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Conceptual Change Through the Lens of Newtonian Mechanics

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Abstract. Throughout its long history, the conceptual change literature assumed that student 'misconceptions' in mechanics have been formed prior to instruction. As an attempt to shed light on conceptual change, this paper examines some of the trends in the literature and argues that misconceptions may be spontaneous rather than preformed, that schema theory may be the most appropriate theory to take into account this spontaneity, that misconceptions should also be viewed through the lens of the subject as a system of well-defined concepts and that any conceptual change model may have to be prescriptive and engage the student with a meta-discourse concerning the abstract nature of the subject.

1. Introduction

The conceptual change literature spans four decades.[1] It is the leading field of research in science education and its domain is extending to other subject areas such as mathematics (e.g. Vamvakoussi & Vosniadou 2002) and religious education (e.g. Pnevmatikos 2002). Crudely speaking, a conceptual change theory is one that describes the nature of alternative concepts ('misconceptions') and prescribes ways in which these concepts can change/modify/evaporate in the exposure to scientific concepts. However, despite the conceptual change literature's long history, the question 'what changes in the conceptual state of the student?' (or, rather, what is it that changes when we speak of conceptual change?) has yet to be satisfactorily answered and only recently have there been attempts to answer this question (Caravita 2001). According to Caravita (2001), alternative conceptions research has been descriptive and discrepancies still exist in assessing, describing and 'utilising' students' prior knowledge.

This paper is an attempt to go some way in answering this question with mechanics in particular. Throughout its history, conceptual change research has assumed students carry with them these alternative concepts that have been formed prior to instruction. This paper reviews some of the trends in the conceptual change literature and argues:

(1) 'Alternative concepts' may not be concepts and may not have existed prior to instruction, but arise spontaneously in response to considering a scientific concept within its scientific context for the first time. Schema theory may be the most appropriate theory to take into account the spontaneity of alternative 'concepts' because it is able to identify the perceived *dominant features* of motion that may trigger these concepts.
(2) Ultimately, we may have no choice but to look at intuitive concepts through the lens of the subject as a *system* of well-defined concepts. The intuitive schemata of force and motion does not account for all different types of motion but are instead dependent on the dominant features of motion. This contrasts with the Newtonian concept of force because the laws of motion can account for different types of motion (projectiles, circular motion, etc.) without having to change the definition of force with respect to each type.
(3) Any model of conceptual change may have to be prescriptive in the sense that misconceptions are analysed in the light of attempts to move the student towards a conceptual understanding of the Newtonian system. To be successful, any such move may require Halloun's (1998) 'middle-out' strategy of introducing force as the central unit of analysis from which all concepts of the system are discerned – as opposed to the gradual, piecemeal, instant-by-instant, episodic teaching approach. It is in this sense that conceptual change may be seen as a dramatic affair rather than 'Instant-by Instant'.
(4) Moving the student towards a conceptual understanding of the Newtonian system would involve the use of thought experiments. The 'issue' of conceptual change then becomes the issue as to how the student responds to this form of mediation.

2. What is Conceptual Change? From Spontaneous Reasoning to a System of Concepts

Research into conceptual change began with what may be described as the 'misconceptions literature' with mechanics in particular. The misconceptions [2] literature found that, cross-culturally and across the age range, including physics graduates, many students exhibit intuitive beliefs regarding force and motion that are at odds with the concept of force in Newtonian mechanics (e.g. Helm 1980; Peters 1982; Jagger 1985; Boeha 1990). For example, that a thrown ball must have a force pushing it in order to overcome gravity. It has often been stated that misconceptions are persistent, either in the sense of intransigence or in the sense that they are unaffected by ('traditional') instruction. For example, many instructed students who are able to correctly identify the forces acting on a thrown ball in a question that demands an algebraic response nevertheless apply the non-existent 'impetus' force to a vertically thrown ball (Perkins & Simmons 1988). Such students are said to have a dual perspective in mechanics (Gilbert et al. 1982; Berry & Graham 1991), that is, a quantitative understanding of force and motion appropriate to questions that demand a quantitative response, yet exhibit misconceptions when asked to account for force and motion *qualitatively*. An example of intransigence is the unwillingness of someone to change their mind in the light of anomalies with their argument.

What is a misconception: a misunderstanding, an alternative understanding, an alternative concept, a different point of view? With the possible exception of the first, they seem to suggest a 'theory like' way of looking at the world and a different way of reasoning. Since the seminal paper 'Pupils and Paradigms' (Driver & Easley 1978) it has been assumed by many researchers that pre-instructed children carry with them conceptual or alternative frameworks that are at odds with the scientific framework.[3] The most influential conceptual change theory is the original theory of Posner et al. (1982) and the extent of its influence can be found in psychology and education textbooks, such as Howard's (1987) excellent coverage in *Concepts and Schemata*. From a sample of 50 articles on conceptual change identified in four science education journals of the period 1980–2000, the most influential articles cited are Posner et al. (1982) at 72% and the revised theory of Strike and Posner (1992) at 22% (Soto-Lombana & Sanjose 2002). The original theory viewed conceptual change as a (Kuhnian) paradigmatic change from intuitive concepts to the scientific framework. According to the theory, change can occur by the creation of cognitive conflict through the presentation of anomalies. However, the question what changes in conceptual change has yet to be answered. Do individual concepts change, for example, from 'force implies motion' to 'force implies a change in motion' or the 'alternative framework'/'forms of reasoning' to which the individual concept is embedded? The alternative framework metaphor to describe intuitive ideas (in the sense of a paradigm) is very popular and some researchers argue that it would be more appropriate to speak of *conceptional* (mental structure) change rather than conceptual change (e.g. White 1994; Tynäjä et al. 2002).[4]

A 'conceptual change' seems to suggest a kind of theory change, but can we speak of misconceptions as theory like? It has often been presumed that 'misconceptions' are something that the pre-instructed student has formed prior to instruction and carries with her into the classroom (for example, McCloskey et al. 1980; Bliss & Ogborn 1994; Biemans et al. 2001; Mason 2001; Mildenhall & Williams 2001; Vosniadou et al. 2001; Duit 2002). With reference to the literature prior to 1992, Orton states that 'our experiences of force and motion throughout life lead us to draw conclusions which may be incorrect. *Intuitive beliefs extracted from our own experiences explain mechanics* for us in a way which we find acceptable and perhaps even helpful, but they may be wrong' (Orton 1992, p. 22, emphasis added). This does seem to suggest that misconceptions are fairly well formed, coherent (hence theory like) and acquired from the world of the preinstructed student. This suggestion is still very popular. For example, Biemans et al. (2001) define preconceptions 'as domain-specific conceptions constructed by students based upon their concrete everyday experiences or interactions with particular natural phenomena before formal instruction' (p. 266). Mildenhall and Williams (2001) attribute non-instructed students with such an intuitive model: 'to be that which has been developed informally through day to day experiences' (p. 645) and 'We found that most children start their Newtonian mechanics instruction with a well established intuitive Aristotelian model' (p. 653). The generality in the results may imply that intuitive models are 'well-established', but it does not imply that the pre-instructed child is walking around carrying a well-established model.[5] This does not undermine the results of the Mildenhall and Williams' study; the point is that the results may be an indication of what kind of misconception is prompted *or constructed* by what kind of question. This is perhaps the biggest assumption made throughout the history of the conceptual change literature: misconceptions are theory-like (paradigmatic) and formed prior to instruction.

