of causation. This activity could lead to a discussion of the usefulness of each description and the assumptions it makes, developing students' abilities to make conscious decisions about the type of causal explanation they can adopt in a given context.

6.4.4 The development of coherence

Some authors have argued that structuring learning progressions around 'big ideas' can support students to develop integrated knowledge structures (Fortus, Sutherland Adams, Krajcik, & Reiser, 2015). An alternative approach would be for teachers to discuss the assumptions that underlie both student-developed coherences and the coherence of scientific explanations. For example, a teacher might discuss with Daniel the factors he perceived drove his coherence in the context of circular motion in Figure 5.26 and compare this with the coherence of the accepted scientific explanation. This approach might focus on the three factors proposed in this thesis: First, teachers might assess whether any misconceived knowledge elements are being activated and seek to promote the use of more appropriate conceptual resources. Second, teachers may find it useful to probe students' epistemological assumptions to uncover their expectations regarding coherence. It may be useful to teach the meta-cognitive skill of monitoring one's own thinking and making students aware of strategies to adopt in the case of feelings of incoherence or an awareness of multiple coherent positions (as in the case of Amy and Ben in Section 5.2.4.2). A key idea to convey to students is that feelings of coherence can be both a useful indicator of a well-made argument, and potentially misleading. It may, therefore, be helpful to introduce students to cases in which erroneous feeling of coherence have led to the development of alternative scientific models. The cases of 'outsider physics' described by Margaret Wertheim (2011), for example, Jim Carter's 'circlon' atomic theory, and the historical examples discussed by Thagard (1992), such as the caloric model of heat, may be useful examples for students. Finally, to avoid the formation of alternative coherences that are driven by a particular context, students might be taught

the skill of checking if a constructed coherence applies to a slightly altered context or across a range of situations. This practice requires an appreciation of the assumption that explanations in science typically generalise across a defined range of different contexts.

6.4.5 The rate of conceptual change

It has been argued that conceptual change should be considered to be an alteration in the frequency with which a concept or set of concepts is applied in a given context. The data presented in this thesis suggest that the transition between different understandings of a scientific concept does not happen in a single discontinuous transition at one point in time. This observation suggests teachers may wish to adopt an approach that revisits a concept at multiple points in time, as proposed by Bruner (1960) in his notion of the spiral curriculum, in order to support students' transition between ideas. The oftenness model of conceptual change suggests that evidence from multiple points in time is required to make claims that learning has occurred, a proposition that might encourage teachers to develop a more nuanced view of assessment. For example, evidence of change inferred from behaviour elicited between a starter question and plenary activity is not strong evidence for stable conceptual change. Teachers should be sensitive to variation in a student's application of an idea in a particular context and continue to support change until sufficient evidence has accrued to suggest the change has some degree of stability.

One description of strategy acquisition, the overlapping waves model, proposes that students typically possess multiple strategies at any given time, and, that over time, the relative frequency of application of some strategies increases while the frequency of others decreases (Siegler, 1999). The model implies that the rate of change of the application of strategies is not constant over time. Due to a lack of studies which sample data at sufficiently high frequencies, it is not, currently, possible to make a similar claim for conceptual learning related to science. Over a century ago, Edward Thorndike's (1913) investigations of learning curves led to an argument that a student of chemistry, for example, may initially need to gain familiarity with a large number of pieces of information, a process that takes time; but, once the knowledge elements are sufficiently well known, more rapid progress might be expected. If teachers and researchers were to develop an understanding of the rate at which conceptual change

typically proceeded for different learners, it might be possible to develop resources to target particular moments during conceptual development where learning is slow. Alternatively, it may be useful for educators to gain an appreciation that learning cannot be expected to proceed at a constant rate for all learners, and to accept periods of apparent slow progress as part of normal conceptual development. It is hoped that the construct of the rate of conceptual change will spur further investigations into the manner in which learning about science progresses.

6.4.6 Conceptual change and conceptual span

The separation of conceptual change in a particular context from the ability to apply ideas across a range of contexts emphasises that a teacher's role is not simply to encourage students to possess expert-like conceptual resources in their conceptual ecologies but also to develop expert-like usage of those elements across a range of contexts (Sabella & Redish, 2007). A particular challenge of teaching is that the ability to make sense like an expert implies an ability to find appropriate responses in situations that are novel to the learner; hence, making sense has been described as resulting in a potential for behaviour. Consider the case of a hypothetical student's understanding of the behaviour of elastic materials. The student has correctly answered a number of questions describing how the extension of springs will vary if the load on the spring constant is changed. The student might therefore be described as having some level of understanding of this domain. They might then be set the following problem:

A weight is hung on a spring. The original spring is replaced with a spring:

- made of the same kind of wire.
- with the same number of coils.
- but with coils that are twice as wide in diameter.

Will the spring stretch from its natural length, more, less, or the same amount under the same weight? (Assume the mass of the spring is negligible compared to the mass of the weight).

(Clement, 1989, p. 350)

It might be expected that the student described above possesses the knowledge to answer the question, but they may find developing an appropriate explanation challenging. Clement (1989, p. 351) reports that some professors and advanced graduate students, produced solutions which were 'quite complex' and some participants took up to 50 minutes to complete the task. A student's ability to make sense cannot be assessed simply by determining whether they do, or do not, possess certain concepts; rather, it should be evaluated by uncovering the range of contexts in which they can, and cannot, appropriately apply their knowledge.

The ability to go beyond the replication of past performance to make use of knowledge in novel contexts might be a characteristic that differentiates rote learning from making sense. However, defining the nature of a novel context is challenging, as it has been observed that expert and novice physicists have different perceptions of the categorisation of problems (Chi et al., 1981). It seems that the kind of problems that are well suited to assessing students' ability to make sense are those which activate knowledge a student already possesses but require the knowledge to be applied or organised in a novel manner. This condition may be challenging to meet practically as individual learners have varying experiences and those who have already encountered the solution to a problem can solve it via recollection. Vygotsky (1978) defined a learner's zone of proximal development as the set of tasks that are not accessible to a student working independently, but which become achievable with support from teachers or peers. In a similar way, a set of tasks for the assessment of a student's ability to make sense may be defined as those which a student requires no additional knowledge to solve, but for which the student has not previously encountered the solution. The problems in that set will exist across a spectrum of conceptual demand, from those that trivially differ from previously solved problems, to those that require novel approaches. Researchers have distinguished systematic problems, which require the application of known procedures, from insight problems, which are resistant to algorithmic solution (Maloney, 2011, p. 5). If making sense is considered as a potential, it may be distinguished from rote learning only on problems with solution paths that are unfamiliar to most students. However, it has been reported, at least in the case of some chemistry contexts, that the questions set by

examination boards in England are based largely on recall and direct application, with little examination of application to novel situations (Wheeldon et al., 2012).

Making sense, like understanding, is not an all-or-nothing concept (Davidson, 2010; Newton, 2001; White & Gunstone, 1992), students may make sense to varying degrees. As has been argued, the presence of a particular piece of propositional or procedural knowledge is not a sufficient warrant for claiming a student has made sense. For example, Wittgenstein (1953, p. 48§143), who spent some years as a teacher, described assessing whether a pupil has understood how to write a series of number of numbers starting from 0 and increasing by one unit. He argued it was impossible to define a limit on the sequence that would indicate understanding had occurred. As Rudner (1953, p. 2) has suggested: ‘...since no scientific hypothesis is ever completely verified, in accepting a hypothesis the scientist must make the decision that the evidence is sufficiently strong or that the probability is sufficiently high to warrant the acceptance of the hypothesis’. The same principle may be applied to assessment: a student’s ability to make sense can never be completely verified, but a body of assessment evidence may be used to support a claim of understanding. Kosso (2006, p. 175) argues that multiple choice exams or true and false questions cannot be used to assess understanding, rather ‘longer answers in which ideas must cooperate’ are required to probe the concept.

Some models of understanding claim that a few misconceived beliefs do not threaten a wider understanding of a domain (Elgin, 2009). Assessment of making sense, then, might be likened to the process of triangulation in social science research, that is, data from multiple sources may be presented to increase confidence in findings (Bryman, 2003) but no single datum can count as necessary and sufficient evidence to support a claim of making sense. Learning science is not simply an additive process and even experienced scientists can, in certain contexts, revert to the use of intuitive concepts that differ from the generally accepted models of science (Goldberg & Thompson-Schill, 2009; Kelemen et al., 2013; Shtulman & Valcarcel, 2012); and learners may possess multiple understandings of a concept that are triggered in different contexts (diSessa, 2002; Mortimer, 1995; Taber, 2000b). Therefore, assessment cannot resemble Popper’s (1963, p. 48) ‘falsifiability’ demarcation criterion, that is, evidence

of misconceived beliefs does preclude the possibility a student has made sense. For example, a student may possess both Newtonian and Aristotelian models of force, and, that a student may link force with motion on some occasions, does not necessarily indicate they lack understanding of the Newtonian model.

6.5 Implications for research and future directions for research

The findings of this research lead to a number of suggestions for changes to research and teaching practice. These proposals are outlined in the sections below, organised around the six themes of the research.

6.5.1 Methodological implications

A number of studies in science education have used the microgenetic method to develop representations of change; however, researchers investigating change often fail to mention assumptions related to the construction of change and, hence, a number of recommendations for future microgenetic research are proposed (Brock & Taber, 2017b):

- **The density of observation should be high compared to the rate of change of the phenomenon being studied.**

Authors should present evidence of meeting Siegler and Crowley's (1991, p. 606) core criterion by providing an argument for an assumed rate of change of the phenomenon being studied and show that the pattern of observations made can be expected to reveal such changes.

- **Analysis may be quantitative or qualitative but should retain a sense of moment-by-moment change.**

A study that does not report moment-by-moment change does not have the character of a microgenetic study: reports of several disconnected incidents within an interview do not constitute a microgenetic study.

- **A discussion of the static interval and its relation to the phenomenon being studied is required.**

The object of study should be stated (a particular strategy, a single concept, a conceptual area) and a case made that the static interval is appropriate for that object. The static interval may be a whole or a part of a session.

- **Researchers should justify the length of observation period.**

The extent of observations made is significant for distinguishing change in concepts from the presence of multiple concepts, and for assessing the stability of constructions. However, given reports of the extended nature of conceptual learning, Seigler and Crowley's (1991, p. 606) requirement for observation to cover the entire period of change may not be feasible. On such occasions, useful data may be derived from observations covering shorter periods, providing suitable caveats regarding future change are made. For example, a two-year-long study of a student's understanding of the nature of chemical bonding provided evidence of significant changes without a complete abandonment of initial alternative concepts (Taber, 2001a).

- **The degree of similarity between measures should be appropriate to the phenomenon being investigated.**

The appropriateness of the types of probes for the phenomenon being investigated should be discussed and justified. Probes with higher or lower degrees of similarity are acceptable, though each type influences the data in particular ways. Where probes have lower surface similarity, researchers need to offer an explicit case for how the range of probes used can be considered to offer alternative prompts for accessing the same underlying skills or cognitive resources.

Chinn's (2006, pp. 443–444) criticisms of small-scale microgenetic studies apply inappropriate expectations of generalisability and validity to small-N studies. Instead researchers should justify the appropriateness of different methods for the study of different phenomena. It is appropriate to use counterbalanced tasks and identical measures for phenomena that can be studied in relatively short static intervals, for example, a strategy. However, phenomena that require longer static intervals are more challenging to study, and are likely to require more complex and non-identical probes.

- **The microgenetic method may be used in small-N studies providing caveats regarding generalisability, validity and reliability are provided.**

Similar kinds of justifications to those commonly found in small-scale research projects are required in small-scale microgenetic projects. It would be appropriate for a small-scale study to make use of analytical generalisability rather than statistical

generalisability (Taber, 2000a). A qualitative conception of validity (Creswell & Miller, 2000) would be appropriate for such work, and may be supported by: a) the use of multiple methods (such as concept-maps or concept inventories) within the microgenetic framework (Shenton, 2004, p. 65); b) a clear statement of theoretical position and assumptions (Creswell & Miller, 2000, p. 127); and c) rich description of data (Onwuegbuzie & Leech, 2007, p. 244). Reliability, as in case study research, might be conceptualised as reducing ‘errors and biases’, and could be supported by reporting details of the methods and data (Yin, 2009, p. 45).

6.5.2 Research questions that arise from the themes of discussion

The research in this thesis leads to a number of open questions that might form the basis of future studies:

- Does a pattern of ontological development, from contextual, loosely grouped entities to more general abstracted concepts, occur for students in general?
- What kinds of conceptual compounds form, and what factors determine their stability and application in different contexts? Are there patterns across students in the manner in which concepts are related?
- Are patterns of development of causality common across topic areas and between students?
- What factors lead to students’ judgements that concepts fit together?
- What are the typical patterns of conceptual change over both short and long timescales?
- Is there a typical pattern to the manner in which the activation of concepts in particular contexts develops into expert-like application?

6.6 Development as a researcher

The process of writing this thesis has had a profound effect on my development as a researcher. Over the pilot and main interviews, I have honed my ability to carry out qualitative interviews and practised the difficult skill of listening for, and responding

to, emerging themes in the moment. The application of a relatively little-used technique to science education, the microgenetic method, has allowed me to gain expertise in a specific technique and to publish a review paper on the use of the approach (Brock & Taber, 2017b). With the support of my supervisor, colleagues, editors and reviewers, I have developed my academic writing skills, leading to the publication of a number of book reviews, articles, chapters and a book (Agarkar & Brock, 2017; Baker, Evers, & Brock, 2017; Billingsley, Brock, Taber, & Riga, 2016; Brock, 2015, 2017; Brock & Taber, 2017a). I began the research assuming I would develop a model of what it means for students to make sense of topics in physics, but the project has shown me that making sense is a complex process that involves many different facets that are not easily reducible to a single process. The data gave me a new awareness of the difficulty of the task facing physics students: not only must they develop novel ontologies, which are rarely explicitly discussed, but they must also come to understand systems with complex causal relationships, relate abstract concepts and apply ideas in contexts which they perceive as disparate. I was, despite years of experience as teacher, surprised at the limited rate of conceptual development of some of the students, even during a period when they received nearly daily teaching. These observations have increased my interest in carrying out further research into making sense in order to develop pedagogies to support students' learning about physics.

6.7 Concluding remarks

This research began from a student's complaint that they had memorised many facts related to science, yet were left with the perception that the subject failed to 'make sense'. It is hoped that, the themes raised in this work, suggest approaches to support such a student move beyond the simple acquisition of facts. For example, a teacher might examine the way in which the student had defined key concepts, and assist them to understand how those concepts related, with a particular focus on the role of causes, to help the student develop coherent conceptual compounds. Further, the student might be supported to broaden the range of contexts in which they could apply concepts, and reassured that conceptual change is often a slow and messy process.

The development of a model of making sense may go some way to unifying the different models of learning that have been proposed in science education. Recently, there has been a call for the development of models of how systems of conceptual resources interact (Amin et al., 2014; Taber, 2009, p. 326). In this thesis, an attempt has been made to generate an in-depth description of how five learners activated and combined concepts related to physics across a range of contexts. The application of the microgenetic approach allowed for the construction of processes of change that are not representable in typical longitudinal studies of conceptual change. The themes developed in this thesis have been used to propose some ideas for a pedagogy of making sense which is sensitive to the changeable and contextually-situated nature of learning about science (See Section 6.4). Such a pedagogy might develop students' understandings of ontology and causality; encourage students to seek, and then question, perceptions of coherence; and develop forms of assessment that conceptualise making sense as an 'emergent potential' that is not reducible to the possession of particular skills or knowledge. Hence, the focus of teaching might move beyond a focus on the possession of concepts to an epiconceptual model, in which supporting the expert-like activation and combination of concepts is seen as a significant goal. A pedagogy that emphasises the appropriate activation and development of relationships between concepts may be able to avoid the unsatisfactory case of a student who knows many facts about science but finds the information meaningless and difficult to apply. If I were able to talk to the student who triggered the research again, I would advise her that she had achieved the first part of the processes of learning; and next came the harder, but more exciting, task of relating the elements, evolving conceptual compounds, learning when to apply principles and developing coherence. By analogy, science education researchers are in a similar position: they have completed the first stage of identifying many of the conceptual resources students may possess; but now begins the harder, and perhaps more exciting, task of understanding how patterns of conceptual relationships and contextual activation develop over time.

7.0 References

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8.0 Appendices

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8.1 The Microgenetic method in science education

8.1.1 Search criteria for developing a catalogue of microgenetic studies in science education

- Studies that self-define as microgenetic were included, regardless of the density of observation (E.g., Van der Steen et al. (2014) has a spacing of 3 months between sessions and the research is defined as both longitudinal and microgenetic). Some studies that are defined as longitudinal may have relatively short intervals between observations (E.g. Pearsall, Skipper and Mintzes (1997) use a spacing of four weeks between observations): such studies have not been included where their authors do not describe them as microgenetic.
- Only studies related to science education in school or university contexts were included. For example, the context of a research laboratory in the study by Roth (2014) was not deemed relevant to this catalogue.

These criteria appeared in Brock and Taber, 2017

8.1.2 Microgenetic studies in science education

Microgenetic studies in science education. Where details are unclear in the original study, this is indicated in the table. In cases where authors have described change as occurring over multiple tasks in one session (E.g. Opfer & Siegler, 2004), those tasks are defined as separate observations. The papers are listed by year of publication. This table appeared in Brock and Taber, 2017.

