Chapter 2

Background

1. Introduction

The aim of this chapter is to position this study in the field of related research. The literature on teaching/learning mechanics is extensive. It is impractical if not impossible to give an account of what people have done to understand and improve teaching/learning mechanics that comes close to being complete. Some way of selecting and systematising is therefore in order. A first selection is that I will restrict myself to starting upper level pre-university students (age 16). The research on and approaches to teaching/learning mechanics presented in section 2 and discussed in section 3 are organised around four focal points:

1. What are the goals for teaching/learning mechanics? This point will illustrate what types of goals are considered normal in teaching mechanics.
2. What are the problems in teaching/learning mechanics? This is an important point because differences in the problem analysis naturally might have consequences for the approach to teaching/learning it.
3. What approaches to teaching/learning mechanics are expected to solve the problem and contribute to reaching the goals? Together with a design to solve the identified teaching/learning problem one would expect to find an argument of how this design is expected to do that. Without such an argument the (sometimes impressive) learning outcomes are difficult to relate to elements of the design. It will turn out that sometimes more attention is given to presenting learning outcomes than to this type of argument.
4. To what extent did the design work in solving the problem and reaching the goals? And how was this found out. Here the empirical outcomes and research methods are presented.

After presenting literature organised around these points it will be critically discussed using the same organisation in section 3. So for instance several problem analyses will be presented in section 2.2 and discussed in section 3.2. In the same way section 2.3 corresponds with section 3.3 et cetera. In this way I aim to show what has already been achieved in teaching/learning mechanics that is worthwhile and to be adopted, what has proven less successful and is to be abandoned and what is still unanswered and to be researched. Such an account, which is necessarily incomplete, will position this research project in what has already been done.

2. Teaching/learning mechanics in the literature

In this section relevant research will be presented around the mentioned four focal points.

2.1. Goals

In this section I will give an overview of a number of goals for mechanics formulated in influential curriculum projects concerned with upper level pre-university education in the past 40 years, to get a feel for the range and type of goals that are considered to be important.

The first goal is knowing how mechanics works, i.e. understanding the conceptual structure of mechanics. As Matthews (1994) describes an aim of PSSC (Physical Science Study Committee), a major project in the US in the sixties: "Its intention was to focus upon the conceptual structure of physics, and teach the subject as a discipline: applied material was almost totally absent from the text". Understanding mechanics is of course an obvious goal, which is quite common for most mechanics courses. In addition to this common goal for mechanics I will present three more goals that have been aimed at: Mechanics as illustrating 'science at its best', mechanics as illustrating science as a humanistic enterprise and finally mechanics as raising the motivation of students for physics.

Mechanics can be used to illustrate 'science at its best'. In Harvard Project Physics (Holton, Rutherford, & Watson, 1970) one aim was stated as: "To help students increase their knowledge of the physical world by concentrating on ideas that characterise physics as a science at its best, rather than concentrating on isolated bits of information." A unit on mechanics was titled 'the triumph of mechanics' which illustrates this aim quite well.

Another addition to the goal of understanding mechanics is to use mechanics to illustrate the humanistic enterprise that physics is. This is stated in HPP as: "To help students see physics as the wonderfully many-sided human activity that it really is. This meant presenting the subject in historical and cultural perspective, and showing that the ideas of physics have a tradition as well as ways of evolutionary adaptation and change." In HPP and also in PSSC this adaptation and change is presented as a development from Aristotle to Galileo to Newton. Inquiry is also an aspect of the human activity of doing mechanics[1]. French described this aim in the PSSC course 30 years later:

> "The PSSC course would seek to present physics as an integrated intellectual activity, not as a set of mechanical rules for solving problems and manipulating nature. The course would be designed to reflect a spirit of inquiry, presenting both theory and experiment as processes of successive approximation, not as definite or final knowledge. […]. The goal was to get students to think and act like professional scientists: to learn to ask questions, collect and analyse data and form reasoned conclusions" (French, 1986).

[1] Physics by Inquiry, developed by McDermott, is another course that is specifically concerned with this aim (McDermott, 1996). This course does not address dynamics, only kinematics, and is therefore not included in this chapter. Another course developed by McDermott, Tutorials in Introductory Physics, does address dynamics, but in a way in which the inquiry element is not emphasised (McDermott, Shaffer, & Group, 1998).

The PSSC way of teaching included lots of experiments, reflecting this inquiry aspect of the humanistic aim. This latter characteristic seemed to apply even more to the equally influential English Nuffield-Physics project.

The elements of inquiry, history and development of the subject or the specific emphasis on the discipline made these three projects more suited for the academically inclined brighter students, although both HPP and Nuffield did in fact aim at a larger audience.