Strike and Posner (1992) have radically revised their conceptual change theory and is quite a departure from their original theory:

> [I]t is very likely wrong to assume that misconceptions are always there in a developed or articulated form during science instruction. This conclusion may be wrong even in those cases where widespread misconceptions have been documented. Misconceptions may be weakly formed, need not be symbolically represented, *and may not even be formed prior to instruction....* (Strike & Posner 1992, p. 158, emphasis added).

They also argue that misconceptions may be the result of misplaced metaphors arising from the students' 'conceptual ecology'. So rather than bombard the hapless student with anomalies, they suggest that instruction ought to create the awareness of scientific concepts distinct from their everyday contexts. This idea of misleading metaphors and plural conceptual schemes has become very popular. For example, there has been a social constructivist/sociocultural trend that has regarded student conceptions as socially situated within the everyday and that the instructors job is not to challenge these conceptions but to enable the student to contextualise the concept with respect to its appropriate domain, whether scientific or everyday (e.g. Linder 1993; Driver et al. 1994; Kuiper 1994; Mortimer 1995; Leach & Scott 2003). However, the point is, whether a conceptual change model assumes that 'misconceptions' or intuitive beliefs arise out of the child's interaction with the physical world or, alternatively, as 'ways of speaking' within appropriate or inappropriate domains, nevertheless there seems to be a majority consensus that these conceptions are fairly well formed prior to instruction (and quite contrary to Strike and Posner's revised theory). However, if that is the case, then these ('theory like') conceptions ought to be consistent in student reasoning, but this is a very moot point.[6]

Strike and Posner's revisionist theory challenges the idea that 'prior conceptions' are 'theory like' in the Kuhnian sense. This implies that it is very unlikely pre-instructed students will bring into the classroom an intuitive but explicit 'framework' or alternative concept-map of force and motion. If misconceptions may not even be formed prior to instruction (Strike & Posner 1992) then the majority of students may have to think about a qualitative question concerning force and motion for the first time. In this sense, misconceptions may be seen more in terms of spontaneous reasoning rather than 'well established intuitive models' or misplaced everyday metaphors. Spontaneous reasoning may be defined as reasoning applied to an unfamiliar situation, is usually the 'first thing that comes to mind' and can be influenced by what stands out in the question. Viennot (1979) reported that even teachers and experts tend to make similar mistakes when answering in a hurry or when there is lack of time to reflect. In spontaneous reasoning, 'students are not usually conscious of the 'notion' they use and may call it, sometimes indifferently, 'force', 'impetus', 'energy', 'momentum', and so on' (Viennot 1985, p. 433). In spontaneous reasoning of an unfamiliar situation in mechanics, the first thing that springs to mind may be an original thought in the sense that the person thinking it may not have had the thought before. What any research instrument 'captures' and terms a 'misconception' (or 'alternative framework' etc.) may be such an original thought. Of course, a misconception may be prompted that is not an original thought, it may have been constructed in the attempt to understand a prior science lesson, or from the memory of having to push something. The point is, we cannot *assume* that a 'misconception' is formed prior to its revelation. It would be better to assume the converse: that misconceptions are spontaneous, they are evoked ('constructed') rather than revealed. Later we will argue that misconceptions that are spontaneous may also contain elements that have been formed prior to evocation, and that one of the aims of research ought to be to discern those elements (and not merely assume them).

The aim of conceptual change theory is to capture and model the *shifting* event (Caravita 2001) and one of the fundamental issues is what changes when conceptual change occurs (Tynjäjä et al. 2002). However, what changes in conceptual change may be interpreted in different ways according to what model defines the structure of intuitive concepts, such as, for example, Rumelhart's schemata, Johnson or Vosinadou's mental model, Carey's domain-specific theories or Chi's ontological categories (Mason 2001). After nearly four decades the question 'what changes?' has yet to be answered and the problem, according to Tynjäjä et al. (2002), is that the philosophical foundations of these models are seldom explained or explored. For example, the research has paid little attention to the variety of meanings given to the concept of 'concept' (Tynjäjä et al. 2002). According to Limón:

> The questions about stability, coherence and universality of misconceptions in the domain of science are still unanswered. Some theoretical models of conceptual change have tried to describe features of this prior knowledge, but there is a lack of precision, in our view, to clarify what we are talking about – ideas, beliefs, theories, misconceptions, preconceptions, mental models, students' misunderstandings or failures to learn something," (Limón 2001, p. 367)

Unfortunately there is no space to give a review that would do justice to the various models that have developed recently. Justice requires a book. Needless to say, however, that many of these models have not examined the logical structure of the system that is presumably the culmination of conceptual change (with notable exceptions such as Hestenes 1992, and Halloun 1998, for example). If misconceptions have spontaneity then they must have specificity to the scenario in mechanics that has prompted the misconception. That specificity ought to be examined through the lens of Newtonian mechanics. That lens is the understanding of the subject as a system of concepts and may enable us to put into perspective the nature of intuitive concepts and the nature of conceptual change.

What does it mean to have a conceptual understanding of force? Well, to *think* in concepts is to think of a concept within a system of concepts (Vygotsky 1987) and that would be a necessary condition for conceptual understanding. For example, a conceptual understanding of bird is the understanding of the concept embedded within a system of concepts such that robin is subordinate to bird, and animal is a superordinate concept to both bird and robin. However, a conceptual understanding of force would involve more than realising gravity, reaction, friction, etc. are superordinate to force or the ability to include various instances of force in the category of force – *it involves how real and ideal situations can be explained according to the laws of motion*. For example, that acceleration due to gravity is the same for all objects *in vacuo* because the greater the mass the greater the force of gravity required to give the same acceleration. A hallmark of conceptual understanding has to be the ability to explain an unfamiliar situation according to the laws of motion. Why the laws of motion? Because they are the defining axioms of force that gives mechanics its unified form (Wittgenstein 1974) within which *work*, *energy*, *power* and *pressure* are superordinate to force.