Author(s)	Number and age of Participants	Phenomenon being studied and context	Length of Study	Number of observations	Spacing of observations	Length of individual observations	Type of observation
Kuhn & Phelps, 1982	15 students aged 9-11 years old	Problem solving in chemistry	12 weeks (including 1 week of vacation)	11	1 week	Unclear	Questions based on interactions with practical equipment
	15 students aged 9-11 years old	Problem solving in chemistry	14 weeks	Up to 13 sessions but participants left study after 8 sessions if stability in strategy use achieved	1 week	Unclear	Questions based on interactions with practical equipment
Kuhn & O'Loughlin, 1988 (Study 5)	20 students aged 8-12 years old	Evaluating scientific evidence	9 weeks	9 sessions	1 session per week	30-45 minutes	Task involving evaluating evidence related to different types of balls, participants interviewed whilst completing task
Kuhn, Schauble, & Garcia-Mila, 1992	12, 10-year old, fourth graders	Theory and strategy revision about factors affecting the speed of cars and boats	9 weeks	19	2 sessions in a week	20-30 minutes for car domain 30-45 minutes for boat domain	Problem solving sessions with practical equipment or computer simulation, interview sessions

	20 fifth-sixth graders	Scientific reasoning about factors affecting the speed of cars and balls	7 weeks	7	1 week	30 minutes	Problem solving sessions with practical equipment or computer simulation, interview sessions
Nuthall & Alton-Lee, 1993 (Study 1)	3 students aged 9-10 years old	Learning about conservation, erosion and endangered species	31 days	Transcript divided into 15 second long sections- unclear as to total number or spacing	Transcript divided into 15 second long sections- unclear as to total number or spacing	Total of 129 hours- unclear as to individual duration or spacing	Continuous observation, video and audio recorded. Pre-test then post-test and interviews after observations, and again 12-months after observation
Johnson & Mervis, 1994	16 five-year-old students	Knowledge of shorebirds	17 days	5	Four, one hour long sessions at intervals of 3-5 days, 30 minute session within 2 days of fourth session	Four, one hour sessions and one 30 minute session	Tests of knowledge, triad task, general sorting task
	1 four-year-old boy	Knowledge of shorebirds	17 days	5	Four, one hour long sessions at intervals of 3-5 days, one 30 minute session within 2 days of fourth session	Four, one hour sessions and one 30 minute session	Tests of knowledge, triad task, general sorting task
Zohar, 1995	25 students at community college, mean age, 32 years	Reasoning about variables	10 weeks	20	Two sessions per week	30 minutes	Five tasks on reasoning about variables, recordings of sessions
Magnusson, 1996	8 fourth grade students	Learning about sound	3 months	Unclear	Weekly or biweekly	10 minutes	Classroom activities videotaped and observed, student presentations videotaped, individual interviews and post intervention interviews

Schauble, 1996	10 fifth and sixth graders 10 unrelated adults	Scientific reasoning about objects immersed in fluids and placed on springs	2 weeks	6	Six sessions over 2 weeks	40 minutes	Interviews at start and end of sessions, data record cards from practical sessions
Chinn, 1997	61 sixth and seventh grade students	Knowledge about molecules and chemical reactions	6.5 weeks	13	Two sessions per week	60-80 minutes	Guided interviews with instructors involving engagement with experiments and texts. Think aloud protocols produced
Duit, Roth, Komorek, & Withers, 1998	25 tenth grade students	Conceptual change related to chaotic systems	2 weeks	4	Unclear	90 minutes	Pre-test, students interactions with experiments and simulations videotaped
Hogan, 1999	12 eighth grade students	Personal frameworks related to the nature of matter	12 weeks	Unclear	Classes recorded two or three times a week	Unclear	Interviews before and mid way through course. Classes video and audio taped
Nuthall, 1999 (Study 6)	5 students (average age 11.8 years)	Knowledge of the habitat of Antarctica	6 days	Unclear- 13.4 hours of observation over 6 days	Unclear- 13.4 hours of observation over 6 days	Unclear- 13.4 hours of observation over 6 days	Written multiple choice pre- and post-tests, classroom observation with video-cameras, record of students writing in class, records of students homework, interviews at end of observations and long-term (12-month later) post-test and interview
Chinn, O'Donnell, & Jinks, 2000	105 fifth grade students	Argument structure in group work on electrical circuits	2 sessions over 1 day	2	2 sessions over 1 day	50-60 minutes	Students carried out experiments, wrote conclusions and evaluated pre-written conclusions. Discussions were recorded and transcribed

Izsak, 2000	24 eighth-grade students (students worked in pairs)	Knowledge structures related to the winch	3-4 weeks	3-4	1 week	60 minutes	Problem solving, with physical apparatus, videotaped
Azmitia & Crowley, 2001	24 undergraduates	Scientific thinking in the context of building towers to withstand earthquakes	1 week	6 sessions (4 individual, 2 collaborative. Individual sessions preceded and followed collaborative sessions)	1 week	15 minutes	Questioning, and collaborative sessions videotaped
Roth & Welzel, 2001	8 tenth grade students	Use of gestures and scientific discourse in the context of electrostatics	10 weeks	20	2 per week	45 minutes	Videotaped lessons, pre- and post- interviews, and written tests in week 4, 10 and 15
Wiser & Amin, 2001	4 students just finished eighth grade	Conceptual change in the domain of thermal physics	5 weeks	Unclear	Several mornings a week	2 hours	Teaching-learning sessions audiotaped. Individual interviews were conducted before, during, immediately after, and 6 months after the teaching sessions
Gelman, Romo, & Francis, 2002	22 ninth grade, ESL students	Conceptual and language learning across various science topics studied by ESL students	1 academic term	10 units	Unclear	Unclear	Students' writing and concept maps in notebooks based on experimental sessions
Eichler, Del Pino, & Fagundes, 2004	8 students aged 14-17 years old	Conceptual development linked to air pollution	As many sessions as required to complete the task	Unclear	Unclear	45 minutes	Logfiles from engagement with computer simulation, texts written whilst using simulation, audio transcripts recorded during use of simulation.

Opfer & Siegler, 2004	80 kindergarten students aged 5-6 years old	Conceptual change in the categorisation of living things	1 session	3 tasks in 1 session	3 tasks in 1 session	Unclear	Pre-test, post-test categorisation tasks, questioning
Veal, 2004	2 prospective secondary chemistry teachers	Pedagogic content knowledge	1 year	Unclear	Observations, daily for 1 hour, 5 days a week for first semester. Vignettes shown to participants once every 3 weeks	Unclear	Pre, during and post interviews Observations of teacher, teachers' journals and responses to vignettes
Feldon & Gilmore, 2006	154 students (52 members of sixth grade science class, 42 free-choice users of online site)	Scientific problem solving in the context of infectious diseases	Unclear and user dependent	2 Sessions (possible multiple uses of simulations by participants in each session)	Unclear and user dependent	Unclear and user dependent	Data from interaction with computer simulations
Pata & Sarapuu, 2006	53 Secondary students aged 15-17 years old	Reasoning processes in the context of genetics	Unclear	Use of collaborative virtual workshop divided into 4 phases	Unclear	Unclear	Pre-essay, post-essay, discussion whilst using collaborative virtual workshop
Garcia-Mila & Andersen, 2007	15 fourth grade students and 16 community college students aged 22-47 years old.	Developmental change during note taking in scientific inquiry	10 weeks	20	2 in a week	30-45 minutes	Students carried out various practical, computer and paper-based tasks. Students' notes in notebooks collected

Soong, 2008	37 students aged 15-16 years old	Computer mediated collaborative physics problem solving	9 weeks	4	Weeks 1, 2 and 7, 8	1.5 hours	Computer based problem solving. Data taken from students' chat logs
Kuhn, 2010	40 sixth grade students	Scientific argumentation skills	7-8 weeks	13	2 in a week over 7-8 week period	Unclear	Students engaged in argumentation via a computer-based system, reflection sheets
Parnafes & diSessa, 2013; Parnafes, 2007, 2010 <i>(Note: Data from one study analysed in three papers)</i>	16 students aged 14-18 years old. Students worked in pairs	Learning, and the development of epistemological complexity related to simple harmonic motion	1 session, 1.5 hours long	3 sections within 1 session	First two sections last 25-40 minutes. Final section 10-15 minutes	First two sections last 25-40 minutes. Final session 10-15 minutes	Students videotaped interacting with physical oscillators, then with computer simulations and finally a discussion with researchers about the main conceptual issues
Garcia-Mila, Andersen, & Rojo, 2011	34 sixth graders aged 11-13 years old	Laboratory record keeping in the context of plant growth	4 weeks	7	Twice a week	30-45 minutes	Tests of content knowledge in first and final sessions, questioning during sessions, students' notes
Srivastava & Ramadas, 2013	5 students, aged 17-19 years old, in the 1 st year of a bachelor degree course	Understanding of the 3D nature of DNA	9 days	6	Unclear	1-1.5 hours	A clinical interview-cum-teaching sequence was videotaped. The students drew diagrams and engaged with models.
diSessa, 2014	1 grade 8-10 student	Construction of causal schemes related to cooling curves	2 sessions	Change within one session and into start of next	2 days	3 hours	Students carried out experiments, produced a computer model and were videotaped

	Unclear but multiple, grade 8-10 students	Construction of causal schemes related to cooling curves	1 session	Change within 1 session	Change within session	22 minutes	Students were videotaped in discussions around drawing a graph following a practical experiment
Van Der Steen, Steenbeek, Van Dijk, & Van Geert, 2014	1 boy aged 4-years old	Understanding of air pressure	6 months	3	3 Months (Change also assessed within sessions)	15 minutes	Practical tasks involving syringes were videotaped
Berland & Crucet, 2016	2 fifth/sixth grade students	Epistemological sophistication related to plate tectonics	1 session of 90 minutes	Change within session	1 session	Variable	Students' model construction was videotaped, post interview
Ha, Lee, Lim, & Yang, 2016	9 sixth grade students	Understanding of the particle model	6 days	6 sessions	1 day	Unclear	Students were videotaped in semi-structured interviews creating models
Haglund, Jeppsson, & Schönborn, 2016	46 students aged 9-11 years old (Analysis is of subgroup of students)	Understanding of heat	9 minutes 35 seconds	4	Session divided into 4 episodes- length unclear	Unclear	Practical tasks and class presentations and demonstrations videotaped

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<http://doi.org/10.1002/tea.3660321005>

8.2 Risk assessment form

Faculty of Education



UNIVERSITY OF
CAMBRIDGE

RISK ASSESSMENT FORM

Name: Richard Brock
Course of study/area of work: PhD- Making Sense of making-sense
Activity to be undertaken: Microgenetic interviews of year 12 students Location: Davenant Foundation School, Chester Road, Loughton, Essex, IG10 2LD
Date of departure: September 2013
Date of return: July 2014
If working away, please give details of supervision arrangements for this period: I will continue my normal supervision arrangements during this period
Brief details (write no more than is necessary for clarity): I will carry out frequent (one/twice) brief (20-30 mins) interviews with ¾ year 12 students to develop an understanding of how they make-sense. The interview will involve students' reflections on their own learning and their attempts to make sense of a novel piece of apparatus.
List particular hazards associated with the activity: There are no particular hazard associated with this research <i>List only hazards which you could reasonably expect to result in harm to you or others under the conditions in which you are working.</i>
Are the risks adequately controlled? If so, list the existing controls: N/A

Fieldwork Risk Assessment 2006

List the precautions you have already taken against the risks from the hazards you have identified, or make a note where this information may be found. Include reference to staff training, if appropriate.

List the risks which are **not** adequately controlled and the **precautions to be taken**.
N/A

Do any other Risk Assessment relate to this activity? No If so please attach a copy

Emergency measures N/A

Checklist have you specified

When the activity will take place ✓

Who is involved ✓

What the activity will involve ✓

The purpose of the activity ✓

Are there any special risks ✓

Cross ref to other risk assessments N/A

Travelling arrangements in place? N/A

Health issues checked? N/A

Equipment requirements checked? ✓

Insurance issues check? N/A

Where the information is kept/available ✓

All involved informed? ✓

Form completed by (signature):

Date: Name (in capitals): R.BROCK 13/6/13



In the case of students, signed by Supervisor:

Date: 2013-06-16

Name (in capitals): Dr KEITH S. TABER

One copy of this form must be retained by the signatory (signatories) and one copy sent to the Secretary of the Faculty for reference

8.3 Ethics checklist

RESEARCH ETHICS REVIEW CHECKLIST FOR FACULTY OF EDUCATION

Question: Who needs to complete this checklist?

Answer: Any student or member of staff on the Faculty of Education's payroll who is planning to undertake research involving the collection of information from children, young people, teachers or other adults working in educational organisations, parents and other human subjects.

Note: *Do not fill in this form if you are already completing the Cambridge University Psychology Research Ethics form*

The Faculty's Three Stages of Ethical Clearance

Stage 1 involves you in completion of this Ethics Review Checklist. This is the first stage of three. It will help you (and others) decide to what extent you need to become involved in the second and third stages. When you have completed it you (and the Faculty) will be in a position to make this judgement.

Stage 2 will involve you in discussing any ethical dimensions of your research in some depth with another 'knowledgeable person of standing'; this is a very likely outcome of completing the checklist. Further details are provided on page x.

Stage 3 will involve you in obtaining formal 'ethical clearance' through the Faculty of Education's procedures; some projects will need to proceed to this stage. Further details are provided on page 6.

Details of the Project

Project Title: Making Sense in Physics Education

Name of Researcher: Richard Brock

Position in Faculty: undergraduate student / PGCE student / Masters student / **Research Student** / Member of Staff

Email address: rb423@cam.ac.uk

Usual contact address: 9B Trevor Road, Woodford, Essex, IG8 (AJ)

Phone number: 07969404045

Students Only

Course of study: Part-time PhD

Supervisor's name: Keith Taber

Supervisor's email: kst24@cam.ac.uk

Supervisor's contact address: Faculty of Education, University of Cambridge, 184 Hills Road, Cambridge, CB2 8PQ, UK

All the questions on this checklist deliberately offer you just two answers ('yes' or 'no'). You will probably find that you can answer many of the questions unequivocally one way or the other. However, sometimes you may wish there was an 'it depends' response category. If you find yourself in this position, please give the answer which suggests that, at this preliminary stage, there might be an ethical issue requiring more discussion at Stage 2.

Code of Practice relating to Educational Research

1a) Have you read the *Revised Ethical Guidelines for Educational Research* (2004) of the British Educational Research Association (BERA)? (if you have not read it, the latest version is available at <http://www.bera.ac.uk/files/2011/08/BERA-Ethical-Guidelines-2011.pdf>)
Yes

1b) Is this Code relevant to the conduct of your research?
If you have answered 'no', please briefly explain why:

Yes

1c) Do you agree to subscribe to the Code in carrying out your own research?

Yes

2) Are there any aspects of your proposed research which, in the context of BERA's Code of Practice, might give rise to concern amongst other educational researchers?
If you have answered 'yes', please briefly list possible causes for concern below:

No

a)

b)

c)

Obtaining 'Informed Consent'

3) Are you familiar with the concept of 'informed consent'? (if you are not familiar with this concept you should first consult the following source: page 6 of the BERA guidelines above).

Yes

4) Does your research involve securing participation from children, young people or adults where the concept of 'informed consent' might apply?

Yes

If you have answered 'yes' to Question 4 above, please answer the following questions.

5a) Do you believe that you are adopting suitable safeguards with respect to obtaining 'informed consent' from participants in your research in line with the Code of Practice?

Yes

5b) Will all the information about individuals and institutions be treated on an 'in confidence' basis at all stages of your research including writing up and publication?

Yes

5c) Will all the information collected about individuals and institutions be presented in ways which guarantee their anonymity?

Yes

The Involvement of Adults in the Research

6a) Will your research involve adults?

No

If you have answered 'yes' to Question 6a above, please answer the following questions; otherwise move to Question 7.

6b) Will these adults be provided with sufficient information *prior* to agreeing to participate in your research to enable them to exercise 'informed consent'?

6c) Will the adults involved in your research be in a position to give 'informed consent' themselves with respect to their participation?

6d) Will these adults be able to opt out of your research in its entirety if they wish to do so by, for example, declining to be interviewed or refusing to answer a questionnaire?

6e) Will these adults be able to opt out of parts of your research by, for example, declining to participate in certain activities or answer particular questions?

The Involvement of Children, Young People and other potentially Vulnerable Persons in the Research

7a) Will your research involve children, young people or other potentially vulnerable persons (such as those with learning disabilities or your own students).

Yes

If you have answered 'yes' to Question 7a above, please answer the following questions; otherwise move to Question 8.

In educational and social research 'informed consent' regarding access is often given by a 'gatekeeper' on behalf of a wider group of persons (e.g. a head or class teacher with respect to their pupils, a youth worker working with young people, another person in an 'authority' position).

7b) Who will act as the 'gatekeeper(s)' in your research?

Please list their position(s) briefly below and, where this is not self-evident, describe the nature of their relationship with those on whose behalfs they are giving 'informed consent'.

i) Chris Seward, Headteacher, Davenant Foundation School

ii) David Liebeschuetz, Head of Science, Davenant Foundation School

iii)

7c) Will you be briefing your 'gatekeeper(s)' about the nature of the questions or activities you will be undertaking with the children, young people or other potentially vulnerable persons involved in your research?

Yes

7d) If another person (such as a teacher or parent of a child in your study) expressed concerns about any of the questions or activities involved in your research, would your 'gatekeeper(s)' have sufficient information to provide a brief justification for having given 'informed consent'?

Yes

7e) If unforeseen problems were to arise during the course of the research, would your 'gatekeeper(s)' be able to contact you at relatively short notice to seek advice, if they needed to do so?

Yes

7f) Could your 'gatekeeper(s)' withdraw consent during the research if, for whatever reason, they felt this to be necessary?

Yes

7g) Might other people consider that you yourself are the 'gatekeeper' for the research (e.g. projects involving gathering information from your own students or pupils)?

No - reasonable precautions have been taken to avoid students considering the researcher as the gatekeeper. The consent form indicates the head of department as the point of contact with any concerns about data collection

Other Ethical Aspects of the Research

8) Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g. covert observation of people in public places)

No

9) Will the research involve the discussion of topics which some people may deem to be 'sensitive'? (e.g. sexual activity, drug use, certain matters relating to political attitudes or religious beliefs)

No

10) Does the research involve any questions or activities which might be considered inappropriate in an educational setting?

No

11) Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?

No

12) Will blood, tissue or other samples be taken from the bodies of participants?

No

13) Is pain or more than mild discomfort likely to result from the study?

No

14) Could the research involve psychological stress or anxiety or cause harm or negative consequences beyond the risks encountered in normal life?

No

15) Are there any other aspects of the research which could be interpreted as infringing the norms and expectations of behaviour prevailing in educational settings?

No

16) Are there any other aspects of the research which could be to the participants' detriment?

No

17) Will the study involve prolonged or repetitive testing?

No - although I do plan to use a microgenetic method which will involve a series of related sessions with the same student over a time period of weeks. In my judgement, the sessions will be not de unduly prolonged or repetitive for a 16/17 year old student

18) Will financial inducements (other than reasonable expenses or compensation for time) be offered to participants?

No

What Further Steps to Secure Ethical Clearance are Required?

Please transfer your responses to all the questions to the grid below by ticking the appropriate boxes.

Question	1a	1b	1c	2
Yes	✓	✓	✓	
No				

Question	3	4	5a	5b	5c
Yes	✓	✓	✓	✓	✓
No					

Question	6a	6b	6c	6d	6e
Yes					
No	✗				

Question	7a	7b	7c	7d	7e	7f	7g
Yes	✓		✓	✓	✓	✓	
No							✓

Question	8	9	10	11	12	13	14	15	16	17	18
Yes											
No	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗

Interpretation of Results

If you have ticked any of the shaded cells above, then you should assume that further discussion involving Stage 2 procedures is required because some aspect of your proposed research is likely to be 'ethically sensitive'. In practice, many issues can be resolved at this stage.

Members of staff should be especially careful about research involving their own students (question 7g). *If you have ticked 'yes' in response to one or more of questions 8 to 18, both Stage 2 **and** Stage 3 clearance will definitely be required.*

Stage 2 Clearance

Any 'ethically sensitive' responses identified above should be discussed with a 'knowledgeable person of standing'.

In the case of students within the Faculty, this person will, in almost every case, be the person supervising your research.

Members of Faculty staff will need to exercise some care in selecting such a person. S/he is likely to be someone with considerable experience of research in a cognate area to your own and quite likely to be one of the more senior members of the Faculty. S/he should not be someone who is also involved in the research nor should they be someone with whom you regularly collaborate (whether in relation to research, teaching or administration). The test, in every case, should be whether an outsider would judge the person chosen to be 'independent'.

On completion of the discussion, the 'knowledgeable person of standing' is asked to choose one of the following three responses, to delete the other two and to affirm their views by adding their signature.

a) I have discussed the ethical dimensions of this research and, as outlined to me, I do not foresee any ethical issues arising which require further clearance. In particular, I note that:

(re: 17) The microgenetic method does require repeated assessments, but is an acceptable research technique and is only valid as long as participants remain engaged in the activity (so Richard would not persist with any techniques unless his participants remain engaged).


(re: 7a) We have talked in depth about appropriate safeguards, and I foresee no problems in this research involving young people. In any case Richard already has responsibilities towards these participants that are also the subject of professional ethics as a teacher.

(re: 5c) As is always the case with practitioner research, *it will not be possible* for Richard to report his work in a way which is both open about his dual teacher-researcher role (which is important in producing an authentic account) AND yet avoids the possibility of others being able to identify the institution where the research will take place as his employment at the school is a matter of public record.