Vygotsky (1987) makes a distinction between thinking in concepts and thinking in 'complexes', the former is aided by concepts within a system of concepts whereas the latter is influenced by perceptual features. To throw light onto the nature of student conceptions of force and motion, Nikolaou and Watson (2004) raises Vygotsky's distinction and this may be very fruitful in understanding intuitive ideas: that 'misconceptions' may not be concepts at all, but complexes that do not admit to a hierarchical order and the meanings of which are contextualised with reference to what the student deems as the salient features. Nikolaou and Watson's study is an attempt to see how Vygotsky's theory of concept formation can apply to 'misconceptions' of force and motion and the fruitfulness of the study may well lie in showing how 'misconceptions' can be modelled, not as concepts, but as intuitive responses that have a spontaneity in their formation. How fruitful the distinction by Vygotsky remains to be seen. Will the distinction enable us to account for the intransigence of intuitive 'beliefs', for example?

How can we model conceptual change as a dynamic process, that is, as a change from spontaneous ideas to understanding the structure of the Newtonian system and the way the system can be brought to bear on the physical world? Conceptual change is part of the learning process and a model of conceptual change must include the learning situation including the method of teaching. However, the model must also 'capture' and put into context the formation of 'misconceptions' and how these misconceptions change in the light of instruction. Schema theory may the most appropriate theory to account for the formation of misconceptions in terms of spontaneous reasoning with respect to situations that demands a 'Newtonian response'.

Howard (1987) has provided an extensive introduction to schema theory and the following is a very brief description taken from his book. A schema may be defined as a cluster of related concepts that help us make sense of the world; for example, *face* is not only a concept (part of the human body) but is also a schema that helps us organise how the concepts of *eye*, *mouth*, *ear* and *nose* are arranged. A schema consists of a set of expectations about how parts of the world are organized. For example, if we walk into a dark room and see a pair of eyes then we would *instantiate* our *face* schema. A schema has *slots* or *variables* that are filled with concepts and are organised in a certain way. Most schemata are often hard to 'dislodge' as a consequence of their function as a filter: once we feel that the world is organised in a certain way then we are reluctant to abandon that view. Discrepant data is therefore either ignored or the data changes the schema in idiosyncratic ways. According to Rowlands et al. (1999), the student who is asked to account for motion in terms of force will slot 'force' into his or her schema instantiated to account for the motion: 'force' will be used to account for the motion in some way and the slotting in of 'force' will depend on the way the student conceives the motion (e.g. for a thrown ball, a force is 'required' to push the ball in order to overcome gravity; to maintain circular motion, there 'must' be a force that acts radially outwards). In other words, 'force' may be utilized by the student as a metaphor to describe motion and spontaneous reasoning in mechanics may be the instantiation of vague notions that are arranged, re-arranged or modified to account for a phenomenon for the first time. *If a schema of motion is instantiated with force as one of the slots, then the definition of the student's intuitive concept of force is dependent upon its relation to the other slots in the schema.* For example, if a student's schema of a thrown ball includes a force pushing the ball, then the definition of the student's concept of force in this instance is specific to that which overcomes gravity to maintain motion (Rowlands et al. 1999). This, however, is nothing new, Champagne et al. found that:

> Motion-of-objects schemata of uninstructed students are *situation-specific*, thus suggesting that no naïve abstract representation is extant in the schemata to make them appear to be applicable to a large number of physical situations... For example, students do not recognise that the same physical laws apply to objects in free fall and to objects sliding down an inclined plane (Champagne et al. 1982, p. 36, emphasis added).

It is not as if students bring with them into the classroom pre-instructed 'items' of knowledge such as free-fall and motion down inclined planes. The difference in the items must lie in the way they are situation-specific. This is not to suggest, however, that the student's schemata of force and motion arises out of a vacuum. What may already exist beforehand is what Stinner (1994) refers to as a 'personal kinesthetic memory' upon which we base our 'commonsensical' notions of force when asked to account for force and motion for the first time. Personal kinesthetic memories aren't theories or 'mini-theories', they are memories that can be 'evoked', or rather, *instantiatiated.* For example, to respond 'force maintains motion' with a memory of pushing a large, heavy box with a constant push so as to maintain a uniform motion. That evocation/instantiation may be something that is triggered by what stands out for the child/student/adult in situation specific reasoning. According to Rowlands et al. (1999), in situation-specific reasoning we tend to focus on the *dominant features of* motion ('up', 'down', 'moving horizontally', 'large body', etc.) and force as a concept is instantiated a number of different ways according to the various schemata of motion – *it is as if student reasoning tends to focus on the body in the context of motion (to which force is* *instantiated), rather than the motion in the context of forces acting on the body.*

For example, Viennot (1985) found that 'V–F' reasoning, a common belief that the force acting on an object is proportional to its velocity, occurs mainly when motion is a striking feature of the proposed physical situation. From an interview with a student, Marton (1986) found that 'the conception the student shows initially (the force in the direction of the movement exceeds the sum of the forces in the opposite direction) is always linked with focusing on the fact the body is moving (instead of being at rest)' (p. 46). The point is, misconceptions tend to be context-specific and it may well be the case that, for some students, several different contexts exhibit the same dominant feature which activates a particular kinesthetic memory. What is deemed the dominant feature may perhaps only be ascertained by research, but it might give a clue as what it activates. The following are implications of modelling conceptual change using schema theory:

- According to Viennot (1985), a taxonomy of student misconceptions may be impossible because the consideration of misconceptions requires a specificity regarding the context from which the misconceptions occur, such as what kind of problem prompted the misconception. However, a taxonomy of student misconceptions with respect to what dominant features prompted them may be possible, but this taxonomy would depend upon schema structure and instantiation and would not necessarily reflect previously held ideas. Existing taxonomies may in fact reflect instantiations specific to what prompted them.
- Misconceptions are resilient, not because misconceptions have been formed over years and years of experience, but because of the cognitive strain in forming an intuitive schema of force and motion to account for examples of force and motion for the first time (Rowlands et al. 1999).
- Although misconceptions are spontaneous and not theory-like, they may nevertheless exhibit elements of kinesthetic memory or meanings of force as a metaphor in everyday speech. A model of conceptual change needs to discern these elements and, if possible, to capture persistent dominant features, their consistent activation of these elements and how these elements are expressed. Of course, not all responses are misconceptions. 'A constant push is required to maintain a large, heavy box in uniform motion' may be a legitimate expression of a previous experience of pushing boxes, but the sentence may have either been employed to explain an initial response that force is required to maintain motion or may have been part of the cause of the response. The point is, the initial response *may* be independent of the kinesthetic memory employed in justifying it. We can not merely assume that kinesthetic memory is the mechanism whereby misconceptions are formed.

3. Misconceptions through the Lens of Newtonian Mechanics

According to Halloun (1998), schemata can only be explored indirectly through the construction of scientific concepts. He adds that the ultimate aim of science education is to empower students with schemata that are compatible with that of the scientist and this can only be achieved through the negotiation of scientific constructs. In other words, we can only view misconceptions through the lens of Newtonian mechanics and conceptual change can only occur with explicit reference to Newtonian mechanics. The implication, as stated by Halloun, is that the evaluation of student schemata and its development (i.e. misconceptions and conceptual change) cannot be in the abstract but by comparison with *desired* standards. It is not how the child sees the world (although for some constructivists this ought be the major, if not the only, object of the research) or how different the view is from that of the scientist. Rather, it is how student reasoning develops in the attempt to move the student to a Newtonian understanding. It is in this sense that we cannot view misconceptions outside of the teaching/learning situation. There is a tradition within conceptual change research that has yet to be fully acknowledged, and that is the contextualsing of misconceptions in the teaching/learning situation explicitly with respect to Newtonian mechanics (e.g. Arnold Arons, Lillian McDermott, Ibrahim Halloun, David Hestenes).

The intuitive schemata of force and motion does not account for all different types of motion but is instead dependent on the dominant (or particular) features of motion. On the other hand, the Newtonian concept of force is implicitly *well-defined* by the laws of motion (Hestenes 1992) and can account for different types of motion (projectile motion, circular motion, motion down an inclined plane, free-fall, etc.) without having to change the definition of force (or, rather, what is to count as force) with respect to each type. There are many implications that follow from this. For example:

- A ‘Newtonian understanding’ of the force concept in the qualitative sense of understanding what forces are acting on which body and the effect of those forces on the body would require the student’s appreciation that his or her intuitive schema of force and motion lacks the same consistency or coherence compared to the Newtonian system. Hence Hestenes’ (1992) proposed non-separation between ‘modelling games’ or ‘model centred instruction’ and the ‘evocation’ of misconceptions: different questions concerning different ‘scenarios’ or phenomena but *which all have the same explanation under the Newtonian system* can be asked so as to illicit inconsistencies in student reasoning. Of course, how students respond to their own inconsistencies is still speculation. Whether they make rapid attempts to correct their reasoning when they become aware of contradicting ideas (e.g. Minstrell 1982; Marton 1986; Hake 1987) or they are intransigent (e.g. Viennot 1979; Howard 1987; Burbles & Linn 1988) maybe dependent on the use of anomalies as directional signs and stepping stones towards understanding the subject.

- To involve the student with modelling games will necessarily require the student to think of abstract, 'possible worlds' which are impossible in the real world, for example, to ask the student how a stationary puck on a frictionless horizontal table can be given uniform motion. Students independently of whether they are concrete or formal thinkers can be invited to enter the 'Newtonian world' which provides the perfect opportunity to consider 'if then' abstract possibilities that may well lie within their capabilities that might otherwise be restricted to the concrete. It is in the nature of the system that the mediation has to involve abstract thinking and the main vehicle for this are thought experiments.
- Mechanics is not only a system of concepts, it is also a hierarchical system of concepts structured by the laws of motion as axioms (Wittgenstein 1974; Hestenes 1987, 1992). For example, energy is the capacity or ability to do work and work is the product of force and displacement. The point is, 'misconceptions' of force and motion are fundamental because understanding the Newtonian concept of force and motion is essential in understanding the system as a whole. Misconceptions about energy are not so fundamental. For example, many science textbooks and articles in the conceptual change literature speak of energy, in the scientific context, as a possession that can be 'converted' or 'transferred' (e.g. Trumper 1990). This is a misconception: energy is a thing that can be transformed or passed on from one object to another. Nevertheless, provided that energy is taught as the ability to do work, then this way of speaking is acceptable, *but it is still a misconception nevertheless*. It would be better to express the law of conservation of energy as the work that a body can do is equal to the work done on the body. That way, the Newtonian system can be conceptualized for the hierarchical system of concepts it is – a necessity if the student is to understand how this system can be brought to bear on the physical world.
- To 'view misconceptions through the lens of Newtonian mechanics' is to suggest a certain sense in which we cannot view children's ideas 'in their own terms' but only with respect to the demands placed on children to account for examples according to Newtonian mechanics. In this sense, children's ideas are seen as responses to those demands. To view children's ideas 'in their own terms' might

be to divorce those ideas from the very stimulus that prompted those ideas. This is not to suggest that meanings should be imposed that were otherwise intended, the point is that questions asked have a correct explanation under the Newtonian system and require an intellectual engagement. Misconceptions should be seen in this sense of engagement more than the retaining of firmly held 'beliefs' or ideas. Indeed, teaching experience has shown that some students who have a sense of this engagement enthusiastically defend (what may then be defined as, depending on the input of the teacher/researcher) Aristotelian/impetus theory.

4. Is Conceptual Change Dramatic or 'Instant-by Instant'? Looking through the Lens

There are differences of opinion in the literature as to whether conceptual change is evolutionary or revolutionary (Wiser & Amin 2001). Since the 'revisionist theory' of Strike and Posner (1992), there has developed a majority consensus that conceptual change is a slow revision of the 'initial conceptual system' rather than a revolutionary paradigmatic affair (e.g. Vosniadou et al. 2001). Duit (2002) argues that learning science should be a gradual process such that 'initial conceptual structures based on children's interpretations of everyday experience are continuously enriched and restructured' (p. 8). We seem here to have a twofold contradiction. One the one hand, initial conceptions are to be 'enriched' yet 'misconceptions' may in fact be obstacles to a conceptual understanding of force and motion and not something to enrich. On the other hand, students need to become aware of the shift in their initial views towards the 'metaconceptual perspectives of science knowledge' (p. 8), which implies change, not enrichment.