Student signature: 

Date of discussion: November-December 2012

Signature of 'knowledgeable person of standing'



2012-12-02

(Supervisor)

Lodging this form

It is your responsibility as the researcher to lodge this form with the appropriate person well in advance of undertaking your research.

Students should provide their supervisors with a copy which can be lodged with other papers their supervisors are keeping about their work. If Stage 3 clearance is required, supervisors will take steps to initiate these procedures.

Members of staff should lodge a completed copy of this form with the Secretary to the Director of Research. They should draw attention, albeit briefly in the first instance, to the nature of the issue(s) arising. The Director of Research will then advise on the appropriate Faculty procedures to be followed to enable the research to be considered for Stage 3 clearance.

Researchers should be aware that Stage 3 discussions could involve them in making modifications to their research design or proposed procedures and may, in certain circumstances, result in ethical clearance being withheld.

8.4 Information sheet for participants

Physics Learning Interviews Information Sheet for students



What is the purpose of the study?

This study aims to collect data to examine the way students learn physics concepts. The interview aims to examine your current understanding of a topic in physics and examine the way new information is integrated into existing ideas. The study is part of my PhD in physics education.

Why am I being asked to take part?

You have been identified as a student who has particular learning characteristics that may shed light on the process of learning.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

Whilst choosing to take part in this project may help with your understanding of physics, the assessment of your thoughts about physics will be used only for the purposes of the research and not inform assessment decision for your school studies.

What will happen to me if I take part?

You will be asked to participate in a series of 5 interviews over this half-term. The interviews will last around 25 minutes. A mutually convenient time at lunchtime or after school will be arranged. During the interview I will ask you about your learning in the topic of forces and ask you to answer some questions. I will introduce you to some new apparatus you have never seen before. Do not consider this section an assessment; no part of the process is an assessment for the purposes of your course. The questions will explore the nature of your learning. There is the possibility, if you consent, to complete a series further series of 5 interviews in a subsequent half-term.

The interview will be audio recorded and then a written record will be prepared.

What are the possible benefits of taking part?

Participation will allow you to engage in a piece of research and give your views on learning. The process may also help you consolidate your understanding of the topic.

What are the possible risks of taking part?

It will require you to give up some time- 5 sessions of around 25 minutes over the next half term. Your comments may be used in an anonymous form and may published in a thesis (the final report of this project), journal articles or other publications. The data may also be used in presentations to other teachers and researchers.

Will what I say in this study be kept confidential?

All information collected about the individual will be kept strictly confidential (subject to legal limitations). The recording and transcript will be held securely and you will be assigned a pseudonym in the transcript and any subsequent published work including published papers and theses.

What should I do if I want to take part?

If you wish to take part please complete the consent form.

What will happen to the results of the study?

The results of this study will be analysed and may be used in my research. The data collected may appear in a thesis (the final report of this project), journal articles, presentations to teachers and researchers, and in other publications. To obtain a copy of any publications please e-mail rb423@cam.ac.uk

Who is organising and funding the research?

My name is Richard Brock and I am carrying out the research as a PhD student at the Education Faculty, University of Cambridge. My supervisor's name is Dr Keith Taber, E-mail: kst24@cam.ac.uk

Contact for Further Information

If you have any concerns about the way the research is being conducted please contact David Liebeschuetz, Head of Science, Davenant Foundation School, david.liebeschuetz@davenant.org If you have any further questions please contact me at rb423@cam.ac.uk

Thank you for taking the time to read this form

8.5 Consent forms

8.5.1 Headteacher consent form

Headteacher Record of Consent Form



Research project title: *Physics learning interviews*

Researcher: Richard Brock, Faculty of Education, Cambridge University,
rb423@cam.ac.uk

Please read the statements below and, if you agree to the conditions, sign at the bottom of the form to indicate your consent.

The above study has been fully explained to me and I have had the opportunity to ask questions and to withdraw the school from the research.

Parents/guardians of each child participating in this study have been fully informed about the nature of the research by letter sent home to parents/guardians

Parents/guardians have been given a reasonable period of to withdraw their child from participating in the study.

_____	_____	_____
Name of Headteacher	Date	Signature

_____	_____	_____
Researcher	Date	Signature

Researcher Contact Details: rb423@cam.ac.uk

Project Supervisor Contact Details: kst24@cam.ac.uk

8.5.2 Parent information and consent form



Dear parent/carer,

Your son/daughter has been selected to take part in a research project into physics learning. The details of the study and issues relating to confidentiality are given on the enclosed information sheet.

If you are willing for your son/daughter to participate in the research please complete the consent form attached. If you have any additional questions regarding the research please contact me at rb423@cam.ac.uk.

Yours faithfully,

Richard Brock

Physics Learning Interviews Information Sheet for parents



What is the purpose of the study?

This study aims to collect data to examine the way students learn physics concepts. The interview aims to examine your current understanding of a topic in physics and examine the way new information is integrated into existing ideas. The study is part of my PhD in physics education.

Why is my son/daughter being asked to take part?

Your son/daughter has been asked as a student who has particular learning characteristics that may shed light on the process of learning.

Does my son/daughter have to take part?

It is up to you and your son/daughter to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

Whilst choosing to take part in this project may help with your son/daughter's understanding of physics, the assessment of their thoughts about physics will be used only for the purposes of the research and not inform assessment decision for their school studies.

What will happen to your son/daughter if they take part?

Your son/daughter will be asked to participate in a series of 5 interviews over this half-term. The interviews will last around 25 minutes. A mutually convenient time at lunchtime or after school will be arranged. During the interview I will ask your son/daughter about their learning in the topic of forces and then you to answer some questions. I will introduce them to some new apparatus they have never seen before. The interview is not an assessment; no part of the process is an assessment for the purposes of their school course. The questions will explore the nature of your learning. There is the possibility, if they consent, to complete a further series of 5 interviews in a subsequent half-term.

The interview will be audio recorded and then transcribed

What are the possible benefits of taking part?

Participation will allow your son/daughter to engage in a piece of research and give their views on learning. The process may also help them consolidate their understanding of the topic of forces.

What are the possible risks of taking part?

It will require your son/daughter to give up some time- 5 sessions of around 25 minutes over the next half term. Their comments may be used in an anonymous form and may be published in a thesis (the final report of this project), journal articles or other publications. The data may also be used in presentations to other teachers and researchers.

Will what your son/daughter says in this study be kept confidential?

All information collected about the individual will be kept strictly confidential (subject to legal limitations). The recording and transcript will be held securely and only the researcher and his supervisor will have access to the information. Your son/daughter will be assigned a pseudonym in the transcript and any subsequent published work including published paper and theses to give them anonymity.

What should I do if I want my son/daughter to take part?

If you wish your son/daughter to take part please complete the form on the next page

What will happen to the results of the research study?

The results of this study will be analysed and may be used in my research. The data collected may appear in a thesis (the final report of this project), journal articles, presentations to teachers and researchers, and in other publications.

To obtain a copy of any publications please e-mail rb423@cam.ac.uk

Who is organising and funding the research?

My name is Richard Brock and I am carrying out the research as a PhD student at the Education Faculty, University of Cambridge. My supervisor's name is Dr Keith Taber, E-mail: kst24@cam.ac.uk

Contact for Further Information

If you have any further questions please contact me at rb423@cam.ac.uk

If you have any concerns about the way the study is conducted please contact David Liebeschuetz, Head of Science david.liebeschuetz@davenant.org

Thank you

Thank you for taking the time to read this form

Parent Record of Consent Form



Research project title: *Physics learning interviews*

Researcher: Richard Brock, Faculty of Education, Cambridge University,
rb423@cam.ac.uk

Please read the statements below and, if you agree to the conditions, sign at the bottom of the form to indicate your consent.

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions.

I understand that my son/daughter's participation is voluntary and that they are free to withdraw at any time, without giving reason.

I agree to my son/daughter taking part in the above study.

I agree that the data gathered in this study may be stored (after it has been anonymised) and may be used in a PhD thesis (the final report of this project), journal articles or other publications. The data may also be used in presentations to other teachers and researchers.

I agree to the interview of my son/daughter being audio recorded

I agree to the use of anonymised quotes ifrom my son/daughter in publications

Name of Parent

Date

Signature

8.5.3 Participant consent form

Student Record of Consent Form



Research project title: *Physics learning interviews*

Researcher: Richard Brock, Faculty of Education, Cambridge University,
rb423@cam.ac.uk

Please read the statements below and, if you agree to the conditions, sign at the bottom of the form to indicate your consent.

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions.

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason.

I agree to take part in the above study.

I agree that my data gathered in this study may be stored (after it has been anonymised) and may be used in a PhD thesis (the final report of this project), journal articles or other publications. I agree that the data may also be used in presentations to other teachers and researchers.

I agree to the interview being audio recorded

I agree to the use of anonymised quotes in publications

_____ Name of Participant	_____ Date	_____ Signature
_____ Name of Researcher	_____ Date	_____ Signature

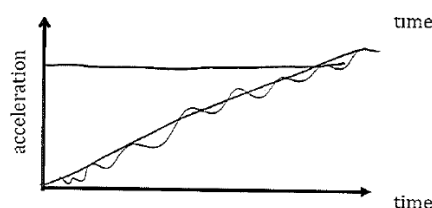
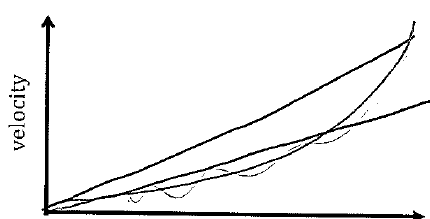
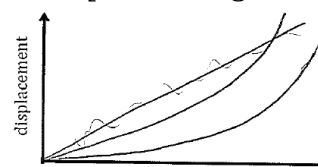
8.6 Sample transcript

Student: Amy Year: 12

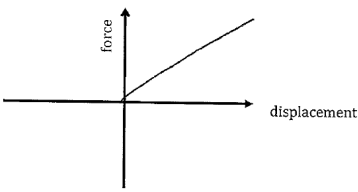
Date: 14th Oct

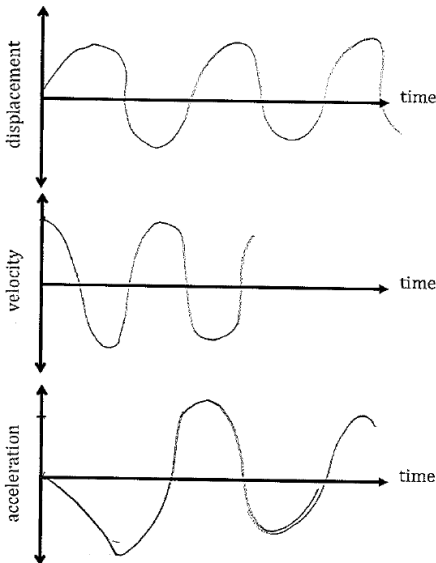
Interview No: 3

1	I	So today is the fourteenth of October and I am with Amy um starting question for today is
2	P	Mhm
3	I	Here is a spaceman
4	P	Yep
5	I	They are far away from any planet the only force on them
6	P	Yep
7	I	Is that thrust
8	P	Yup
9	I	Um describe how they will move
10	P	OK um so [pause] they would do you want me to draw the graphs
11	I	If you want to do it that way
12	P	With displacement would just move from that would just go from zero to positive so it would look like [pause] er like that [draws diagonal straight line]
13	I	Yep
14	P	Um and then the velocity I would say would be [pause] he'd move at a constant velocity so I'd say [pause] wait no because it would accelerate because there is not backwards force on him so it would probably be something like [pause- adds curved line] that um and then acceleration however would be constant so that would be like that [adds diagonal line]
15	I	Is that a graph for constant acceleration?
16	P	No it's not. No that's constant acceleration on a velocity graph er so that would be something [adds horizontal line] like that
17	I	So a horizontal line?
18	P	Yes a horizontal line
19	I	OK um one thing to think about look at the velocity graph you've drawn
20	P	No No-that would be a straight line [changes line to steeper diagonal line]
21	I	Why would it be a straight line?



22	P	Because its constant acceleration
23	I	Good and what about the displacement one now
24	P	Erm the displacement [pause] wait would that be a curve [adds higher of two curves]
25	I	Why would it be a curve?
26	P	Um because [pause] if it's accelerating then it's going to be moving a greater distance as time goes by
27	I	What on a displacement time graph links to velocity?
28	P	Erm the gradient
29	I	And um because the velocity is going up the gradient
30	P	The gradient will be getting steeper
31	I	Yep excellent one more question on there if I doubled the mass of the spaceman. Thrust force remains the same
32	P	Yes
33	I	What would change?
34	P	Um would the acceleration change? Yeah because I know I am relating it to the equation Force equals mass times acceleration
35	I	Yes
36	P	So if the force is the same the mass is the same then the acceleration must change
37	I	Yep so if we double the mass the and the thrust is the same the acceleration would be
38	P	Half
39	I	Half and what would happen to the velocity time graph
40	P	The velocity time graphs would therefore the line would be it would still be constant acceleration but the line would be a bit not as steep [adds lower gradient diagonal to graph]
41	I	OK yep good and on the displacement time graph?
42	P	Erm that would be [pause] [adds lower of two curves] like that
43	I	Great OK just before we start playing with the mass on the spring um any moments this week when things have made sense or
44	P	Um not really no [laughs] well obviously its made sense but I haven't if you are talking about moments where it has just clicked then not really relating to physics no
45	I	Do you think those kind of moments are rare?
46	P	Er well thinks week in physics its been sort of much of the stuff in GCSE so it does vary what we're covering
47	I	Yes
48	P	If it's new things then I will have moments when things click but this week it's been stuff that's quite familiar to me already so I haven't had any moments like that
49	I	OK great now we're going to look at this mass on a spring um first thing I want to think about is um how does the force vary with distance so if I put a hundred grams on there do you want to just measure the length of the spring
50	P	Er where about five centimetres
51	I	About five centimetres. Um actually let's start let's measure it like that with no mass on

52	P	About two point two
53	I	So at two point two if I put um that was about five so how much longer has a hundred grams made it eget?
54	P	About twice as long
55	I	So it's about three point something. It was two point two
56	P	Yeah so now it's five so it would be two point something
57	I	If I put another mass on what you expect it to
58	P	Would it increase by [pause] would it[pause] or because I am just trying to work this out in my head [laughs] would it increase by the same amount again
59	I	Yep so how much did it that made it increase by two point
60	P	About two point
61	I	Something yeah
62	P	So it would increase by about two point something again
63	I	So it should be about seven
64	P	Six seven [pause] yeah seven point something
65	I	Lt's have a look give it a
66	P	That's increased by more I think er it's about eight, eight point five
67	I	OK I know our equipment' not going to be perfect what would you expect if I doubled the force on it
68	P	If you double the force on it you'd expect the spring to be double as long
69	I	So if I drew a graph of force against displacement
70	P	Er you would would it just be a [pause] straight line 
71	I	Yes
72	P	'Cos they're proportional to each other
73	I	Yep now what I want to do rather than you drawing as we did last week for the pendulum the graphs for displacement velocity acceleration we have this um an ultrasound ranger so it can measure by sending out little ultrasound clicks which bounce off the mass um it can measure the distance to the um mass and it therefore also measure its velocity and its acceleration
74	P	OK
75	I	So I can use this datalogger to um get all those graphs
76	P	OK
77	I	So if you just set it into motion
78	P	So
79	I	Gently pull it down or up and ok [ranger clicks]
80	P	Ah it's quite cool [ranger clicks] [computer beeps]
81	I	Right what your job is now is

82	P	Yes
83	I	To explain those shapes of graphs
84	P	Each of the graphs OK
85	I	And there's space there if you want to sketch them
86	P	<div style="display: flex; align-items: center;">  <div style="margin-left: 20px;"> <p>OK so if I sketch it out first I find it easier to read off the paper than the screen so [drawing] that's just like that so the displacement keeps moving from like increasing and decreasing</p> </div> </div>
87	I	How just explain that if we call that the zero point [indicating on mass spring system]
88	P	OK
89	I	So that's the equilibrium so if its above it
90	P	Yeah
91	I	It's positive displacement
92	P	Positive
93	I	And below is negative
94	P	So it keeps returning to its original position which is why the displacement keeps increasing and then decreasing um is that enough for the displacement graph?
95	I	We'll do some more detail in just a second
96	P	OK
97	I	But give me now you've just got to be careful that where the displacement is kind of zero which is kind of this point here [indicating on apparatus] you've got to read down because you started yours there
98	P	Oh right OK yeah oh yeah yeah yeah so it started a bit
99	I	Well That's fine so where would you start your velocity graph? If that's my zero disp When my displacement is zero
100	P	Yep
101	I	What's the velocity like?
102	P	The velocity at it's highest point
103	I	Yeah so if you want to sketch it in to
104	P	OK what so the velocity one?
105	I	Yep
106	P	So it would be [drawing velocity graph]
107	I	Yeah
108	P	Like that

109	I	Yeah
110	P	Yeah so the velocity it starts at its highest point and slows down as it moves so it slows down when the mass moves upwards
111	I	Yep
112	P	Because when its at the top its got zero velocity so then it then [pause] yeah so as it's moving up it's slowing down and then when its moving downwards it's speeding up so tat's why there's a curved shape for the velocity graph
113	I	OK do you want to sketch in the acceleration one
114	P	OK
115	I	This should start well can you tell me when all your graphs start from the equilibrium position
116	P	Yep
117	I	Now I know we you've got to think about not a zero 'cos if it's in the equilibrium it's not just spontaneously start vibrating so think, about it we've just started drawing our graphs we let I go and we start drawing our graphs when it is going through the mi
118	P	When it's going through the motion
119	I	The middle for the first time So we've let it go it's go through the middle
120	P	Yep
121	I	And then we start drawing. Displacement goes positive
122	P	Yeah
123	I	Yeah?
124	P	Yep
125	I	That kind of idea so what's its acceleration like at that equilibrium point
126	P	So when at the equilibrium point it would be decelerating because the velocity is decreasing I think is that right so it would going [pause]
127	I	Do you think um what's another way to tell what the acceleration from what you've already got?
128	P	Do you mean like the gradient of the velocity graph?
129	I	Yes yeah
130	P	So it would be decelerating
131	I	Look very carefully at the first instant
132	P	Oh right at the first instant it would be what so where it would start off from on the graph
133	I	So time equals zero there
134	P	Yes
135	I	Well if you look at this velocity time graph
136	P	Yeah
137	I	What's the gradient right at that first instant
138	P	It's [pause] well it's really steep
139	I	You can use a ruler to go along [indicating with ruler on graph how ot indicate gradient]
140	P	I am confused
141	I	I am really just asking what's the gradient because
142	P	Yeah

143	I	We want to find the acceleration um what's the gradient of this graph which will tell us the acceleration what's the gradient of that graph right at the first instant?
144	P	Oh so that would be t at this one
145	I	Yeah
146	P	So it would be there
147	I	You're saying there's a big positive gradient at the start?
148	P	[pause]
149	I	Put your ruler along the line of the graph and follow the gradient so there [runs ruler along graph]
150	P	Like that
151	I	So the gradient here is
152	P	Yep
153	I	Kind of
154	P	Yep
155	I	Fairly steep an negative now as we go back to zero what's happening to the gradient?
156	P	Er
157	I	See I'm following the gradient here
158	P	It's getting less steep which means it would be accelerating
159	I	And right at the point here
160	P	Yes
161	I	If I try and make my ruler go right along the top of the graph. What's the gradient right at the top?
162	P	It's got no gradient
163	I	Where should we start?
164	P	Here
165	I	Yep
166	P	And would it be then it wouldn't be constant acceleration
167	I	Well for a start which way will my acceleration which way is the gradient?
168	P	It will be going so it will be accelerating because the gradient is getting less steep
169	I	Well which way is this a positive or a negative gradient after?
170	P	Oh that's a negative gradient
171	I	So and we start off at zero and the gradient gets more and more and more steep
172	P	So it would be getting if it decelerating
173	I	It's getting a bigger and bigger
174	P	Bigger and bigger deceleration
175	I	Deceleration. Starting from
176	P	Here so it would then be [pause] so it would be if it's getting bigger and bigger would it be something like that [adds acceleration curve up to x-axis in first $t/4$ period]
177	I	And then um so it gets bigger and bigger but here the gradient starts going back to
178	P	Zero then it so then it starts acceleration which would be like that[adds line up to first maxima]

179	I	And then
180	P	And then would it just follow through [completes wave]
181	I	That kind of idea
182	P	Like that
183	I	We do get that kind of curve
184	P	Yep
185	I	Same kind of sine wave kind of shape now what I would like you to do given what we've said about how the spring works so double the displacement double the force
186	P	Yeah
187	I	Why do we get these graphs. You might want to start thinking about the acceleration one
188	P	Acceleration so why does are you essentially asking why does it decelerate and then accelerate?
189	I	Yeah why do we get these shapes?
190	P	OK so when it is well if you think this is when it's at its starting point its zero velocity and then when it goes up
191	I	Is it Is it zero velocity in a normal cycle. [pause] Ping it so middle position is somewhere
192	P	Yeah
193	I	Is it zero velocity when it goes through the middle position?
194	P	No
195	I	Where is the velocity zero?
196	P	When it's changing direction. So when it is when it springs up it is essentially slowing down
197	I	Yes
198	P	So it would be accelerating and then when it gets to the top it will then change direction and then it will speed up again so it will be accelerating and do I need to explain why it goes forward and back ward?
199	I	Link Link link to in terms in terms of forces
200	P	Yep
200	I	Explain the changes in acceleration by what's happening with the forces
201	P	Oh so you've got the mass because mass is two hundred grams and so the force of weight will always be pulling down on it and the [pause] when you make it spring the upward force of the spring isn't as great as the weight so it is going to slow down as it moves upwards and speed up when it moves down
202	I	OK why does it speed up and slow down when it is moving?
203	P	Because the weight is greater than the upwards force the tension
204	I	The wei... so is this when it's moving up or when it's moving down?
205	P	Well when it's moving up it slows down because the weight is greater than the upward force acting on it the weight
206	I	OK so when does it start to slow down at which part of its motion so if I release it from the bottom. Initially it will start to [pause] it starts to
207	P	It would [pause] ss [pause] it would speed up then slow
208	I	So up to where does it speed up?