Indeed, Linder's (1993) 'conceptual appreciation delimited by context' or Kuiper's (1994) 'instant-by-instant dealing of incoherent student ideas' are piecemeal, instant-by-instant gradual modification approaches to conceptual change and these approaches have become very popular. For example, von Glasersfeld (1995) argued that a significant change in the nature of and relationship between concepts can occur through 're-conceptualisation': from 'force implies motion' to 'force implies acceleration'. However, Champagne et al. (1982) argued 13 years earlier that the change from 'force implies motion' to 'force implies acceleration' does not involve the simple modification of ideas and that a more dramatic conceptual change must take place. If students tend to see force as a property of the object (for example, children use grammatical constructions such as 'the marble has no more force', see Leboutet-Barrell 1976) rather than a relationship between two objects, then this would seem to imply that a conceptual change would have to be a dramatic one and not a simple modification of the elements of a schema (and at least as dramatic as an ontological change). The schema itself has to change. However, a dramatic conceptual change is not to say that the change is paradigmatic from the alternative framework to the scientific one. The change may be dramatic if it involves the active construction of *new* concepts within a *new* framework:

> Newtonian forces are relations between two or more bodies. Students, however, conceive of 'motion' as a process that bodies undergo and believe that *all* motion needs an explanation.... Changing existing representations requires that they be taught how to construct the new concepts and work these into a quite different representation of the phenomena. We can also see that calling this process 'restructuring' is potentially quite misleading. It makes it seem like the elements of the conceptual structure are fixed and all that is required is to rearrange these elements, as one would the furniture in a room. However, *learning a scientific conceptual structure requires more than rearranging existing elements and also more than fitting new facts into an existing framework. ... it requires constructing new concepts and working them into a new framework*. I, thus, prefer to refer to this process as conceptual change (Nersessian 1992, p. 50, emphasis given).

The implication is that we cannot really separate the misconception from the 'new framework': the misconception (or spontaneous conception) has to be seen in the light of Newtonian mechanics and the job of the educator is to enable the student to realise his or her misconceptions in the same light. Schema theory may be able to explain not only the formation of misconceptions but also the shift in conceptions as responses specific to teaching strategies that attempt to model the world through Newtonian mechanics. Duit's (2002) 'metaconceptual perspectives of science knowledge' (p. 8) may be an essential approach for conceptual change to occur in that students may have to be engaged in a meta-discourse concerning the nature of force in order to reflect on their own ideas and to see the disparity. If so, schema theory will have to accommodate such features as a meta-discourse of force and motion, whatever the form of the meta-discourse. For example, an historical introduction to the epistemological obstacles of force and motion (e.g. Arons 1990; Matthews 1994, 2000), or the Socratic method of revealing, identifying and discussing misconceptions in the light of Newtonian mechanics (e.g. Hake 1987; Arons 1990; Hestenes 1992).

According to Vosniadou et al. (2001), misconceptions may be tied to years of confirmation and if they are to change then the entrenched presuppositions that gave rise to the misconceptions must also change and this is a gradual affair. This implies that misconceptions are pre-instructional, but what these 'entrenched' presuppositions are supposed to be is unclear. However, Vosniadou et al., are in accord with the majority of researchers who, according to Caravita (2001), no longer view conceptual change as a result of a crucial experience but instead dependent on other factors such as motivation. Now while there is a sense in which conceptual change is a gradual affair involving the construction of new concepts and working them into a new framework (plus the motivation to do this), nevertheless, according to Hestenes, a piecemeal (instant-by-instant) approach is ineffectual because such attempts to eliminate misconceptions of force have concentrated on individual misconceptions separated from the others and *"ignores one of the most fundamental characteristics of the force concept, the coherence of the Newtonian theory"* (Hestenes 1992, p. 742, italics added). Hestenes (1992) argues that the most critical misconceptions are the Impetus and Dominance principles and if they are dealt with effectively then most other misconceptions tend to fade away when the general force concept is integrated into the students' thinking.

There has been a tendency in research to examine only single concepts and not the complete student understanding of mechanics, and so the research has tended to overlook the *coherence* of the Newtonian theory (Hestenes 1992). What Halloun and Hestenes (1987) propose is a general strategy for dealing with misconceptions (*model-centered instruction or the method of paradigm problems*). They state that the laws of motion are revealed by applying the laws to construct and validate models of specific physical phenomena *and that the strategy should elicit from the students explicit formulations of alternatives to Newtonian concepts to be analysed and evaluated*. This implies a non-separation between the teaching of modelling in mechanics and the consideration of misconceptions which we shall discuss further in the next section. Meanwhile, the implication of model-centered instruction is that we teach what Halloun calls 'middle-out', that is, from force as the central unit of analysis to the rest of the system. This way, the learner learns what Davydov (1988) calls the 'kernel' of the discipline from which all other items of knowledge from the discipline are derived. This is by far a superior form of teaching than the 'episodic' method of introducing concept after concept such that force becomes awash in a sea of concepts and detail and no longer becomes the central unit of analysis (Halloun 1998). There is a danger that the piecemeal (instant-by-instant) approach to misconceptions becomes episodic such that the student fails to accommodate the kernel of the discipline and hence fails to understand the Newtonian system as a coherent whole.

5. Instigating Conceptual Change through Newtonian Mechanics

Supposing a clinical interview study of student reasoning in mechanics manages to eliminate all interviewer bias. The interviewer's question elicits a response that can be classified as a 'misconception'. If the interviewer follows the question up with another question then the interviewer may well be evoking a cognitive response from the interviewee with respect to mechanics. This illustrates the interview as a teaching episode, despite the elimination of bias. We may have no option but to accept that any method of data gathering regarding misconceptions may be the very genesis of those misconceptions. For example, a student's response to a test item in a mechanics questionnaire may be a response to a question for the first time – it may be something that the student has not thought about before – and may not reflect, in any way, what is in the student's 'head' prior to the questionnaire. Of course, the response may contain elements of prior ideas with respect to kinesthetic memory or the use of force as a metaphor, *but these elements have to be discerned, it cannot be assumed that the response reflects or comprises these elements*. The major implication from this is that it may be impossible to develop a model of conceptual change that is purely descriptive – any research instrument may in itself become a form of intervention that encourages a cognitive response and prompts a conceptual change. In other words, a model of conceptual change may have to be prescriptive and it may well be the case that no satisfactory conclusions can be established from the plethora of descriptive accounts.

If a model of conceptual change has to be prescriptive, then the model has to accommodate the attempt to move the student towards a conceptual understanding of the Newtonian system. The 'issue' of conceptual change thus becomes *how the student response cognitively to the mediation*, whether the mediation takes the form of questioning, answering a test item, use of a metaphor, etc. The question as to what changes in conceptual change then becomes how responses change in the light of mediation. Whether or not the response is a result of reflection (meta-thought) may well depend on the nature of the mediation. The mediation, however, ought to engage students with abstract 'if then' possibilities (thought-experiments) from which a qualitative understanding of how real situations are modelled can be developed. An historical example is how Galileo's ideal pendulum can be used to model real pendulums (see Matthews 1994, 2000).