209	P	Erm it would speed up but when gets to the equil equilibrium point that's where it speeds up but when it gets past the equilibrium point it will slow down
210	I	Good so in terms of forces when I am at the equilibrium tell me what the resultant force is like
211	P	There is no resultant force it's balanced
212	I	And then when I move below the resultant er below the equilibrium point the further down I move
213	P	The tension in the spring is greater than the weight pulling it down so that is why it speeds up when it gets to the equilibrium point but past the equilibrium point the weight is greater than the tension in the spring yeah
214	I	So there is a
215	P	Um
216	I	So at the equilibrium point is there a resultant force
217	P	No but below it there is a resultant force upwards and above it there is a resultant force downwards
218	I	Now let's think in terms of the acceleration so what will the acceleration at the equilibrium position be?
219	P	It would be zero
220	I	Because?
221	P	Because there is no resultant force acting on it however below the equilibrium the acceleration would be positive it would be increasing because it's moving it speeds up as it goes but past the equilibrium upwards it would slow it would be negative acceleration because the weight is greater than the upward force.
222	I	Good
223	P	That makes sense now [laughs]
224	I	Good what I'd like to do now is go back to last week
225	P	Mmmhmm
226	I	And we looked at the pendulum
227	P	Yep
228	I	Now are there any ways in which um those two situations are similar any ways in which they are different
229	P	Um well they are similar because there is a change in acceleration and there's a change in the velocity so as [pause] in what sense do you mean in which ways are they similar do you mean
230	I	Is there anything in the physics between those two version that's similar
231	P	Well when there both like still not moving acceleration at equilibrium the forces are balanced on them and the force when they're pendulum moves upwards to the side there's a resultant force acting on it which causes it to slow down as it goes up and then with the mass on the spring there's also there's a resultant force acting on it that causes the change in velocity um yeah [laughs]
232	I	Are they particularly similar?
233	P	I wouldn't say they are that similar no because
234	I	What makes them different?

235	P	Because [pause] this one with the pendulum when the pendulum moves to the side it's the [pause] I am thinking now that they would be similar because its there because the resultant force decreases as the pendulum moves to the side which causes it to slow down and with this um [mass on spring] when it's moving upwards [pause] the resultant force [pause] when it's moving up to the equilibrium point from here to there the resultant force acting on it upwards decreases as well which causes a change in velocity so yeah I don't really know [laughs] I am not very good at explaining that one [laughs]
236	I	Do how how with that thought how how similar do you think they are? I'll ask again
237	P	Erm I wouldn't I'd say quite similar
238	I	Why quite similar now?
239	P	A bit because it is the change in the resultant the resultant forces which act which changes the velocity however with this it's the wait because it's the direction of the resultant that changes this [mass/spring] velocity where as it's not necessarily the direction of this [pendulum] resultant force it's the size of the resultant force causing it to
240	I	Does the resultant force change direction in the pendulum?
214	P	[long pause] um when it's moving there it's slowing down
242	I	So when you are holding it to one extreme which way is the resultant force
243	P	resultant force well when it's falling that way resultant force is that way and when it's moving up like that the resultant force has got to be moving that way so yeah it is a change in I'll just say they are similar [laughs]
244	I	So we said on with the mass on the spring if I displace it
245	P	Yeah
246	I	I have a resultant force which moves it vertically. Displace it down
247	P	Yes
248	I	There is a
249	P	Resultant force upwards
250	I	Yup and how much I displace it if I double the displacement from the equilibrium position I will have
251	P	A double resultant force
252	I	Double the resultant force OK so if I now displace the pendulum um which was is the resultant
253	P	Resultant force is [pause] oh if move it
254	I	Let's rotate it so its easier to visualise [rotates pendulum] so if I move it to the left of
255	P	The resultant force would be that way [indicating away from equilibrium position]
256	I	It'd be left?
257	P	Yeah, Right, left
258	I	In terms of the equilibrium position is it towards or away
259	P	Oh away to the left
260	I	So if I let go it will move to the left
261	P	No it will move to the right

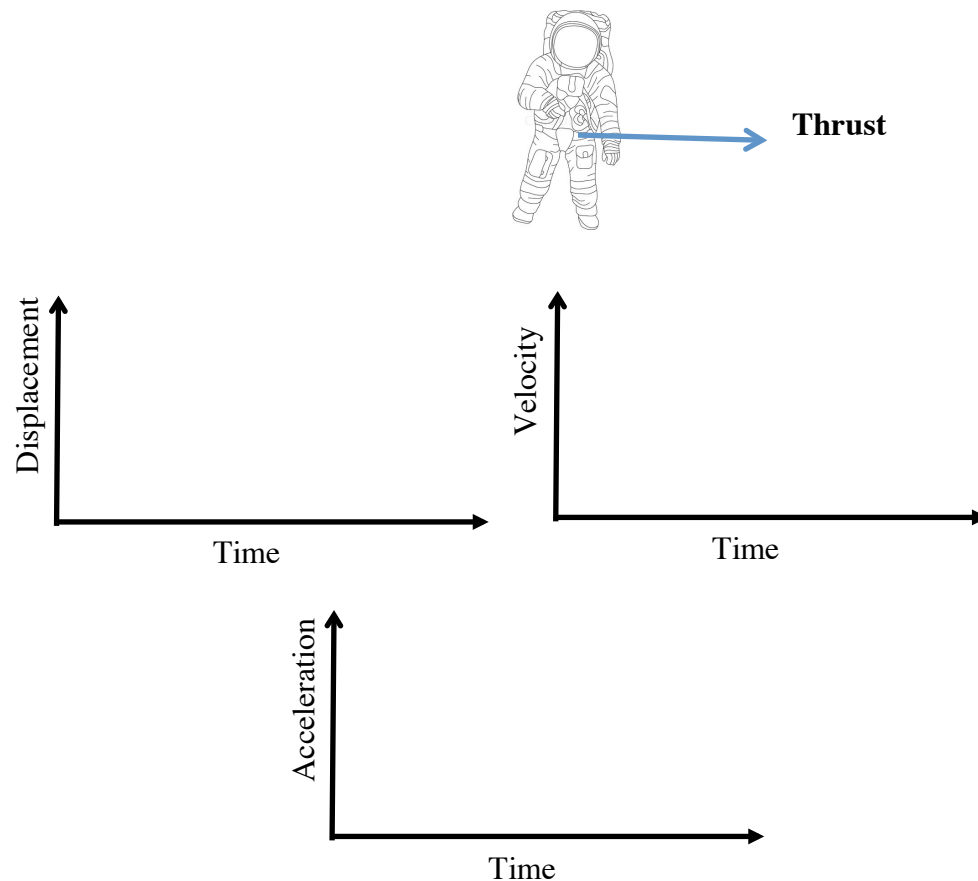
262	I	Which way is the resultant force?
263	P	The resultant force is to the right
264	I	If I hold it up here [out to other side] which way is the resultant force
265	P	To the left
266	I	If I move it if I double the distance I move it away what will happen to the size of the resultant force?
267	P	It will double so- they are very similar yeah
268	I	Why?
269	P	Because the further you move the weight so in this case the pendulum in this case the mass away from the equilibrium um the resultant force doubles like it increase in proportion to how far it is away from equilibrium so in that case they are similar
270	I	What would happen if I I don't know if you can remember back what would the displacement time graph for the pendulum look like?
271	P	Erm the disp [pause] would it [pause] would it be something similar to the first one about the same
272	I	What would the velocity time graph for the pendulum look like?
273	P	That would be the same as well and then would the acceleration be the same as well. So yeah they are very similar
274	I	They are very similar yeah. What underlying thing is causing their motion to be very similar
275	P	The resultant forces acting on them and their [pause] direction
276	I	So the key fact is that the resultant force depends on
277	P	The mass of the
278	I	What does the resultant force depend on
279	P	The dr what do what
280	I	Look at your graph [indicating force displacement graph]
281	P	Oh the displacement
282	I	So in both cases the resultant force depends on
283	P	The displacement and how far it is away from equilibrium
284	I	And in both case the resultant force always acts
285	P	In proportion to displacement
286	I	And in which direction so if I displace it up
287	P	If you displace it up it will act downwards
288	I	And the same in the pendulum
289	P	Yep
290	I	So the resultant force always acts back towards
291	P	The opposite direction
292	I	Yeah or back towards the equilibrium
293	P	Back towards
294	I	OK that's interesting. [pause] I think we shall finish there

8.7 Interview prompts

8.7.1 Sample Semi-structured prompts (Interview 3)


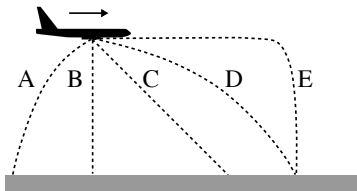
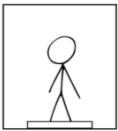

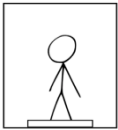
Astronaut Question

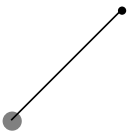
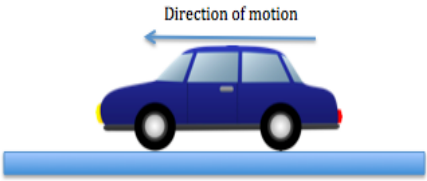
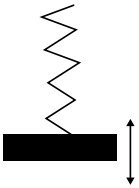
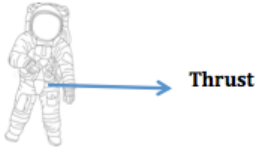
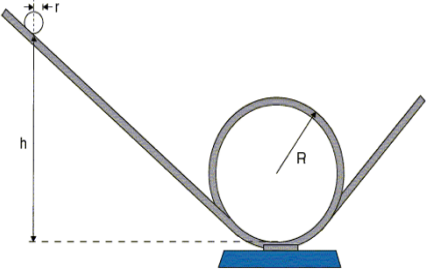
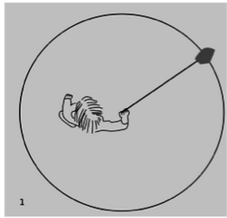
- a) The astronaut below is in space, far from any planets? What will the astronaut do? Describe how its displacement, velocity and acceleration will change over time?

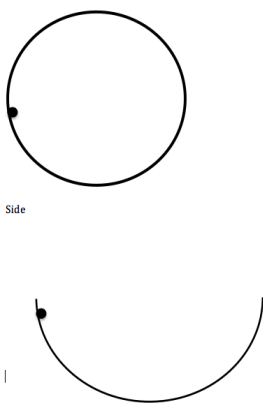
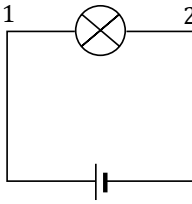
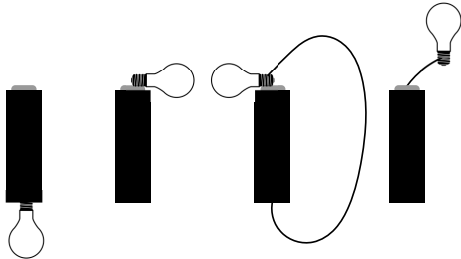
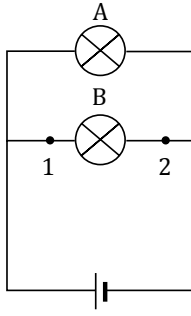
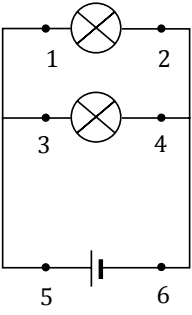


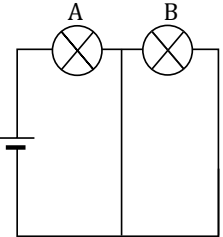
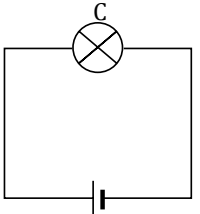
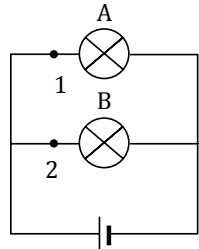
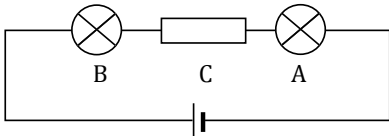
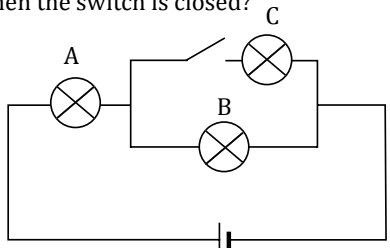
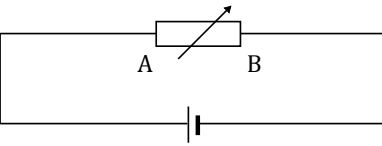
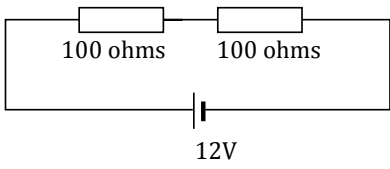
- Review any moments of making sense in previous week
- Examine mass on spring system- elicit ideas around relationship between force and displacement and sketch graph
- Use datalogger and ultrasounder to plot displacement, velocity and acceleration time graphs for mass spring system
- Ask for explanation of graphs
- Ask student to draw force diagram
- Ask for prediction of effect of different displacements on motion of mass and spring
- Ask student to reflect on similarities and differences between mass spring system and pendulum observed in pervious week

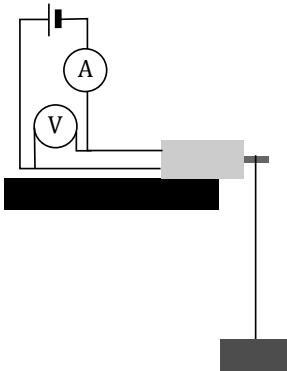
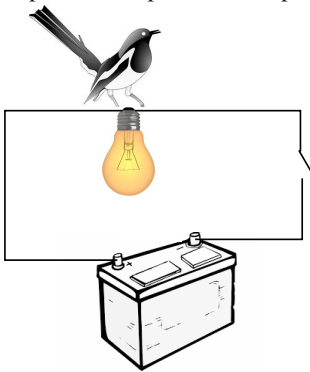
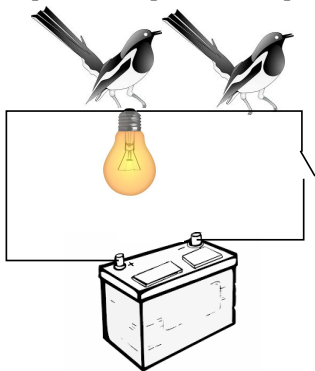
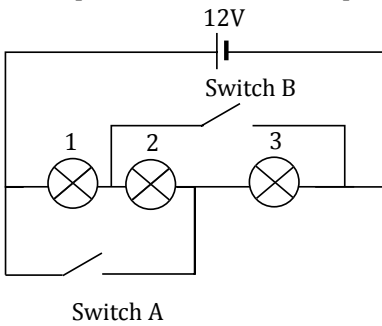
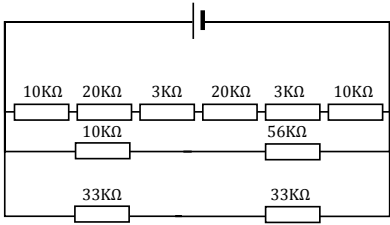
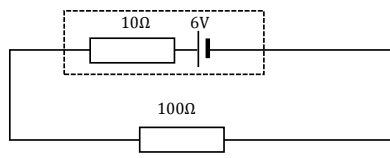
8.7.2 Interview Prompts

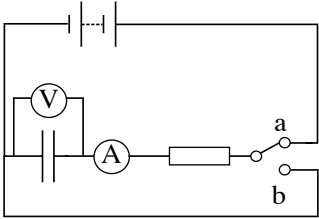
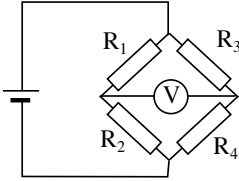
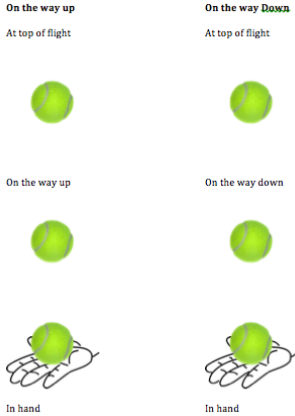
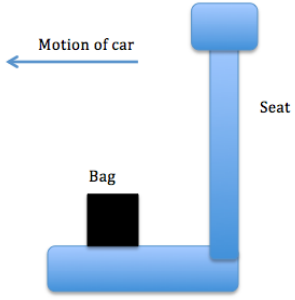
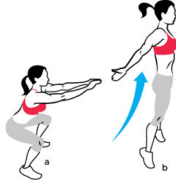
<p>(a) Dropped Balls, Interview 1, 15, 22 (Adapted from Epstein, 2009, p. 27)</p> <p>Two metal balls are dropped at the same time, from the same height. The balls have the same diameter but one ball has a greater mass than the other. Which option best describes the outcome? Explain your answer.</p>  <p>a) the ball with greater mass hits first b) the lower mass hits first c) the balls hit at the same time</p>	<p>(b) Balls projected off table, Interview 1, 15, 22 (Adapted from Hestenes, Wells & Swackhamer, 1992, Q2)</p> <p>The two metal balls in the pervious question roll off the edge of a table with the same speed. Which option best describes the outcome:</p> <p>a) both balls hit the floor at about the same horizontal distance from the base of the table b) the heavier ball hits the floor at about horizontal distance from the base of the table than the lighter one c) the lighter ball hits the floor at about horizontal distance from the base of the table than the heavier one d) the heavier ball hits closer than the lighter one but not necessarily half the distance d) the lighter ball hits closer than the heavier one but not necessarily half the distance</p>
<p>(c) Free fall, Interview 1, 15, 22 (Adapted from Hestenes, Wells & Swackhamer, 1992, Q3)</p> <p>A stone is dropped from the top of a building. Which of the following sentences best describes its subsequent motion:</p> <p>a) accelerates then reaches constant velocity b) constantly speeds up as gravitational attraction increases as it gets close to Earth c) speeds up because of constant force acting on it d) falls because gravity and air resistance push it down</p>	<p>(d) Projectiles from a plane, Interview 1, 15, 22 Adapted from Epstein, 2009, p. 133</p> <p>An aeroplane is travelling with constant velocity when it drops a ball. Which path best describes how the trajectory of the ball would look to an observer on the ground? Explain your answer</p> 
<p>(e) Collision, Interview 1, 15, 22 (Adapted from Hestenes, Wells & Swackhamer, 1992, Q4)</p> <p>A lorry travelling at constant velocity collides with a stationary small car. During the collision:</p> <p>a) The lorry exerts more force on the car than the car exerts on the lorry b) The car exerts more force on the lorry than the lorry exerts on the car c) Neither exerts a force, the car is smashed as it is in the way d) Only the lorry exerts a force on the car, the car does not exert a force e) The lorry exerts the same force on the car as the car exerts on the lorry</p>	<p>(f) Forces on a person in a lift, Interview 1, 4, 15, 22 (Adapted from Pople, 1982, p. 27)</p> <p>At rest</p>  <p>Traveling up at constant velocity</p>  <p>Accelerating up</p>  <p>A person travels in a lift whilst standing on a set of scales. Describe the reading on the scale relative to their 'normal' mass in each situation. Label the forces that act.</p>

<p>(g) Simple pendulum Interview 2, 15, 22 Student is shown a simple pendulum system</p>  <p>The student is given the following prompts:</p> <ul style="list-style-type: none"> • Describe the motion of the bob (sketch graphs of displacement, velocity and acceleration against time) • Explain the motion of the bob • Draw force diagram to illustrate your answer • Predict what will happen when the mass of the bob is increased 	<p>(h) Forces on a car, Interview 2</p>  <p>a) Describe the forces acting on the car when it is moving at a constant speed of 30mph b) Describe the forces acting on the car when it is moving at a constant speed of 70mph c) Describe what happens to the forces acting on the car when it brakes to a complete stop. Which way is the resultant force When the car is stopped are there any forces acting on the car?</p>
<p>(i) Mass on a spring, Interview 2, 15, 22 Student is shown a mass-and-spring oscillator</p>  <p>The student is given the following prompts:</p> <ul style="list-style-type: none"> • Describe the motion of the mass (sketch graphs of displacement, velocity and acceleration against time) • Explain the motion of the mass • Draw force diagram to illustrate your answer • Predict what will happen when the mass on the spring is increased 	<p>(j) Astronaut in space, Interview 3, 16, 22</p>  <p>The astronaut below is in space, far from any planets? What will the astronaut do? Describe how its displacement, velocity and acceleration will change over time? Sketch a graph of each.</p>
<p>(k) Marble Loop-the-loop, Interview 4</p>  <p>Release the marble and let it run round the loop. How can the marble travel upside down at the top of the loop? Describe the forces which act on the marble.</p>	<p>(l) Swung ball, Interview 4</p>  <p>A child swings a ball on a string in a horizontal circle. Explain how the ball can travel in that motion. What will happen if the string breaks?</p>

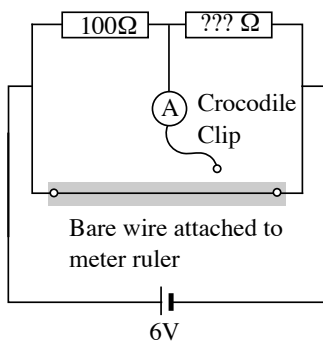
<p>(m) Ball in a bowl, interview 5,15,16, 22 Place the marble on the side of the cooking bowl and release it-observe the oscillations</p> <div style="display: flex; align-items: center;"> <div style="text-align: center;"> <p>Above</p>  <p>Side</p> </div> <div style="margin-left: 20px;"> <p>Describe the motion of the ball. Explain its motion. Use the diagrams to support your answer.</p> </div> </div>	<p>(n) Comparing Currents, Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q8)</p> <div style="text-align: center;">  </div> <p>Compare the current at point 1 and 2. A) The current is larger at point 1 than point 2 B) The current is larger at point 2 than point 1 C) The currents are the same</p>
<p>(o) Lighting a bulb, Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q9) In which circuit will the bulb light?</p> <div style="text-align: center;">  <p>A B C D</p> </div>	<p>(p) Speed of current, Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, 1992, Q11)</p> <p>Explain why the lights in your home come on almost immediately</p> <p>A) Charges are already in the wire. When the switch is closed there is a rapid rearrangement of charge B) Charges store energy. When the switch is closed energy is released C) Charges in the wire travel very fast D) The circuits are wired in parallel. There is already current flowing in the wires</p>
<p>(q) Parallel Circuit, , Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q15) What happens to the potential difference between 1 and 2 if bulb A is removed?</p> <div style="display: flex; align-items: center;"> <div style="text-align: center;">  </div> <div style="margin-left: 20px;"> <p>A) Increases B) Decreases C) Remains the same</p> </div> </div>	<p>(r) Current Ranking, , Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q17) Rank the currents at the marked points from highest to lowest</p> <div style="display: flex; align-items: center;"> <div style="text-align: center;">  </div> <div style="margin-left: 20px;"> <p>A) 5, 1, 3, 2, 4, 6 B) 5, 3, 1, 4, 2, 6 C) 5=6, 3=4, 1=2 D) 5=6, 1=2=3=4 E) 1=2=3=4=5=6</p> </div> </div>

<p>(s) Circuit Comparison, Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q8)</p> <div style="display: flex; justify-content: space-around; align-items: flex-start;"> <div style="text-align: center;"> <p>Circuit 1</p>  </div> <div style="text-align: center;"> <p>Circuit 2</p>  </div> </div> <p>Compare the brightness of bulbs A and B with bulb C. Which bulb or bulbs is the brightest?</p> <p>A) A B) B C) C D) A=B E) A=C</p>	<p>(t) Circuit Connection, Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q19)</p> <div style="text-align: center;">  </div> <p>A wire is connected between points 1 and 2. What happens to the brightness of bulbs A and B?</p> <p>A) Increases B) Decreases C) Stays the same D) A becomes brighter than B E) Neither bulb will light</p>
<p>(u) Increasing Resistance, Interview 6, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q26)</p> <p>If resistance C is increased, what happens to the brightness of bulbs B and C?</p> <div style="text-align: center;">  </div> <p>A) A stays the same, B dims B) A dims, B stays the same C) A and B increase D) A and B decrease E) A and B remain the same</p>	<p>(v) Switch Circuit, Interview 7, 17, 21 (Adapted from Engelhardt & Beichner, 2004, Q29)</p> <p>What happens to the brightness of bulbs A and B when the switch is closed?</p> <div style="text-align: center;">  </div> <p>A) A stays the same, B dims B) A brighter, B dims C) A and B increase D) A and B decrease E) A and B remain the same</p>
<p>(w) Variable resistor, Interview 7</p> <div style="text-align: center;">  </div> <ul style="list-style-type: none"> • What happens to resistance of the resistor when slider is moved? • What happens to current in the circuit at A? at B? • What happens to the P.D. across resistor? • What happens to the EMF across the battery? 	<p>(x) Potential divider, Interview 7 Simulated using PHET simulation available at: https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc</p> <div style="text-align: center;">  </div> <p>Predict the potential difference across each resistor What is the general rule, if the resistances and the EMF change?</p>

<p>(y) The motor lifting a load, Interview 7 A motor lifts a load attached to it by a string</p>  <p>How will the potential difference and current measured on the meters shown be different when a heavier load is lifted? Explain your answer.</p>	<p>(z) Bird on Bulb, Interview 8 (Adapted from Epstein, 2009, p. 409)</p>  <p>When the switch is closed, will the bird get a shock? Explain your reasoning.</p>
<p>(aa) Two birds on a wire, Interview 8 (Adapted from Epstein, 2009, p. 411)</p>  <p>When the switch is closed, does either of the birds get a shock? Explain your reasoning.</p>	<p>(ab) Switch Circuit, Interview 8 (Adapted from Grimvall, 2007, p. 32)</p>  <p>Which bulbs light when: a) no switches are closed; b) A only is closed; c) B only is closed; d) both A and B are closed?</p>
<p>(ac) Potential Difference, Interview 8</p>  <p>Choose two points where a voltmeter may be connected to give a reading of zero volts</p>	<p>(ad) Internal Resistance, Interview 9 Simulated using PHET simulation available at: https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc</p>  <p>What is the potential difference across the 100Ω? Why is it less than 6V?</p>

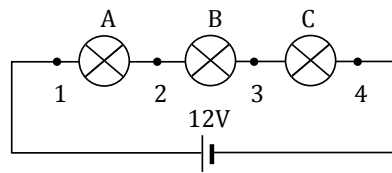
<p>(ae) The capacitor and potential difference, Interview 9</p>  <p>Move the switch from a to b. Describe what happens to the potential difference and current (sketch a graph). Explain your observations.</p>	<p>(af) Wheatstone Bridge Circuit, Interview 10 Simulated using PHET simulation available at: https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc</p>  <p>Predict the potential difference when: $R_1=10\Omega$, $R_2=10\Omega$, $R_3=10\Omega$, $R_4=10\Omega$ $R_1=10\Omega$, $R_2=20\Omega$, $R_3=10\Omega$, $R_4=20\Omega$ $R_1=50\Omega$, $R_2=50\Omega$, $R_3=50\Omega$, $R_4=50\Omega$</p>
<p>(ag) Ball thrown vertically, Interview 11 A ball is thrown vertically. Describe its motion and label the forces at the points on its flight</p> 	<p>(ah) Bag in braking car, Interview 12</p> <p>Shopping bag on a car seat</p>  <p>A shopping bag rests on a car seat. The car brakes. Describe and explain the motion of the bag.</p>
<p>(ai) Leaping from a crouch, Interview 13</p>  <p>A girl crouches down and leaps into the air. Explain how she is able to jump above the ground.</p>	<p>(aj) Weightlessness, Interview 14</p> <p>Watch the following clips of astronauts:</p> <p>[Astronauts on space station] https://www.youtube.com/watch?v=QF2w2Dx_QMs</p> <p>[Astronauts on training aircraft] https://www.youtube.com/watch?v=2V9h42yspbo</p> <p>The state of the astronauts is sometimes described as 'weightlessness'. Why are they 'weightless'? Are the two situations the same?</p>

(ak) Sliding wire potentiometer, Interview 17



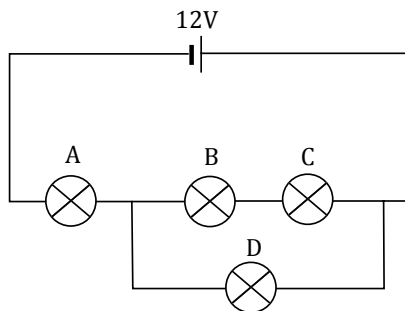
Move the wire till the Ammeter reads zero amps.
What can you deduce about the unknown resistor?
Explain your reasoning

(al) Potential Energy, Interview 18



Describe how the potential energy of an electron varies as it passes round the circuit.

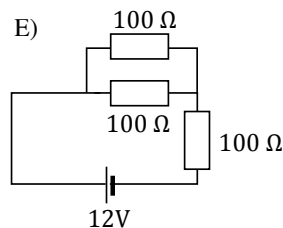
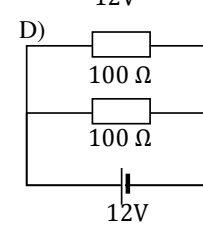
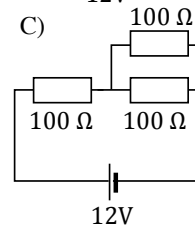
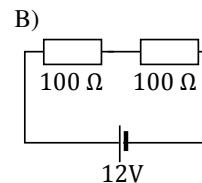
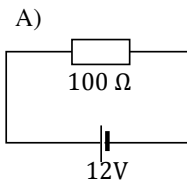
(am) Circuit Problem, Interview 18



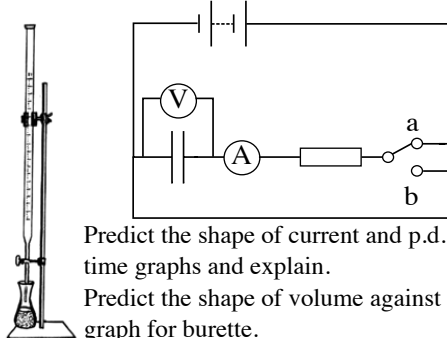
Find the potential difference across bulbs A, B, C and D

(ao) Sequence of circuits, Interview 19

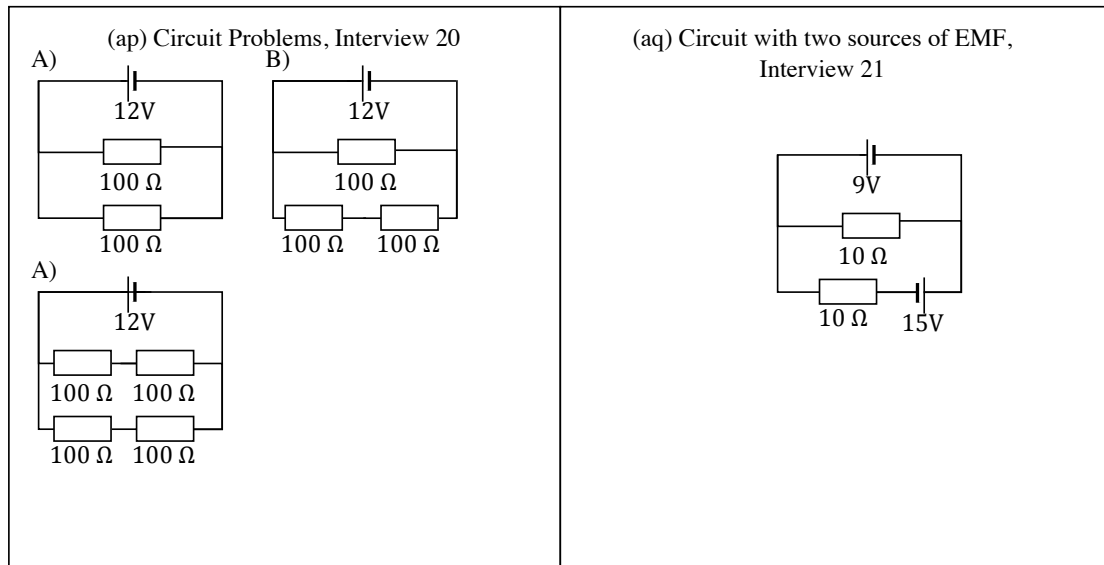
Calculate the p.d. across each resistor



(an) Capacitor and Burette, Interview 18
(Adapted from Taber, 2007, p. 40)



Predict the shape of current and p.d. against time graphs and explain.
Predict the shape of volume against time graph for burette.
Compare to data and reflect on differences.
Discuss similarities between contexts.
Draw a concept map of each scenario.
Draw links between the two maps to show similarities between the situations.



Works cited in interview prompts

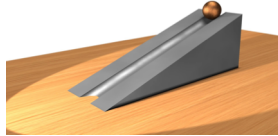
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- Taber, K. S. (2007). *Enriching school science for the gifted learner*. London: Gatsby Science Enhancement Programme

8.7.3 Card Sorts

8.7.3.1 Situation card sort

Sort these questions into groups you think are similar. Describe what makes the groups similar.

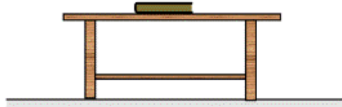
A) A ball rolling down a slope



F) A parachutist in free-fall



E) A book at rest on a table



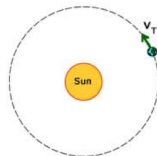
D) A car driving along at constant speed



C) A tennis ball thrown upwards



B) The Earth orbiting the sun



8.7.3.2 Problem card sort

Sort these problems into groups you think are similar. Describe what makes the groups similar.

A) A coin is dropped from a tower of height 100m. Calculate how long it will take to hit the ground. Ignore air resistance and assume $g=9.8\text{N/Kg}$

B) A car's engine develops a thrust of 2000N. As it drives along a road, a force due to air resistance of 500N and of friction of 1500N act. The car's initial velocity is 20m/s. How far will it travel in 10 seconds?

C) A ball is placed on a slope of angle 30° to the horizontal. The slope is 2m long. How long will it take the ball to run down? Ignore air resistance and assume $g=9.8\text{N/Kg}$

D) An electron is placed in an electric field that causes it to accelerate at $1.2 \times 10^{-30}\text{ m/s/s}$. How long will it take to travel one meter?

E) A thrust force of 5000N causes a jet-ski to travel at constant velocity of 15m/s. What distance will it cover in 1 minute?

F) A sprinter runs at 8.2m/s how long will it take them to cover 50m?

G) A projectile is fired from the ground at 10m/s at an angle of 30° to the horizontal. What horizontal distance will it travel from its starting point?

8.7.3.3 Causality Card sort

Place the concept cards below along the continuum of cause and effect below.