6. Conclusion

A misconception may be a spontaneous response in attempting to provide an answer to a given question. Student reasoning in trying to defend the response might reveal components that can be said to be 'pre-instructional', such as the personal kinesthetic memory of having to push a large box so as to maintain motion, or regarding the inability to move a box as not being forceful enough. Some components may involve the misuse of scientific words. But what components may be evoked will perhaps be ascertained by a future model of conceptual change that looks for these components and examines them in the light of empirical research, *but* *within a framework that views conceptual change as a dynamic process of spontaneous reasoning as directed towards a conceptual understanding of the subject domain*. To gain a fuller picture, such a future model may have to incorporate adaptations of other models and theories, such as Chi et al.'s (1994) ontological differences between everyday and scientific concepts or Vygotsky's theory of concept formation (Nikolaou & Watson 2004).

Such a model will have to prescribe teaching strategies specifically designed to evoke 'misconceptions' and to instigate conceptual change. Any research as to what changes can only be in the light of the teaching strategy. The teaching strategy itself has to be designed in a way that attempts to move the student's towards a conceptual and qualitative understanding of the force concept, that is, how the concept of force structures the Newtonian system and how this system models the world. Such an attempt must involve a meta discourse component that encourages students to reflect on their misconceptions and the coherence of the Newtonian system. One such component is the use of concept and parallel questions (Rowlands et al. 1999). A concept question might instantiate an intuitive schema of force and motion. What parallel question to ask (a question that requires the same explanation as the original concept question but to a different scenario) is determined by the response to the concept question but is structured according to the Newtonian system. The idea is to create anomalies that can be explained by the Newtonian system. This way, the student can be led through reasoning to a situation whereby any explanation has a greater chance of becoming more meaningful.

The use of concept and parallel questions may induce cognitive conflict, but it isn't the only method. Analogies and metaphors or discussion may lead a student to a meaningful cognitive conflict (Limón 2001) and the many examples of the use of historical narrative in *Science & Education* springs to mind. In other words, conceptual change may have to be seen in terms of involving the student/s with a meta-discourse in which evocation and change occur as a process of reflection. Conceptual change then becomes a change in mind, and mind that is engaged with modelling forces in a way that it can reflect on its own initial response to the concept of force as part of the process. Conceptual change can be seen as the inclination and ability to model an unfamiliar situation according to the laws of motion, as well as (perhaps) an intuitive gut response that could be categorised as a misconception. There is a sense in which conceptual change occurs when the child/student/adult/expert realises that their gut response may be inadequate. Conceptual change is an intellectual engagement open to all learners that cannot be meaningfully divorced from the very intervention that instigated it, whether that intervention is teaching in a classroom, a clinical interview, answering test items or reading a book.

Intuitive reasoning that does not bear a similarity with Newtonian reasoning in a clinical interview may be a reflection of not knowing what kind of answer is expected to a given question. To give any hint as to what kind of answer is expected would be to introduce an element of bias, but bias may be unavoidable. Why not embrace the bias and examine conceptual change in the light of intervention, enabling the student to construct a scientific understanding of force? We may never know the ideas of the pre-instructed student, but we may get a glimpse of those ideas as the student responds cognitively to the mediation. A mediation that enables the student to think of abstract, idealised worlds that are used to model the real one (and perhaps independently of whether the student is a formal or concrete thinker). In other words, to think in what Hestenes (1992) calls the 'Newtonian World'.

Of course, what we have outlined above is a 'theory' and, as with any theory, empirical evidence is required to show the credibility of the theory. We aim to build a model of conceptual change in the light of empirical data and we are currently in the process of evaluating student responses to the question 'what is force?' and how these responses differ with how the same students answer questions concerning force. Our model will incorporate a method for investigating intuitive schemata of force and motion based on the strategy of Socratic questioning, either within the context of one-to-one interviews or the dynamics of the classroom setting. It is hoped that the construction of our model plus the empirical data it generates will appear in a subsequent article in a journal more suited for empirical data, and that the findings will inform the practitioner via the professional journal.

7. Notes

[1] Perhaps the 'misconceptions' literature began with the following statement by the U.K.'s Mathematical Association's *A Second Report on the Teaching of Mechanics in Schools*: "Pupils are inclined to think that force would be needed to keep a body moving even if resistances could be eliminated – i.e. that force is responsible for speed and not for acceleration – and considerable discussion might be required to eradicate this belief." (M.A. 1965, p. 25).

[2] The very term 'misconception' is controversial and many authors prefer to use other terms that reflect the approach and the assumptions made with regard to student ideas of force and motion. Arons (1990), for example, argues that 'misconceptions' is both derogatory and misleading leaving the impression that the misconception is to be removed through asserting the correct notion. He prefers 'preconceptions' since student concepts were initially held by many of our predecessors. Driver et al. (1994) prefers 'plural conceptual schemes' as this shifts the focus from being right or wrong to the way the student constructs an understanding specific to different social settings. Viennot (1979) prefers 'intuitive notions' that reflect vagueness in student ideas rather than ideas which are well articulated. We

would like to stress at the outset, however, that 'misconceptions' may be an appropriate term to use if only because the student may be judged right or wrong in relation to the Newtonian system, although a misconception can be utilized as a 'teaching aid'. For example, the teacher may say 'that is not the right answer, but it is a *good* answer because that was the answer given by Aristotle and accepted for two thousand years until challenged by Galileo', etc. The problem with the term 'misconception', however, is that it implies concepts that are fairly well formed. This paper argues that misconceptions may not be concepts.

[3] Although much of the literature has assumed that intuitive concepts, whatever they are, are fairly well formed prior to instruction, there is disagreement as to the nature of these concepts. For example, diSessa (1993) questioned the 'theory-like' characteristic of intuitive reasoning and argued that intuitive ideas are instead composed of self-explanatory 'phenomenological primitives' ('p-prims'), For diSessa, there is no conceptual change whereby intuitive ideas are replaced by scientific ideas, rather, these intuitive ideas are refined and developed through learning. In student reasoning, p-prims can be discerned. For example, that a bottle at rest on a table does not accelerate due to its weight because the table is in the way or a person in a car that is accelerating is also accelerating because the person is in the car. The problem is that what counts as empirical evidence for p-prims becomes almost arbitrary, which is especially problematic if p-prims are to account for all 'misconceptions'. For example, diSessa and Sherin (1998) interviews a pupil whom they attribute p-prims in her responses to questions that demand a very sophisticated form of reasoning in Newtonian mechanics. Now this is fair enough if the aim is to move the student towards this sophisticated form of reasoning, but if that is the aim then the interview becomes a teaching dyad. However, diSessa and Sherin have attempted to remove all bias.