Force
Acceleration
Displacement
Velocity
Mass
Time
Weight
Momentum
Energy

Effect

Neither

Both cause and effect

Cause

8.7.4 Personal epistemology prompts

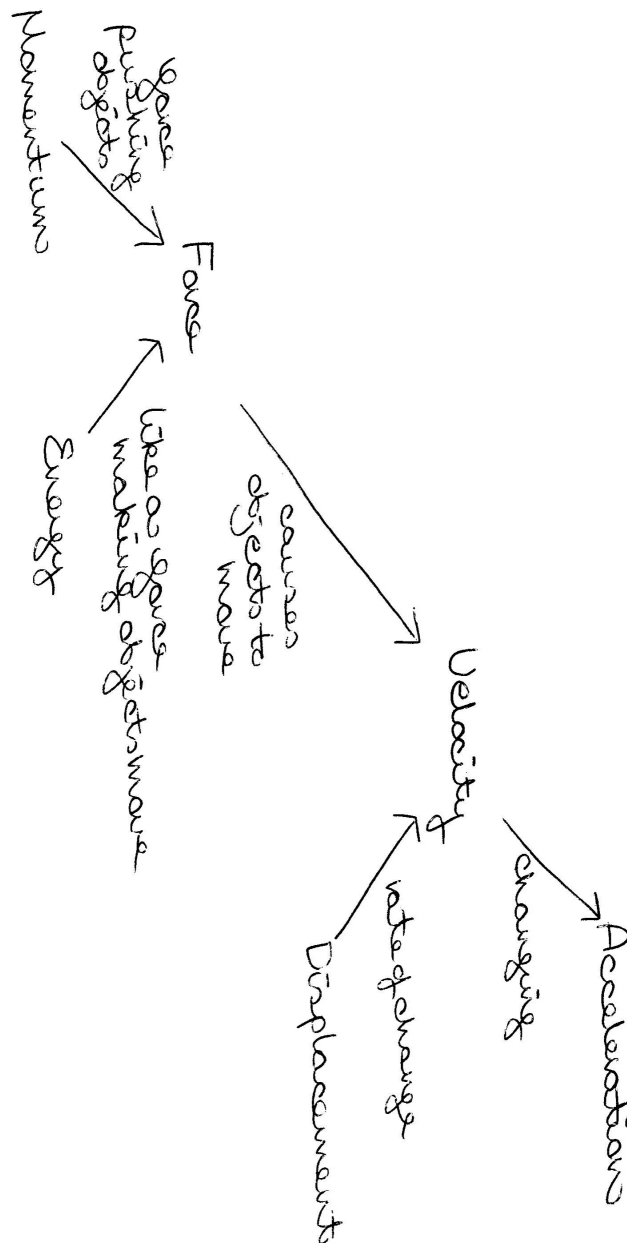
Prompts are taken from (Adams, Perkins, Dubson, Finkelstein, & Wieman, 2005).

To what extent does the statement describe your attitude to learning about physics?

Q11	I am not satisfied until I understand why something works the way it does.
Q13	I do not expect physics equations to help my understanding of the ideas; they are just for doing calculations.
Q23	In doing a physics problem, if my calculation gives a result very different from what I'd expect, I'd trust the calculation rather than going back through the problem.
Q24	In physics, it is important for me to make sense out of formulas before I can use them correctly.
Q32	Spending a lot of time understanding where formulas come from is a waste of time.
Q36	There are times I solve a physics problem more than one way to help my understanding.
Q41	It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.
Q42	When studying physics, I relate the important information to what I already know rather than just memorizing it the way it is presented.

8.7.5 Student's pre-drawn concept map

Look at the concept map drawn by a student. Are there any changes you would make to the map? Explain your reasoning



8.7.6 Causal links between electrical concepts

Use arrows to indicate the relationships between causes and effects. Arrows should start at a cause and point to an effect.

Current

**Potential
Difference**

Resistance

8.8 Coded transcripts

8.8.1 Codes related to causality

8.8.1.1 Codes related to causality in Ben's transcripts

Session; utterance	Utterance	Code
6; 32	Yes sir um I think I would link current and charge because I think they're directly proportional because if you're going to have a greater charge the they'll be more charge passing a fixed amount of time and so the current would increase um as I think one amp is actually one coulomb over	Symbolic
6; 32-34	would increase um as I think one amp is actually one coulomb over One coulomb per second	Symbolic
6;38	I think that they oppose each other because if you have the same amount of potential difference but more resistance then it would be harder for the current to get through but if you've got the same current and you increase the potential then you decrease the resistance providing the temperature isn't changing um [pause]	Symbolic
6; 38	I think I would link current with potential difference because of Ohm's law that the current is directly proportional to the voltage across a conductor provided the temperature remains constant um [pause]	Symbolic
6; 38	I think in the same way that potential difference and resistance oppose each other current and resistance oppose each other 'cos if you have more resistance then the electrons are going to have a lower average drift velocity so the current is going to be less [pause] I think that's most of it	Sub-microscopic
6; 58	I think that point will probably have a lower current because one amp is one coulomb per second	Symbolic
6; 58	and if it's passed through a filament with resistance then it will have a lower velocity when it reaches point one so it will have a lower drift velocity so the current will be less	Sub-microscopic
6; 94	[reading] um [pause] on display um [pause] [indistinct] um I think both one and two will increase because no will it no [pause] I correct I think they will stay the same because you've got the same you're pushing the electrons by the same amount you're going to have more electrons through point one and two but they're not necessarily going to be travelling any faster than they were originally	Sub-microscopic
6; 94	so it'd be the same amount of coulombs per second so it would stay the same	Symbolic
6; 128	current should split evenly because you have equal resistance on the branches and so using that mode [pause muttering] so I think D is the right answer	Symbolic
6; 130	[reading] I think bulb C will be brightest um I think less because you've got more current so in a fixed amount of them you've got more electrons passing through the filament at point C and because of that you'll have more collisions and more energy will be transferred to the ions and so the temperature will and due to the photoelectric effect light will be emitted	Sub-microscopic
6; 132	Because is it because the current splits at the junction for A and B while here the series it's a series circuit so the current hasn't split at any point	Macroscopic
6; 138	So both bulbs will stay/ I think because although you're giving another route for the electricity to flow [pause for talking in background] shall I carry on?	Macro

6; 140	Yes I think that because although you've got more than one route the current if the resistance of the wires is equal will halve at that route and so effectively you've got the same current going to points two and one as before it's just the current along each route is halved the original value	Macroscopic Symbolic
6; 148	I think A will stay as bright because the it hasn't reached the new resistance yet because it will pass point C after point B so point B brightness will stay but then the resistance at point C would decrease the current so bulb A will be less bright	Macroscopic Symbolic
6; 152	A will be less bright because you've slowed down the electrons so less electrons is reaching the bulb second so they'll be less collisions less light energy emitted while the bulb B will stay the same brightness because it hasn't yet reached the resistor so if you change the resistance the bulb B will have the same brightness	Sub-microscopic
6; 154	I think that bulb A would have the same brightness because the current will converge at the end of the junction and so the current reaching A will be the same no matter what route the current takes through B and C um I think B will be less bright because it opens up a new route by closing the switch so half as much current will flow through B as before so it would be half as bright and I think brightness well originally it wouldn't have lit up but now it will be much brighter because you allows the current to flow through point C so there's no longer a gap in the circuit	Macroscopic
7; 40	Because you have twice the resistance there so it's going to use two times the amount of energy to get through per coulomb but all of it has to add up to nine so that we get two thirds of nine that's one third of nine	Symbolic
7; 74	Will the [pause] current become [pause] three no will it be if it's going down then it will be three times as much but if it's going up then will it be a third 'cos the motor is probably going to turn slower because there is more mass on the string which will generate	Macroscopic
7; 80	Because um is it because the same of electricity has to pull up more weight so it's going to so the turns going to be turning less fast and so the current's going to be less	Macroscopic
7; 96	More Oh it has to do more work so there's going to be more coulombs passing it second because more work needs to be done so the current's going to increase	Symbolic
7; 100	Will that also yes I think that will also um increase because more work is needed to be done so more energy will need to be transferred and because one volt is one joule per coulomb the voltage will be higher	Symbolic
7; 114	So more work is having to be done but if the but would the current compensate for the work um is it because [pause] we're using the same supply so it's only going to be giving the same EMF and the work being done that only increases because the current increases and so the voltage can remain the same	Symbolic
7; 124-126	W is equal V Q oh is it because the work no but the work being done has increased as well um / Yes and the charge transferred is more [pause] the for the voltage to decrease the charge coming must be greater than the increase in the time um [long pause]	Symbolic
7; 152	Is it because the wire is heating up at a greater extent 'cos the current is increasing so more electrons are flowing through and so the ions are vibrating and so they are going to have to push through harder to pass though the wire and so the actual amount of potential difference that reaches the motor is less	Sub-microscopic
8; 30-32	Um is it the work done by the electrons when they transfer energy from electrical to other forms um the potential um depends generally on the resistance but also the EMF due to Kirchhoff's is it Kirchhoff's second law / Um I think that's [pause] it also	Symbolic

	depends on the current and the potential difference can also be used to then measure the power because it's the current times by the potential difference um it's the potential difference that causes things to get hot and emit light and usually there's a lot of potential difference so things like lamps aren't very efficient because so little energy is actually transferred as light most is transferred as heat um [pause]	
8; 48	Yes because the here's a high resistance so the electricity is likely to pass through the bird and also there would be a lot less current passing through to the other side of the bird because they'd be lots of potential difference here [the bulb] so the actual current reaching the bulb the bird at this point [right foot of bird on bulb] will be low	Symbolic
8; 98	[pause] I think they will all light but bulbs one and two will be dimmer because the current would have split between the junctions and bulb three will remain as bright because the current when it when the junction ends meets together and so the current reaching bulb three will be the same	Macroscopic
9; 72	Um will the current decrease because if you close the switch then what assumably [sic] would happen is the electrons would um the metal wire would heat or that metal plate would heat and so the electrons feed through the circuit from this plate to the battery should be gradually decreasing in general	Macroscopic
9; 94	Um [pause] will will the current decrease because I'm assuming if you're putting more electrons onto the plate then it general positive charge would decrease so there would be less pull of the electrons and so the electrons will accelerate less and therefore have a lower velocity when they reach the metal plate	Sub-microscopic
9; 98	Because at first [indistinct] at fist you the because sorry because the um charge is decreasing the force decreases and so the current will decrease and its not necessarily constant because the more electrons you have the less force you will have and so the current because the force will be decreasing over time we'll get less and less and les but by smaller and smaller amounts	Sub-microscopic
9; 124	Because you've got a because charge is moving and as charge builds up the actual difference between them in terms of the energy will increase because yes you've got more charge	Sub-microscopic
9; 132	Because because as because the charge difference increases and so the well the difference between the plates should increase and as the electrons are moving in roughly the same pattern as here [indicating current graph] it should be the inverse to the graph of the current and the inverse graph should look like this	Sub-microscopic
9; 144	I think because if there's no current and supposedly you have still resistance then the potential difference must as some point be zero due to Ohm's Law	Symbolic
9; 184	Because at that point the electrons are stationary because there's two high negative charges when more negative to go onto the plate	Sub-microscopic
9; 188/190	Um [pause] when the current is zero amps the potential difference is at it's maximum and when the current is decreasing the potential difference is increasing/ Um is it because this particular the resistance of that [capacitor] as the current as the time increases the resistance increases to a degree	Symbolic
10; 66	Um I begin with Ohm's law because I think that summarises the main parts of electricity the resistance current and the voltage and then I think I would link the resistance to the internal resistance caused by the battery [pause] and then I think I would link the internal resistance back to the terminal potential and the internal so the terminal potential difference	Macroscopic
17; 168	Because you've got more er here the potential difference or the voltage itself splits across the junction rather here all of the energy	Macroscopic

	of each coulomb is used to get past the bulb	
17; 184-186	I think I think the answer is D because one two three and four must all be equal / Because you've got the same resistance and voltage and five and six there isn't any resistance essentially between them is we're assuming the battery doesn't have any internal resistance	Symbolic
17; 225	Because the I think the main idea is if you're going to if you're going to have more current you're going to have more electrons passing and if you've got um and so the voltage would then increase if R remains constant	Symbolic
17; 233	Um and then the resistance I won't link that with current first because if you haven't got any resistance irrelevant to whether you've got a current or not you won't have any voltage	Symbolic
18; 30	[pause] I think er one thing about is it is can be alerted so you it can unlike some things like energy etcetera it can change its value when it goes through a resistor	Macroscopic
18; 58	Um [pause] is it um the energy the chemical energy that is given by the battery	Macroscopic
19;20-22	Is it um the electrostatic repulsion between charges/ Um energy transferred from the battery	Sub-microscopic
19; 30	Um [pause] when a material has some resistance casing the electrons to lose kinetic energy	Sub-microscopic
19; 38-46	is it something impeding the movement of electrons/ It causes them to lose energy /And therefore the current stays down because they can't move as fast through it	Sub-microscopic
20; 43-46	So maybe just write on there to make it clear maybe R are you saying R causes p.d.? Yes OK can you tell me a bit me a bit about that? Because electrons only transfer energy they need to push through something which uses up their kinetic energy in some way	Sub-microscopic
20; 50	And potential difference can't cause resistance 'cos it the they're still potential for resistance even if you don't have any current going through it	Symbolic
20; 64-66	I think [pause] in combination with current and potential difference in some cases...might cause resistance	Symbolic
20; 82-84	I think [pause] EMF [pause] causes current because it's the initial that provides the energy...Oh [pause] I think if more [indistinct] [pause] EMF to some extent causes the potential in the sense that if you vary the EMF you will change the potential difference	Symbolic
20; 91-92	So does changing potential difference alter the EMF? Um [pause] across an entire a circuit yes if you were just going to change on component it would therefore just change the potential difference of another	Macroscopic
20; 164	There's a gap in the circuit allowing the electrons to move	Macroscopic
20; 164	so the new battery provides kinetic energy and then the electrons travel though the path and then they can breach the gap and so they carry on going and then they transfer energy until the energy turns into heat os the current well should temporarily decreases but by a tiny amount and then	Sub-microscopic
20; 165-166	Why does the current decrease? Because I think because they transfer some energy to the bulb they should be moving slower	Sub-microscopic
20; 178	There's a chemical reaction going on I think with lithium and acid and that provides some chemical which the electrons receive but then they have to use some energy to get past all the reactions and molecules and so when they exit the terminal is greater than zero but small enough general to discard	Sub-microscopic
20; 198-200	And then I remembered that the electrons are just going to go well hopefully they're just going to go in one direction ...And so they're going to transfer all of their energy	Sub-microscopic
21; 332-	OK what causes this to exist when do we get a current?	Symbolic

333	Um when a [pause] potential [pause] applied across a point	
21; 335	Um oh when sorry electrons um [pause] I suppose it would well occasionally that doesn't always happen electrons move through material [pause] plus transfer energy [pause] and then in processing of moving they have to transfer energy	Sub-microscopic
21; 336	Um so [writing] It think the best word is blockage so um ions	Sub-microscopic
21; 391-395	Um [pause] wait yes and let if you got the upwards thing resistance I think most of these yes providing the other two remain the same / with potential difference if you have the same sources the same EMF well if you have the same EMF then yes definitely / And through a particular component it would depend on the total resistance across the whole circuit	Symbolic
21; 557	and so they're going to effectively move slower and because they're moving slower the current would decrease meaning the resistance across the component would I mean the potential difference across the component would decrease	Symbolic

8.8.1.2 Codes related to causality in Charlie's transcripts

Session; utterance	Utterance	Code
6; 38	Er potential difference links to current because that gives the amount of I dunno if power is the right word but power for the current the amount of voltage for the current to go round	Symbolic
6; 42	current would link to resistance because resistance would be acting against the current er to slow it down um	Symbolic
6; 42	er potential difference would be linked to resistance erm because [pause] potential difference has got to be more than the resistance for there to be a current so it'd class as a link	Symbolic
6;44	Er then there wouldn't be a current because the resistance would just stop it	Symbolic
6; 54	Erm charge goes through the light and then friction cause friction and then that'd I'm not sure 'cos I think it would convert as well but that answer just doesn't seem	Macroscopic
6; 62	[pause] because [pause] it's um it's a series circuit and so every point would be er equal current	Macroscopic
6; 82	Um because the some of the current is pushed er in the parallel so that's where A is but if it's it's not more current would be pushed er into series so then B would increase	Macroscopic
6; 84-86	Yeah the voltage would there'd be more voltage to go to it so / So it would be lighter	Symbolic
6; 94	'Cos it's in series and tht's parallel [indicating 1 and 2] so more er coulombs would go through the shorter route	Macroscopic
7; 101-104	The current will decrease?/Yeah/Um why?/Because it's more heavy so the voltage going stays the same so that so like a resistor I think	Macroscopic
7; 126-128	Um [pause- sound of motor] is it 'cos more is needed to lift er the weights / So it's going to be more	Macroscopic
7; 130	Er because this [indicating masses] is against the current more current is going to have to be needed so it can pull up the weights	Macroscopic
7; 142	Er [pause] because er [pause] more volts is gonna er be needed to [pause] put the um go into the current er to lift the weights	Macroscopic
8; 90-92	And one would be dimmer erm two would be dimmer three would be brighter/ Um because current splits so one current splits at switch A	Macroscopic
8; 125-127	Oh why there why do you think that will be zero? / 'Cos there's more it's a bigger er resistance than the voltage going in	Symbolic

9; 90-92	Um because the current would decrease as time goes on 'cos of the gap/Why would the gap cause the current to decrease?/Because all the electrons would er would slow down and some of the electrons wouldn't go though the circuit	Sub-microscopic
9; 95-98	Would get to zero? Would it/ Only if [indistinct]/ Sorry?/ Only if the battery ran out but it wouldn't do that in the time	Macroscopic
9; 103-104	Ok um what what would let the current keep flowing? / Um [pause] the battery	Macroscopic
9; 116	Um [pause] because the current would go down so the p.d. would also then increase and then level off because the current would as well	Symbolic
9; 118	Er how much goes through the circuit so the amount of p.d. depends on the er circuit going round the amount of er voltage going round er the circuit	Symbolic
9; 124	Because [Teacher asks questions] there would be more resistance acting against the current so the current would slow down and then it would slow down so it would [Teacher asks questions]	Symbolic
10; 32	Because the cell produces the voltage and the voltage is the same as p.d. um [pause] er current and cells 'cos a cell um [pause] produces the power power for current	Macroscopic
10; 38-40	Er [pause] current and er parallel and series / Because a current can go to parts of erm[pause] a circuit whether its parallel or series um the electron charge [pause] um [pause] can link to current er because of the [pause] I can't remember what equation it was N A	Macroscopic
17; 96	Because it's a series circuit and it's the only bulb and with circuit one there's a parallel so the current splits	Macroscopic
17; 121-124	Why why does most go through three and four/ Because it is the shortest/ Yep / Um distance from Y from the bulb	Macroscopic
17; 162	Mmm can I pout like tri these three are all linked because in V equals I R the equation er changing one of these would have an effect on the others as well so they would all link	Symbolic
18; 30	[Of resistance] Um it er [pause] it lowers the amount of current around a circuit	Symbolic
18; 36-38	[Of resistance] Or [pause] like slow it down how fast it is/ How fast the energy?/ Er is used	Symbolic
18; 194	So then at the start there's high repulsion so it would be a quick current	Sub-microscopic
19; 17-24	Good the next row is what causes there to be a current? / Um [pause]/ Why do currents flow what makes them flow?/ Er because charged particles er travel in a general direction/ What makes the charged particles move?/ Um er their repulsion/ Yeah what what repels them?/ Er everything that has er the same charge / Yeah/ So they repel each other as well	Sub-microscopic
19; 29-32	So if we had to think about in a battery why does charge flow out of one end why are electrons given off from one end of the battery?/ Because er they've got different charges on both sides of the battery/ Yeah/ So the negative would go come out of the positive	Sub-microscopic
19; 35-50	To the positive yeah nest why do we get potential differences in a circuit what causes there to be a potential difference?/ Erm can I say if it's parallel/ Yeah /That's used [writing]/ Could you give me an example of how [pause] that works?/ Erm so [coughs] if there was [coughs] in [pause] er series you measure it from before a bulb and after a bulb /Yeah /Er some of the charge is used for the bulb /Yeah /So then they'll be less voltage voltage read / Yep / So then they'd be a er potential difference Across Between between the two points / Yeah/ and Across the battery	Macroscopic
19; 56-58	Erm [pause] done this the other day er it's they split the amount /Right/ I think the closest loop gets more	Macroscopic

19; 63-68	No no I've got that on from the conversation great and lastly what causes resistance? What causes things to have resistance? / Er the temperature of a wire /Yep/ And internal resistance and er we calculate from a $V=IR$ / Yeah /Sometimes	Macroscopic
20; 37-54	Um resistance is a cause of potential difference / Give me an example/ Um so there's a cell / Yeah/ With six volts and um [pause] in a there's a component with er three ohms maybe /Yes/ Three ohms? Say ten then ohms er if you [pause] I just making things up on the spot erm / So you're saying would that resistance or / The um [pause] if there was more resistance in a current then there'd be a bigger p.d./ Mmmm /Er because voltage would be lowered by the resistance /So voltage would be lowered by the resistance? /No it won't [pause] it would it would lower the current /Yeah/ Of the voltage getting to that part of the circuit Yes /So then there would be a bigger potential difference and lower if there's lower resistance/ So less current would give more potential difference at that point? /Yeah	Symbolic
20; 56-62	[pause] resistance would cause current /How does resistance / Or not qu like cause a certain current like not the actual current but like like effective / So you're saying if I have a hundred ohms I get current x if I double it I halve the current kind of idea? / Yeah that kind of thing / So the amount of resistance affects the amount current in a circuit / Yeah	Symbolic
20; 80	And say if there's a um [pause] increase of resistance you could say using V equals $I R$ there is a decrease in current	Symbolic
20; 128	Oh OK could you say the EMF causes the p.d. because that's got to be the same	Symbolic
20; 158-160	And then because there's that when you touch it Yeah It allows the coulombs to go across the switch	Macroscopic
20; 216-217	What makes them move? / 'Cos they're negatively charged and they come yeah so they have repulsion between each other and they have a general direction where they flow	Sub-microscopic
21; 8	Er these three [current, voltage, resistance] because they're in the same V equals $I R$	Symbolic
21; 104-106	Erm [pause] to [pause] current er there's nothing like resistors to change / But there's nothing really to [pause] erm the voltage stays the same er and that's a constant resistance so they'll be no change in the amps	Symbolic
21; 118-120	Er because a bulb charge is carried through the bulb so it doesn't affect the current / And with resistance it would slow down the current	Macroscopic
21; 124-126	Because resistors are made to slow down or act against / Yeah/ A current	Macroscopic
21; 182-183	Er because the [pause] the current has to split and three and four is closest to the cell so that would have more than one and two / Yeah How does distance affect it? /Er current wants to go shortest route	Macroscopic
21; 227-235	Can I say it's like a force? /Yeah / [pause writing] /So that says force like acts against current / it's /in the circuit/ It's force like / But not a real force? /No So acts like a force	Sub-microscopic
21; 246-251	Ok um when do I get current what causes a current to flow?/ [pause] when there's charge in a circuit /Yep/ So [pause to write]/ Would it automatically flow if there's charge?/ Er yeah if it's all closed	Sub-microscopic
21; 256-259	And [pause] what causes objects to have resistance /Would that be like heat? / Is heat the only thing?/ No er [pause] heat be [pause] I can't think what else would go for resistance [pause] erm	Macroscopic

8.8.1.3 Codes related to causality in Daniel's transcripts

Session; utterance	Utterance	Code
6; 30	Resistance is urgh resistance is something that resists the current basically so like something that's in a way slowing down the current for some reason in a way	Symbolic
6; 44-46	It would have a certain amount of volts is that how much the cur not the current 'cos there's 'cos what miss was showing us is that if in a circuit there's like six volts from the from the er battery/ Means that six joules is going through I think it's joules I can't remember I think it's six joules is going through the circuit	Symbolic
6; 54-60	OK um resistance links to current because um resistance resists the current and the current is trying to get through the resist so if there's a resistor the current is trying to get through it so that that links together then er charge links to current as well because current is the rate of flow of charge/ And the um charge no [pause] er resistance links to potential difference similar to how what I was saying before I don't know how to word it exactly so it's like if there's two resistors in a circuit um the resistance [pause] does it halve the potential difference?/ So that links together there. Current hmmm [pause] I'm not quite sure how the rest link to potential difference/ Er [pause] yeah charge and resistance in a way because er the resistance is trying to resist the current and the current is the rate of flow of charge so resistance in effect is trying to resist charge as well	Symbolic
6; 104	er would it increase because it doesn't have to share it with bulb A	Macroscopic
6; 112-114	In circuit two because its on its own/ And I think in circuit one bulb A's going to be brighter than bulb B because it's in parallel so does that mean that er more goes more voltage or current goes through A than it does in B	Macroscopic
6; 122	Because it's on its own but its either these two [A,B] will either be the same or one will be brighter than the other	Macroscopic
6; 132	Is it because if the [pause] it's coming through this was [from negative terminal] would it have already gone through here [A,B] and used up by the two bulbs	Macroscopic
6; 138-140	Is it because its already gone through A and there's nothing lie blocking nothing like resisting the current through A/ Until it gets until it comes back out of A and the resistances resisting against the current that wants to get to B	Macroscopic
7; 6-10	If you increase the resistance [pause] does the current go up?/ Why would/ I am just thinking because if it's R equals V over I / Yep/ To get I you have to times R by V so and it'll give you a bigger number than it would	Symbolic
7; 18	Um would it be like the amount going in is used up by the resistor then there's nothing coming out till it goes back to the cell and picks up more	Macroscopic
7; 50	Um there's more like the resistor is resisting the the er current that's going through so not all of it is going to go through as easy as it would ifn the resistance was lower	Macroscopic
7; 116	Um basically it [pause] I worked out that you can just find the ratio of it and then all you do is divide it by what goes how many times they all go into each other basically goes into each other three times so you just divide ten by three	Symbolic
7; 132	Mmmm [pause] is it 'cos it has more [pause] 'cos it's like using more power to lift it up so there's more like [pasue] there's just more current because then if the current was the same it wouldn't be able to lift it up as it would last time so it needs more power basically I think	Symbolic
8; 2-4	Um potential difference is measured in volts/ Um is it the driving	Symbolic

	force behind the current	
8; 16-20	Is it because it's [the bird] like stopping the current from going through and has to go through it and then by the time it gets to here [bird on wire] there's no current because it's all in/ Stopping it from going to the bulb so the current has to go through this bird first then as it by the time it's gone through there's no more current left	Macroscopic
8; 38	'Cos the circuit if it's like closed here [switch A] then it's got um a way to go through here [switch A] and as it's coming up there's one here [junction between 2 and 3] I'm not sure whether it will split but because this is not open [Switch B] this [bulb 3] wouldn't turn on	Macroscopic
9; 34	Is it because not as much er of the current is going through because the resistance inside the battery is a lot already and then by the time it gets to er the resistor there's not nine volts of like potential difference there basically I don't know how to explain it but	Macroscopic
9; 62-64	Would it start off like high and then once it reaches the plate would it go lower because it's not going directly through it has to like go electrons have to transfer from one plate to another / Then into the circuit	Sub-microscopic
9; 70-76	Is it because it's just flowing freely until it gets to that point [positive side of capacitor]/ And then it's like slowing down because it the it's starting to charge the metal plate I think it would just I think it would just move slower than/ Than it would normally/ Mm I'm not sure would the is the metal plate acting sort of like a resistor	Sub-microscopic
9; 82	Mmm um is it because [pause] when it when the electrons touch the metal plate is it like 'cos it's building up and erm so the current that would go is getting lower 'cos there's already charge on the metal plate and over time the is it like the plate has too m like in a limit of charge kind of thing and that's when it starts to plateau out	Sub-microscopic
9; 100- 102	Er I think it's like similar to the the current one but 'cos um the circuit not like connected it's like being blocked by the metal sheet so the the voltage that it could produce isn't being produced as much because of the metal sheets in the way I think/ I think it could like [pause] I don't know how to explain it's like protect it could have let the voltage go across it	Symbolic
9; 118-124	Because because there's like only so much it can have and it's starting from zero the more the more that build up on it / The more electrons that build up on it it's like they over time the there's too much on the sheet so it starts to plateau out but 'cos it's starting from zero the potential difference is going up but it won't reach it's full potential difference and then it starts to plateau basically/ Like 'cos there's sort of like a limit that it could have on the sheet/ Mmmm not sure is it might is just be like the size of the sheet	Sub-microscopic
9; 132	Is it because um potential difference is the is the voltage across two across a component so and if there's only one component then it's the potential difference across them is the same as the potential difference being given from the battery so basically it plateaus at ten because that's just the highest amount of potential difference that can go through the circuit	Symbolic
9; 174	So then like the whole potential difference the potential energy is ten so when you put when you allow the current to go through the current will start as high as it can and then it will start to drop because there's loads of electrons on the sheet already and then the potential difference eventually goes to um [pause] ten on the sheet and ten on the battery which makes it zero	Sub-microscopic
10; 38-42	there's always going to be some sort of like resistance inside the	Symbolic

	bulb so you don't get the the full potential um potential difference um resistance links to no current links to potential difference and both of them link to resistance because to find the resistance you have to do current divided by you have to do current [pause] you have to do voltage over current to get resistance / So that links together there um [pause] potential difference links to potential divider because the potential difference across one component is different from the potential difference across two/Depending on what current is going through everything so current will link to that as well erm [pause] does resistance link to potential divider as well because because there's resisatnce in in the erm in the component does that mean that the potential [pause] it's not it's not like it's maximum potential I don't know the word like pot I dunno It's not it's not at it's maximum	
10; 54	Erm current is what pushes potential difference no isn't potential difference that pushes the current round the circuit	Symbolic
10; 74	like potential difference pushes the current through so that potential difference could be like say if it's a hose connected to it how open how much the tap is open by could be like the potential difference but I don't know what you would call that for water	Symbolic
17; 146-148	I'm just thinking 'os if like they're in a um they're in that's that's one circuit [loop with bulb A and cell in]/ Then this is like extra added on [loop with B in]	Macroscopic
17; 164-168	Yeah um [pause] I think the answer is B erm not a hundred per cent sure why but I just remember us talking about it and how it's like when they're when the circuit's complete like the energy's just quickly it's it's like charge's already there/ But like when you when you close the circuit you're allowing the charge to go through / Straight away so it's like almost instantaneous	Sub-microscopic
17; 182-186	Because the potential difference is er depen muh the voltage that goes through the whole circuit / So if um at one say if it was like nine volts at one it's nine/ And after it'd be nothing init	Symbolic
17; 209-211	'Cos basially um the resistance is higher here then 'os R equals V over I then if you was to rearrange that to I to V times R equals I there less current going through wiat if the resistance is higher/ Then the current is less in B yeah	Symbolic
17; 221-225	Then B would be a bit dimmer / 'Cos there's more that has to split the current in two/ But A's not affected? /Yeah yeah because it's in one circuit	Macroscopic
17; 239-241	So it links to amps um current is the rate of flow of charge / So it links to charge um [pause] resistance links to potential difference and current because to find the resistance you do potential difference over current	Symbolic
17; 249-253	Erm [pause] internal resistance [pause] [indistinct] er chemical energy [pause] is it chemical energy that causes internal resistance/Chemical energy inside the a battery/ Er causes the voltage not to be as high a it would be if there was no internal resistance	Symbolic
17; 259-261	Oh OK [pause] so chemical energy turn is converted into electrical energy/ Which causes internal resistance so they'll link um ohms um resistance is measured in ohms	Symbolic
18; 36	[Of resistance] It resists current [pause writing] um [pause] does it affect the p.d. across circuits	Symbolic

18; 277	<p>Capacitor discharge</p> <p>complete circuit = build up of electrons on plates ↙</p> <p>↓</p> <p>once the circuit is broken electrons begin to repel rapidly ↗</p> <p>↓</p> <p>over time are less electrons are around to repel</p> <p>↓</p> <p>causing the current to decrease.</p>	Sub-microscopic
18; 304-306	But then over time that current drops off erm/ Is it to do with the resistance?	Symbolic
19; 17-18	Next one what causes it what makes a current flow? When do I get a current?/ Um in a complete circuit	Macroscopic
19; 25-26	Yeah and a complete circuit good ok when do I get potential differences?/Depending on the amount of components there are in a circuit um depends on how the potential is shared basically	Macroscopic
19; 31-32	Why do some components have more potential difference and some have less potential difference?/ Um [pause] is it because the [pause] the charge's not fully it's not being able to like flow like perfectly	Sub-microscopic
19; 37-40	And lastly why do things have resistance?/Um [pause] is it because the [pause] the charge's not fully it's not being able to like flow like perfectly/That's true yeah but do you know what might cause that? [pause] in a bit of wire or in a resistor?[pause] what's physically going on?/Is it getting hotter	Sub-microscopic
20; 24	Um [pause] is resistance caused by a current in a way like it's not caused by the current it's caused by what's inside the component the current's trying to go through so	Macroscopic
20; 30	No actually resistance causes current because different resistances mean different currents	Symbolic
20; 121-122	Um why do the electrons move?/ Um is it because of potential difference is pushing them	Symbolic
20; 126	Um because heat energy is like heat energy um which causes the filament inside to light up 'cos it glows and it's hot	Macroscopic
20; 128	Um [pause] is it like when the electrons are is that to do with friction in a way like [pause] how to explain it um [pause] when the current is going through	Sub-microscopic
20; 144	They have more coming in 'cos the voltage is there pushing them through	Symbolic
21; 18-22	Um Ohm's law and Ohm's connects to [pause] both resistance Ohm's because Ohm's law is that [pause] the v I think is the voltage across a component is proportional to the current if the temperature is constant/ Um voltage links to both resistance and	Symbolic

	current because in the in the erm the equation / V equals I R you like to find the voltage you do resistance times current/	
21; 24	Um resistance and currents links together because resistance can make the current smaller or bigger because going through it it's being used up in the thing erm Kirchhoff's first law Kirchhoff's first law links to current and his second links to voltage	Symbolic
21; 69-72	So it's is the charge turned into light or?/ Um [pause] well not directly it has to like when it's moving and it's causing friction / Yeah/ Which then causes heat and the he the filament in the bulb gets hotter gonna start to glow	Macroscopic
21; 102	Because Kirchhoff's second law says that the sum of the EMF or sum of the p.d. and EMF in one in a loop is the same going in and out and A is in one loop and so is C	Symbolic
21; 126	Um Kirchhoff's second law again is that the sum of the p,d, or the EMF in a loop is the same as in an and out	Symbolic
21; 172-174	Because when the current is going through coming from the positive side it's going into the first component which is A so that has a bright like a certain brightness and then 'cos the resistor is in-between it means it resisting some of the current that's like it's not allowing the full current to go through/ So that B doesn't have as much um current as A has so it'd be dimmer	Macroscopic
21; 217-219	So and there's two components as well so [pause] I think I might be getting this wrong but the potential difference across is like it's only it's not shared between two/ Like so it's I think that's the only explanation I can give is that A is on it's own it's not being shared with anything so it's more likely to be brighter than the other two	Macroscopic
21; 274-277	Ok then what makes a current flow?/Erm [pause] /Why do we get a current at all?/ Is it when a circuit's complete	Macroscopic
21; 280-281	Actually is that the only thing we need?/ Need a battery as well	Macroscopic
21; 288-289	When do we get potential differences?/ Across a component	Macroscopic
21; 292-295	And lastly what causes there to be resistance?/ Um [pause] could it be anything from like heat in a circuit / Mmm/ Something that will use up [pause] the I just I don't know how to something that will use up the current	Macroscopic
21; 353-355	Um if you increase the resistance then the current going gets lower/ Erm and if you was to decrease it would get bigger	Symbolic

8.8.1.4 Codes related to causality in Edward's transcripts

Session; utterance	Utterance	Code
6; 22	Er well charge is basically measured in coulombs and that is a collection of electrons and these electrons try to get through the particles but is it the particles in the solids or the ions / If there's more resistance then there's more collisions um so the current doesn't get through as easier er that's basically resistance in a nutshell	Sub-microscopic
6; 30	Erm well less energy is transferred with a lower is it a lower current er 'cos of a higher resistance/If there's a higher resistance the current's less therefore potential difference or energy transferred is less	Symbolic
6; 40	Because the potential is difference is the main factor in producing light but potential difference is the transfer of energy	Symbolic
6; 72	That's sort of joined to the positive side and I think electrons are produced they have a negative charge so they're produced from	Sub-microscopic

	the negative side	
6; 114	the resistance must be the same between the two points because they've both only got one bulb at the same time	Macroscopic
6; 116	Current sort of usually splits depending on the resistance but if the resistance is the same then the current would split about half and half between the two links if er you were to take out bulb A [pause] I mean do you mean the entire wire?	Symbolic
6; 124	And if there is a higher current er potential difference is calculated by current times resistance so double current would just increase it the overall potential difference	Symbolic
6; 126	I would say the points all match each other 'cos the charge going in is the same as the charge coming out um	Sub-microscopic
6; 130	it is more at C I think if A's sort of A's measures a collection of the whole current as it's gone round the whole circuit and there's junctions after A	Macroscopic
6; 134	C would also only get all of the electrical energy seeing as it's in series and it doesn't really split at all so and [pause] the same charge is being produced by the battery	Macroscopic
6; 140	What happens to the brightness of bulbs A and B [pause] mmmm [pause] B probably becomes dimmer 'cos the switch closes that completes the circuit for where C is so any current so before the current wouldn't have would probably have not have split 'cos the circuit doesn't split there	Macroscopic
6; 160	Mmm I would have said it stays the [pause] er I'd say C stays the same the electrical energy reaches the bulb before like the wire connecting one and two anyway	Macroscopic
7; 80	Now that there's more weight acting down er em probably give more gravitational potential energy so the current probably go up	Macroscopic
7; 102	Erm I reckon voltage will probably go up because the formula current time resistance if there's more current then there should be more voltage overall	Symbolic
8; 22	Um [pause] I think perhaps the one with just its feet on the wire normally not like either side because it's like in series with the rest of the thing but with the one with the feet either side maybe the mmm the bulb's resistance might reduce the shock on the bird	Macroscopic
8; 36	Kirchhoff's law says that a volt the input voltage should be the same as the output voltage or something like that	Symbolic
8; 68	well voltage is like a measure of current and resistance er because current only really flows in one direction er one a circuit so joining them two the current wouldn't flow between er er [pause]	Symbolic
8; 118	Mmmm doesn't it act sort of like a as a parallel junction and split the voltage evenly between the two things	Macroscopic
8; 140	Er unless [pause] unless that parallel junction [wire joining between 2 and 3] took some of it because of the bulb has resistance	Macroscopic
8; 150	Would it be eight volt? I don't know actually [pause] potential difference at B would be four volts because of the two bulbs there would have a potential difference of eight volts and then er would it have an overall potential difference of four volts?	Symbolic
8; 176	Well the current should still be able to reach the bulbs with the switches being open because it would just create an in series circuit	Macroscopic
8; 207	Well if the current goes round in the circuit properly then potential at bulb one would be four volts so the potential difference at bulb one would be four volts because twelve before and eight after but when reaching switch B the point before two bulb two and the point after point three would both have a potential difference of eight due to that being used due to the potential at bulb one being four volts so [indistinct] potential difference	Symbolic