There are various problems with this: the interviewer does not make it clear what kind of answer is required, it is not clear whether the conversation is about uniform motion or acceleration (the commentary ascribes the notion 'that the force of the hand is overcoming friction in moving a book', p. 1185, as naïve and contrary to $F=ma$. The ambiguity is in the words 'overcoming' and 'moving'. If the conversation was made clear, then we would have a teaching dyad), the interviewee's reasoning is open to various interpretations, in parts the interviewer and interviewee seem to talk past each other, the interviewee is prompted to use certain terms and the interviewer actually states misconceptions in the process (such as feeling the force of gravity when you hold something, p. 1180). This is not to undermine their critique of the conceptual change literature's concept of what a concept is and their formulation as to what changes in the process of conceptual change. We do not agree with much of their critique, but its analysis is exemplary.

[4] Tynäjä et al. (2002) make the important distinction between the two in terms of Popper's World Two of mental processes and subjective thoughts and World Three of the objective content of thought (scientific concepts). A *conceptual* change or a *conceptional* change, albeit one from the World Two of intuitive ideas to the World Three of the scientific framework, does seem to suggest that intuitive ideas are in a sense 'theory-like' and constitute a 'world-view' (weltanschuung). The central argument of this paper is that pre-instructed pupils may not hold any such theory-like view of force and motion. For Chi et al. (1994), conceptual change is not a theory change, it is a change in the concept's ontology. For example, from the concept of force as a property of the body to the concept of force as a relationship between two bodies. This may well prove to be fruitful in understanding the dynamics of conceptual change as it lays a basis for distinguishing everyday thinking with scientific thinking. For example, a layperson may interpret the proposition 'the ball is red' in the sense of red being a property of the ball; whereas the scientist may interpret the proposition as a shorthand way of saying that when the ball is irrigated with white light it

reflects only the red. On the one hand the ball is predicated the quality red, on the other hand red is seen as a process: the difference is an ontological one and may hold the key in the attempt to develop scientific literacy.

However, Chi et al.'s conceptual change theory has come under criticism. For Duit (2002), it is an example of the one-sidedness of focussing on what he calls the 'rational', that is, the logic of the science. But that is precisely what is required if we want our young learners to be scientifically literate, that is, being able to think scientifically akin to world Three. Duit (2002) may not disagree, for he states that the major limitation of the classical conceptual change model is its emphasis on the content of science rather than *about* the nature of science. Nevertheless, a conceptual change theory must focus on the rational but not exclude teaching method, classroom dynamics, motivation etc. This paper will focus on the 'rational' but will argue that conceptual change cannot be divorced from the learning environment and that a conceptual change theory ought to prescribe a meta-discourse as to the nature of science in the teaching of science.

[5] A 'well established intuitive Aristotelian model' seems to suggest that most children have mental models of force and motion that are Aristotelian. However, children's ideas of force and motion do not have the complexity of Aristotle's theoretical framework and tend to be sporadic and contradictory. This paper will argue that conceptual change may require these sporadic and contradictory ideas to be thought out by the students themselves. In other words, conceptual change may have a meta-thought component.

[6] Especially since consistency in student reasoning may reflect more the ability to reason than the ('theory likeness') consistency of previously held ideas.

References

Arons, A.B.: 1990, *A Guide to Introductory Physics Teaching*, J. Wiley and Sons, New York.

Berry, J. & Graham, E.: 1991, 'Using Concept Questions in Teaching Mechanics', *Internation Journal of Mathematical Education Science and Technology* **22**, 749–757.

Biemans, H.J.A., Deel, O.R. & Robert-Jan Simons, P.: 2001, 'Differences Between Successful and less Successful Students While Working with the CONTACT-2 Strategy', *Learning and Instruction* **11**(4–5), 265–282.

Boeha, B.: 1990, 'Aristotle, Alive and Well in Papua New Guinea Science Classrooms', *Physics Education* **25**, 280–283.

Bliss, J. & Ogborn, J.: 1994, 'Force and Motion from the Beginning', *Learning and Instruction* **4**, 7–25.

Burbles, N. & Linn, M.: 1988, 'Response to Contradiction: Scientific Reasoning During Adolescence', *Journal of Educational Psychology* **80**(1), 67–75.

Caravita, S.: 2001, 'Commentary: A Re-framed Conceptual Change Theory?', *Learning and Instruction* **11**(4–5), 421–429.

Champagne, A., Klopfer, L. & Gunstone, R.: 1982, 'Cognitive Research and the Design of Science Instruction', *Educational Psychology* **17**(1), 31–53.

Chi, M.T.H., Slotta, J.D. & de Leeuw, N.: 1994, 'From Things to Processes: A Theory of Conceptual Change for Learning Science Concepts', *Learning and Instruction* **4**, 27–43.

Davydov, V.V.: 1988, 'Problems of Developmental Teaching: The Experience of Theoretical and Experimental Psychological Research (part 2)', *Soviet Education* **30**(9), 3–83.

diSessa, A.A.: 1993, 'Towards an Epistemology of Physics', *Cognition and Instruction* **10**(2 & 3), 105–225.

diSessa, A.A. & Sherin, B.L.: 1998, 'What Changes in Conceptual Change?', *International Journal of Science Education* **20**, 1155–1191.