9; 88	Mmmmm [pause] I [pause] you were saying ti was an insulator it means it can't conduct electricity so it might work at first but then it wouldn't go past the two metal plates 'cos electronic charge can't be con... er transferred from one side to the other	Macroscopic
9; 104	But as soon as it has conducted it there'd be an increase in current cos current's the rate of flow of charge and if there's like more [indistinct] for charge [??] um repelling like the other negative charge then it would make the current flow faster [initially line with increasing gradient drawn]	Symbolic
9; 120	Er does it make it harder for the um it's already got negative charge on it so it makes it harder for the other electrons to get on to get conducted	Sub-microscopic
9; 148	Er the current increases erm but its only on one side and er it's it's like the same theory as the current really potential difference is basically measuring the difference between cells in voltage or potential and um like current times resistance equals er voltage so if there's more current there's more voltage basically	Symbolic
9; 174	Maybe it's not increased resistance I don't know what it is	Symbolic
9; 186	There are more electrons already on the plate	Sub-microscopic
9; 221	Um because the despite the increased resistance the plate can only still conduct a certain amount of electrons	Sub-microscopic
9; 237	[pause] Er probably ten volts because if the potential difference between one and two i.e. the resistor A is six volts that means basically lost six volts between one and two leaves you with four volts and if B C and D all have er are the same then the potential difference after them should be zero and between one and six at one it was ten volts but six it would be zero volts	Symbolic
9; 243	Same thought of theory really it's just it's like lost six volts at A and then it will would lose another six volts at D when it would bring it down to below zero but the lowest it can be is zero volts	Symbolic
9; 247	Erm 'cos between one and two it lost six volts so at two it starts off with four volts and then um B C and D would take away the rest of the voltage	Symbolic
9; 253	Because um sort of the it's connected in parallel with each other the two branches and to the voltage would be four and then it splits at the junctions actually [pause] trying to think of what a third of four is now	Macroscopic
9; 259	Er because there'd be the same potential at both four and five and there's no resistance in between	Symbolic
9; 267	Erm because at two they'd be four volts and then it splits between the two junctions so that erm the junction where three is would have like er [pause] a third actually it could be one and a third I'm not sure	Macroscopic
10; 132	Because um the voltage would be the same at both points because it's split evenly at point A between them into five volts and five volts	Macroscopic
10; 134	well they'd be a change in the strength of the voltage this time 'cos R one and R three are different resistance	Symbolic
17; 138	Because of Kir one of Kirchhoff Law I can't remember which one	Symbolic
17; 150	The current has to split at the junctions and it's shared between the bulbs A and B	Macroscopic
17; 188	Right hand side it still splits at the junction at the same thing erm like splitness if that makes sense	Macroscopic
17; 207	Mmm er because voltage is current times resistance and increased resistance would increases er voltage	Symbolic
17; 213	Er 'cos the current entering a junction is the same as the current leaving it because of Kirchhoff's law and um it would still to be it would have to be split e evenly if the switch closes	Symbolic

17; 241	that could link in with the equation R equals ρ resistivity times length over cross-sectional area	Symbolic
18; 102	Er there's no other passage way for the current to flow	Macroscopic
18; 110	Um as there's less resistance for the current will flow that way	Symbolic
18; 120	Er the current will flow through the switch B	Macroscopic
18; 186	Er 'cos they're all negatively charged so they're all repelling each other	Sub-microscopic
18; 190	[pause to write] [All electrons are negatively charged and repel each other, the more electrons the faster the rate of flow of charge (current) with less electrons there's less to repel each other so the rate of flow of charge is higher and	Sub-microscopic
18; 190	as $p.d. = IR$, a lower current means a lower p.d.	Symbolic
19; 10	Increases slash decrease in current/Or a change in resistance	Symbolic
19; 24	Erm let's see [pause] length of the wire / or cross sectional area or resistivity	Macroscopic
19; 28	Isn't it vibrating particles colliding with the electrons or something	Sub-microscopic
19; 90	Well when the current er the electrons in the current collide with the lattice ions /Erm again both things are sort of cause a [indistinct] converted into heat and light energy	Sub-microscopic
20; 36	Them two sort of cause potential difference	Symbolic
20; 96	Er [pause] energy in the battery is stored as chemical potential/ And as energy and when it's converted into electrical and heat energy / And electricity is the useful one in this case	Symbolic
20; 104	The charge carriers erm [pause] when they collide with the ions /That's what causes the bulb to light up	Sub-microscopic
20; 116	But as soon as you make the link the electrons can flow through the circuit/ Er they all repel each other	Sub-microscopic
20; 124	Er [pause] sort of releases the energy as it collides with the ions in	Sub-microscopic
21; 8	Obviously linked by like Ohm's law equation	Symbolic
21; 18	Erm you can use the V equals $I R$ current but just exchange voltage for potential difference	Symbolic
21; 102	Kirchhoff's first law	Symbolic
21; 108-110	Yeah it's difficult to explain that with C erm obviously there is just one bulb so there's only one direction for the current to flow/ Erm but with circuit the current would sort of be split at the first junction	Macroscopic
21; 142	The p.d. across a closed loop is equal to the EMF so that total P.d. across the two bulbs is always going to be the same	Symbolic
21; 142	but erm when the current is split at the junction erm 'cos I am assuming the bulbs have equal resistance	Macroscopic
21; 144	And as V equals $I R$	Symbolic
21; 168	Erm the wire would be after where the current's just flowed anyway	Macroscopic
21; 182	Erm well V equals $I R$ and as the resistance increases the current decreases	Symbolic
21; 194-196	I know A stays the same because it's still have the same current flowing through to/ Erm the current split at the junction	Macroscopic
21; 211	Um [pause] negative [pause]	Sub-microscopic
21; 219	Er V equals $I R$ or in this case p.d.	Symbolic
21; 223	Erm the ions make up its structure	Sub-microscopic
21; 255	Erm when the electrons flow in the er current collide with the ions um [pause] it's energy is transferred into heat and light	Sub-microscopic
21; 269	Um [pause] it's used up to um produce heat and light in the lamps	Macroscopic
21; 273	Erm when the electrons collide with the ions	Sub-microscopic
21; 285	Collisions with the ions sort of constantly	Sub-microscopic

8.8.2 Codes related to concepts of force

8.8.2.1 Codes related to concepts of force in Ben's transcripts

Code 1= Force linked to acceleration

Code 0= Force linked to motion

Session	Code	Context	Excerpt
1.45	1	Dropped balls	I think it will probably be that the same for both balls because the gravitational force on each of the balls although it is different because of the masses they both accelerate by ten meters per second squared
1.49	1	Dropped balls	I think um I think it is obvious when you think about force as something that accelerates something instead of something that is just pushing on something
1.54	1	Balls rolled off table	I think probably the heavier one will land closer because although they accelerate by the same amount
1.54	0	Balls rolled off table	Therefore the force acting to the side of it will be less
1.57	1	Dropped stone	Um it will accelerate by 10 meters per second squared um however as it increases in its velocity the air resistance will increase and because the air resistance will increase eventually the air resistance will cancel out the gravitational force and so due to Newton's I think it's first law
1.90	0	Ball from plane	Because I think it would probably the force acting on it would be slightly sideways
1.96	0	Forces on lift	I think the force pulling the lift upwards will be greater than the force of gravity because if there was equal force then the lift would probably be stationary and if there was a force where the gravity was greater then the lift would move down. Therefore for the lift to move up the force pulling on it must be greater.
2.02	0	Car at constant velocity	There's going to be a lot of air resistance because of the high speed although there will be greater push from the engine pushing the car forward because its travelling in the forwards direction.
2.03	0	Car at constant velocity	The force from the engine is much greater.
2.06	0	Car at constant velocity	The friction increases and therefore the resultant force will gradually decrease so that the car will begin to de-accelerate because the friction is in that case bigger than the forwards push from the engine
2.34	1	Pendulum	The gravitational force causes it to accelerate
2.34	0	Pendulum	I am not sure what force would be acting would be acting to cause it to moving upwards
2.36	1	Pendulum	If there was a force it should be accelerating
2.45	1	Pendulum	Because the force of the weight is greater than the force of the tension so the resultant force is acting downwards so it must move downwards and accelerate
2.59	1	Pendulum	The force of tension in its horizontal component when its diagonal component is at its greatest so it will accelerate the most
2.60	1	Pendulum	And well when it drops 'cos there's a force acting on it its velocity will increase
2.60	0	Pendulum	When it has reached its centre then it would have a low velocity 'cos there's very little force of tension acting upon
2.60	1	Pendulum	The acceleration will decrease as gets um farther away from the swing because the force of the tension acting that way trying to pull it to the centre is greater so the resultant force would be less
2.64	1	Pendulum	The force causing to accelerate would be greater and so it will

			accelerate more and so its average velocity will be higher
2.85	1	Dropped balls	Because the mass increase but the force increases so the increases cancel out because you have to divide the force by the mass to get the acceleration
2.93	1	Pendulum	Is it because if as its shorter there's more tension acting on it and so it will move and so it will accelerate more
3.02	0	Astronaut in space	He will move at a constant velocity in whichever direction the thrust force's acting
3.05	0	Astronaut in space	Um he's not accelerating [pause] then that would be the zero end and there should be no change in velocity so the acceleration should be zero let's
3.07	1	Astronaut in space	He's continually accelerating
3.32	1	Mass on Spring	Firstly because you lower there'll be a high force of tension on the spring pulling it upwards. It will accelerate quickly upwards and as the tension decreases the force would decrease so it would it's acceleration will lessen so that we get to here and then
3.39	1	Mass on Spring	Resultant force will be less so the acceleration will um be the gradient of the acceleration will be less
3.42	1	Mass on Spring	So it's velocity will increase and accelerate and then here we would
3.47	0	Mass on Spring	Because the well it's stopped moving completely because the resultant force is zero Newtons.
3.80	1	Mass on Spring	Here it will be stationary at the top because um the tension because the it will de-accelerate as the tension is pulling it up and the gravity is pulling it down
4.44	1	Loop-the-loop	Is it because gravity is causing it to um de celebrate well accelerate towards the centre?
4.59	1	Loop-the-loop	At the top well it's moving it's got velocity when its de-accelerating the only force acting upon it is gravity um it will be moving always about forty-five degrees to gravity
4.70	1	Loop-the-loop	Zero Newtons so it wouldn't accelerate oh so [pause] is it the reaction force bigger
4.79	0	Lift	Because he has to at some point accelerated because he's not stationary but at the same time he's not accelerating any more and so they should be equal and so I am not sure whether the resultant force is greater or the same
4.79	1	Lift	Because he has to at some point accelerated because he's not stationary but at the same time he's not accelerating any more and so they should be equal and so I am not sure whether the resultant force is greater or the same
4.84	1	Lift	Then the resultant force is resultant the reaction force is definitely bigger this time and the weight is the same as previously
5.37	1	Concept map	Cos a resultant force always results in acceleration
5.38	1	Ball in bowl	So the force acting on it downwards decreases because the force is gravitational field strength times by sin theta I think for the acceleration and so as the angle becomes flatter it should the acceleration should be less
11.91	1	Ball thrown vertically	Yes Um here it will still left the hand there doesn't seem to be any I think I until it reaches the hand again
12.19	1	Causal Card sort	Or in conjunction with force acceleration
12.21	1	Causal Card sort	Um [pause] velocity [pause] um that's definitely an effect because it's caused by force or by a lack of force if it's constant velocity
12.42	1	Causal Card sort	And I think in similar way of thinking in line of force acceleration
12.90	1	Bag in	well I suppose if it's slowing down then the friction must be then be

		braking car	greater than the thrust
13.07	1	Discussion of concept	I think force is something that causes something to accelerate
13.60	1	Situation card sort	essentially de-accelerating this way and gravity is acting downwards
13.67	1	Jump from crouch	gravity would cause them to de-accelerate
13.77	1	Jump from crouch	Oh is it zero but she moves at constant velocity so for the gravity
13.98	1	Jump from crouch	A bigger reaction force so when the electron repulsion force is greater than her weight and she accelerates well then she temporarily accelerates upwards
14.15	1	Ontology Table	Um they cause acceleration
14.34	1	Ontology Table	I think something that will change its momentum
14.82	1	Student concept map	Force causes objects to move I would um I would there write I would add accelerates
15.10	1	Concept map	then I would link link force with acceleration
15.20	1	Concept map	But I would link velocity um no we don't no actually I wouldn't do that I was going to say I'd link velocity with force but I've linked acceleration with force and I think that's more accurate
15.31	1	Concept map	if we call something force that force wouldn't be able to make anything accelerate it wouldn't have any impact on the universe
15.40	1	Dropped balls	Because the increased causes an increase in the weight itself of the ball but both balls are being affected by the same gravitational field and therefore will fall with the same acceleration
15.44	1	Balls rolled off table	But the gravitational force is making them both accelerate by the same amount because force is equal to mass times acceleration
15.46	1	Dropped stone	Because I think if there because of the gravitational force it will accelerate and it's weight won't change because it has it's own mass
15.59	1	Swung ball	tension force acting on it there won't be any well except for gravity but there won't be any forces causing it to change its direction from left to right it will carry on
15.70	1	Ball in bowl	Um I'm trying because I'm trying to think how the friction cause its velocity to change 'cos I know it must be well or the resultant force and therefore how the direction the friction acting on it would cause it to change
15.90	1	Ball in bowl	And this means that the ball it would sort of supposedly accelerate but it would accelerate less and less and less
15.98	1	Pendulum	But as it moves nearer the top the tension on the string decreases and so it um the acceleration decrease
16.32	1	Concept map	And then link the forces to um the effect of forces so acceleration types of forces
16.71	1	Astronaut in space	Um and the accel [pause] eration time 'cos the force constant acceleration is constant
22.01	1	Concept map	Like so I'll put the ideas otherwise I'm going to be linking all forces to the same things sometimes so let acceleration
22.11	1	Concept map	Um so the weight causes acceleration
22.34	1	Dropped balls	And so essentially they're going to their accelerations should be the same

22.38	1	Dropped stone	And so what because the forces will then be equal it's not going to accelerate
22.44	1	Ball from plane	I know the response were [pause] Um well it'd have the same horizontal velocity [pause] but it's going to be accelerating downwards and so it be D
22.45	1	Forces on lift	Because it will have because it's going on at constant velocity there can't be a net force acting on it that is not zero
22.50	1	Astronaut in space	er that mean the level of acceleration should be constant
22.52	1	Ontology Table	Um [pause] I think moment change in momentum
22.88	1	Ball in bowl	It decelerates because then the reaction force
22.90	1	Ball in bowl	I think what's happening is there is a force acting on it but it's acting completely opposite to the direction of motion
22.92	1	Ball in bowl	Because um it the force just causes change in momentum and therefore providing it's change in momentum is not nothing

8.8.2.2 Codes related to concepts of force in Daniel's transcripts

Code 1= Force linked to acceleration

Code 0= Force linked to motion

Session	Code	Context	Excerpt
1.35	0	Dropped Balls	So if one ball is twice as heavy as the other it will make more sense for the heavy ball to go down faster because its more dense and it will probably move faster in the air
1.46	0	Balls off table	Because it's heavier when its coming down it will be coming down quicker
1.57	0	Stone	I think it will go at a constant speed like this until it hits the floor.
1.62	0	Collision	I think the large truck will have more force on it because its moving
1.67	0	Circular motion	Like there's more force coming from behind it
1.78	1	Projectile from plane	It is falling directly down like no matter where the aeroplane is going it is still going to go down
1.83	0	Lift	The force of gravity is getting bigger [pause] yeah I think the force is getting bigger as it goes up
1.90	0	Lift	That the gravity the force of gravity is getting bigger but in some ways I feel there is not really an upward force because it's getting wound up by a cable
2.04	0	Car at constant velocity	Then the then the force going forwards is higher than the force going backwards
2.28	1	Pendulum	It's going to go the right more at one point then when it decelerates starts to slow down the force acting behind it gets to an equal point then the force going backwards gets greater than the force going forwards making it go in the other direction.
2.91	0	Pendulum	Does it mean the gravitational pull will be much more so it will basically swing ten times quicker
3.03	0	Astronaut in space	If the forces acting on him is to the right he is just going to go to the right at would it be at a constant speed
3.69	1	Mass on spring	Gravity is greater than the force acting against it so that's when it comes down at the deceleration and it ends at this point here
3.77	0	Mass on spring	So that means that arr the thing is going to go in that direction

4.61	0	Loop the loop	The force of your foot like when after you kicked it
4.68	0	Loop the loop	Is it because the force [pause] the forward force is only being acted on against the force of gravity
5.50	1	Concept map	It's accelerating oh it's like something with a force acting on it to make it move
5.60	1	Concept map	Forces and acceleration because acceleration is something moving with a force
5.94	1	Ball in bowl	Um [pause] Is it acceleration accelerating most at this part [side of bowl] again because gravity is pulling it down?
11.08	1	Concept map	I mean the the force of a parachutist for example you that they're going they're accelerating downwards at nine point eight
11.44	1	Card sort	But um for me just because I always get it mixed up with acceleration yeah and um I always um velocity I always keep thinking there's a force acting on it velocity as well to make something go faster
11.60	0	Ball thrown vertically	And when you throw a tennis ball the gravity er gravitational energy er is trying to er equal with the would you say this is thrust upwards?
11.62	0	Ball on ramp	It's rolling down at a constant velocity I think because there's no like acc there's no force acting on it except from the downwards force
11.83	0	Ball thrown vertically	On the way up the force of thrust is like much bigger than the force of gravity
12.02	1	Card sort	Ok um a force and acceleration I think they're both because for something to accelerate you need a force acting on it
12.07	1	Card sort	Acceleration so it's both um [pause] um so I'd say acceleration is an effect of force
12.72	0	Bag in car	Move
12.79	0	Bag in car	Um there'd be a force that's [pause] there's a force on it after it hits the um the wall
13.06	0	Concept discussion	Is a force that acts on something else to like make it move or something like that
13.45	1	Leap from crouch	There's no force on her when she's going upward because she's already she's off the ground
14.05	1	Discussion of learning	Because the way I always thinking about it is if something's moving and in velocity and acceleration just automatically think it's moving and if something's moving then there has to be a force on it
14.19	0	Ontology Table	Ok um forces usually cause um movement
14.55	0	Concept map	Forces cause velocity
15.04	1	Concept map	acceleration for and force link together because for something to accelerate a force has to be acting on it
15.08	1	Concept map	gravity links to force because it's a force a down acting force um gravity can make things accelerate
15.18	1	Dropped Balls	The same Oh
15.22	0	Balls off table	The lighter ball hasn't got as big a mass as the other one so it has like more time to travel before it hits the ground
15.26	1	Stone	Yeah it just keeps at a constant speed because if it was accelerating it would have to have a force acting on it
15.28	0	Stone	Speed and then it starts to fall down at a constant speed until it hits the floor then it has no velocity
15.35	0	Collision	But then E because it's like depending on how quick if they're both going at the same speed than they have like the same the same like force acting on them
15.54	1	Ball in bowl	Um is it 'cos when it's coming down from the left hand side it's accelerating because the force of gravity's acting downwards on it

15.68	0	Mass on spring	So it's like yeah it does yeah it does 'cos the resultant force is upwards so then it would um follow the direction of the up upward force then
15.77	1	Pendulum	So that like makes it accelerate
15.97	1	Ball in bowl	The gravity gravitational force pulling it down which makes it um accelerate
16.26	1	Concept map	To create acceleration you need a force
16.42	1	Card sort	That um once a force stops acting on you you're not accelerating more
16.56	1	Astronaut in space	It's constant force does that mean that it's always accelerating
22.14	1	Concept map	Acceleration links to friction because if there's a high friction then acceleration won't be like maximum
22.27	0	Stone	Is that if there was a force acting on it for the whole time like a fixed force
22.41	0	Ball from aeroplane	Yeah so the resultant is like a diagonal
22.41	1	Lift	It says that it's moving at a constant speed so that means that there can't that the resultant force has to be zero
22.70	1	Astronaut in space	Because if the acceleration is constant it means that I won't go up or down
22.86	1	Pendulum	Zero
22.90	0	Mass on spring	It's moving fastest once you release it from the highest tension
22.96	0	Pendulum	Just when no like no force is acting on it