Driver, R. & Easley, J.: 1978, 'Pupils and Paradigms: A Review of Literature Related to Concept Development in Adolescent Students', *Studies in Science Education* **5**, 61–84.
Driver, R., Asoko, H., Leach, J., Mortimer, E. & Scott, P.: 1994, 'Constructing Scientific Knowledge in the Classroom', *Educational Researcher* **23**(7), 5–12.
Duit, R.: 2002, ''Conceptual Change – Still a Powerful Frame for Improving Science Teaching and Learning'', *Proceedings of the Third European Symposium on Conceptual Change: A process approach to conceptual change*, June 26–28, 2002, Turku, Finland.
Gilbert, J., Watts, M. & Osborne, R.: 1982, 'Student's Conceptions of Ideas in Mechanics', *Physics Education* **17**, 62–66.
Hake, R.R.: 1987, 'Promoting Student Crossover to the Newtonian World', *American Journal of Physics* **55**, 878–884.
Halloun, I.: 1998, 'Schematic Concepts for Schematic Models of the Real World: The Newtonian Concept of Force', *Science Education* **82**(2), 239–264.
Halloun, I. & Hestenes, D.: 1987, 'Modeling Instructions in Mechanics', *American Journal of Physics* **55**, 455–462.
Helm, H.: 1980, 'Misconceptions in Physics Among South African Students', *Physics Education* **15**, 92–97.
Hestenes, D.: 1987, *New Foundations of Classical Mechanics*, Reidel, Boston.
Hestenes, D.: 1992, 'Modeling Games in the Newtonian World', *American Journal of Physics* **60**(8), 732–748.
Howard, R.: 1987, *Concepts and Schemata*, Cassell Educational, London.
Jagger, J.: 1985, 'Introducing Mechanics – A Response', *Mathematics in Schools* **14**, 24–25.
Kuiper, J.: 1994, 'Student Ideas of Science Concepts: Alternative Frameworks?', *International Journal of Science Education* **16**(3), 279–292.
Leach, J. & Scott, P.: 2003, 'Individual and Sociocultural Views of Learning in Science Education', *Science and Education* **12**(1), 91–113.
Leboutet-Barrell, L.: 1976, 'Concepts of Mechanics Among Young People', *Physics Education* **11**, 462–466.
Limón, M.: 2001, 'On the Cognitive Conflict as an Instructional Strategy for Conceptual Change: a Critical Appraisal', *Learning and Instruction* **11**(4–5), 357–380.
Linder, C.J.: 1993, 'A Challenge to Conceptual Change', *Science Education* **77**(3), 293–300.
McCloskey, M., Caramazza, A. & Green, B.: 1980, 'Curvilinear Motion in the Absence of External Forces: Naïve Beliefs About the Motion of Objects', *Science* **219**, 1139–1141.
MA.: 1965, *A Second Report on the Teaching of Mechanics in Schools*, Mathematics Association, G. Bell & Sons Ltd., London.
Marton, F.: 1986, 'Phenomenography – A Research Approach to Investigating Different Understandings of Reality', *Journal of Thought* **21**(3), 28–49.
Mason, L.: 2001, 'Introduction', *Learning and Instruction* **11**(4–5), 259–263.
Matthews, M.R.: 1994, *Science Teaching: The Role of History and Philosophy of Science*, Routledge, London.
Matthews, M.R.: 2000, *Time for Science Education: How teaching the History and Philosophy of Pendulum Motion can Contribute to Science Literacy*, Kluwer, New York.
Mildenhall, P.T. & Williams, J.S.: 2001, 'Instability in Students' Use of Intuitive and Newtonian Models to Predict Motion: The Critical Effect of the Parameters Involved', *International Journal of Science Education* **23**(6), 643–660.
Minstrell, J.: 1982, 'Explaining the ''At Rest'' Condition of an Object', *The Physics Teacher* **20**, 10–14.
Mortimer, E.F.: 1995, 'Conceptual Change or Conceptual Profile Change?', *Science and Education* **4**(3), 267–285.

Nersessian, N.: 1992, Constructing and Instructing: The Role of ''Abstraction Techniques'' in Creating and Learning Physics, in A. Duschl and R. Hamilton (eds.), *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice*, State University of New York Press, Albany.

Nikolaou, L. & Watson, R.: 2004, ''Analyzing Student's Ideas About Force and Motion Using Vygotsky's Theory of Concept Formation'', paper presented at *NARST Conference*, Vancouver, BC, 1–3 April.

Orton, A.: 1992, *Learning Mathematics: Issues, Theory and Classroom Practice*, Cassell Educational, Londonsecond edition (first published in 1987).

Perkins, D. & Simmons, R.: 1988, 'Patterns of Misunderstanding: An Integrative Model for Science, Math, and Programming', *Review of Educational Research* **58**(3), 303–326.

Peters, P.: 1982, 'Even Honors Students have Conceptual Difficulties with Physics', *American Journal of Physics* **50**, 501–508.

Posner, G.J., Strike, K.A., Hewson, P.W. & Gertzog, W.: 1982, 'Accommodation of a Scientific Conception: Towards a Theory of Conceptual Change', *Science Education* **66**(2), 211–227.

Pnevmatikos, D.: 2002, ''Conceptual Change, Mental Models and Their Internal Consistency Within the Religious Domain of Knowledge'', *Proceedings of the Third European Symposium on Conceptual Change: A process approach to conceptual change*, June 26–28, 2002, Turku, Finland.

Rowlands, S., Graham, E. & Berry, J.: 1999, 'Can we Speak of Alternative Frameworks and Conceptual Change in Mechanics?', *Science and Education* **8**(3), 241–271.

Soto-Lombana, C. & Sanjose, V.: (2002), ''Research on Conceptual Change: A Review in Science Education'', *Proceedings of the Third European Symposium on Conceptual Change: A process approach to conceptual change*, June 26–28, 2002, Turku, Finland.

Stinner, A.: 1994, 'The Story of Force: From Aristotle to Einstein', *Physics Education* **29**, 77–85.

Strike, K.A. & Posner, G.J.: 1992, A Revisionist Theory of Conceptual Change, in R. Duschl and R. Hamilton (eds.), *Philosophy of Science, Cognitive Psychology and Educational Theory and Practice*, SUNY, Albany.

Trumper, R.: 1990, 'Energy and a Constructivist Way of Teaching', *Physics Education* **25**(4), 208–212.

Tynjäjä, P., Merenluoto, K. & Murtonen, M.: 2002, ''What Has Been meant by 'Concept' and 'Change' in Conceptual Change Studies? A Framework for a MetaAnalytical Study'', *Proceedings of the Third European Symposium On Conceptual Change: A process approach to conceptual change*, June 26–28, 2002, Turku, Finland.

Vamvakoussi, X. & Vosniadou, S.: 2002, ''Conceptual Change in Mathematics, From the Set of Natural to the Set of Rational Numbers'', *Proceedings of the Third European Symposium on Conceptual Change: A process approach to conceptual change*, June 26–28, 2002, Turku, Finland.

Viennot, L.: 1979, 'Spontaneous Reasoning in Elementary Dynamics', *European Journal of Science Education* **1**, 205–221.

Viennot, L.: 1985, 'Analyzing Student's Reasoning: Tendencies in Interpretation', *American Journal of Physics* **53**, 432–436.

Von Glasersfeld, E.: 1995, *Radical Constructivism: A Way of Knowing and Learning*, The Falmer Press, London.

Vosniadou, S., Ioannides, C., Dimitrakopoulou, A. & Papademetriou, E.: 2001, 'Designing Learning Environments to Promote Conceptual Change in Science', *Learning and Instruction* **11**(4–5), 381–419.

Vygotsky, L.: 1987, *The Collected Works of L. S. Vygotsky, Volume 1 Problems of general Psychology*, Plenum Press, New York.

White, R.T.: 1994, 'Commentary: Conceptual and Conceptional Change', *Learning and Instruction* **4**, 117–121.

Wiser, M. & Amin, T.: 2001, 'Is Heat Hot?' Inducing Conceptual Change by Integrating Everyday and Scientific Perspectives on Thermal Phenomena', *Learning and Instruction* **11**(4–5), 331–355.

Wittgenstein, L.: 1974, *Tractatus Logico-Philosophicus*, Routledge and Kegan Paul, London.