The third addition to the common goal of understanding mechanics is raising motivation. In the influential Dutch PLON project in the seventies and eighties motivation was attempted to be raised by showing the relevance of mechanics for daily life for all students, not only the academically inclined ones. In this course the physics topics were organised around themes that connect a particular context to particular physics content. Both context and content were meant to provide for a coherent structure. In this way mechanics was organised in the theme 'traffic'. This theme concerned, among other things, important factors in safety in traffic, leading to studying situations like braking and colliding, the relation between speed and braking distance, estimates of forces exerted during collisions and discussion of the use of safety belts.

Another way of trying to raise motivation is to emphasise the theoretical challenge of mechanics. This is applied in the quite recent British Advancing Physics project. In their words:

> "Our aims in this chapter are very ambitious, even immodest. These are that we want students to enjoy and value mechanics and the mathematical thinking which goes with it. Taken together with work on vectors in chapter 8, and looking ahead to work on modelling in chapter 10 which is developed in much of the rest of the A2 course, this is where we make a real start on selling the value and interest of theoretical, mathematical thinking in physics to students. We want students to enjoy these theoretical episodes, and to appreciate the power that mathematical thinking brings to physics. So here for a time the course takes on a strong theoretical flavour, to be sampled as one – though by no means the only – flavour appreciated by those who do physics." (From CDROM Advancing Physics AS 2000 Teacher's version)

2.2. Problem analyses

The second focal point concerns what are considered to be the problems in teaching/learning mechanics. I start with an overview of the main opinions in this regard. Next I will present these in more detail.

Two basic problems that are mentioned in the literature are the lack of understanding after traditional[2] education in mechanics and the lack of motivation to engage in and

[2] The much used phrase 'traditional education' seems to be the type of education with which everything is wrong. In a way this is using a straw man. It would be hard to imagine a type of education that has all the features attributed to this devilish 'traditional education'. However, it can also be read as 'education lacking the feature I am promoting', but at least with the suggestion if not the claim that the promoted feature is indeed lacking in most education.

continue with learning mechanics. The first problem of disappointing learning outcomes is extremely widespread. It is found in all research that took the trouble to measure learning outcomes and in all age groups ranging from lower level secondary education to university education. At least on this point there is strong agreement within the research community. Quite some agreement still exists when the cause of this problem is seen in inadequate attention given in education to students' pre-educational notions, although other causes are also identified which will be considered shortly. Further analysis of status and content of these pre-educational notions, and therefore what *adequate* attention would consist of, leads to widely differing views. Also a distinction is made between paying attention to student notions concerning mechanics itself, and their so-called epistemological notions concerning how knowledge in general and knowledge about mechanics in particular is acquired.

Some researchers try to develop some theory about the nature of the pre-educational notions on mechanics, which might guide others in applying or adapting this theory to education, but do not do this themselves. Others take some theory about the nature of notions on mechanics as starting point in trying to develop improved ways of teaching/learning mechanics.

Different theories about the nature of the pre-educational notions have been suggested. Notions on mechanics can be seen as 'naïve theory' in the sense of a systematic set of concepts with which motion can be explained and predicted or as 'knowledge in pieces'. Seeing these notions as naïve theory considered to be consisting of alternative conceptions still leaves room for disagreement as to whether these alternative concepts are a hindrance or a help in teaching/learning mechanics.

Apart from inadequate attention to students' pre-educational notions other causes for the lack of understanding in mechanics are seen in poor consideration of process knowledge in mechanics education. Process knowledge, in contrast to factual knowledge, concerns explicitly the ways of doing mechanics. It consists of strategies and techniques for developing, validating and utilising factual knowledge. This can be, but not always is, related to epistemological notions. Finally a cause is seen in mechanics' inherent difficulty because of the mathematics involved (Genderen, 1989).

The second main problem that is identified is the lack of motivation. Although this is a recognised and important problem it is by choice not the main subject of this research, though I will briefly return to it in the section on goals. I will now continue with a more detailed presentation of the problem analyses that were broadly sketched above.

2.2.1. Neglect of intuitive mechanics in teaching

Almost every researcher sees as a cause of the problem of students not learning as much as hoped for that the pre-instructional common sense notions about movement and the causes of movement are not properly dealt with in traditional education. There are many names for these common sense notions, such as preconceptions, alternative conceptions, misconceptions, alternative frameworks, alternative schemas, intuitive physics et cetera. Of course these different names are not synonymous. What they have in common is the idea that a student is not a tabula rasa, but has certain ideas (maybe only after being invented at the spot) about motion and how to explain motion. Let us call the situation before education in Newtonian mechanics *intuitive mechanics.* The intuitive mechanics is the set of beliefs a student has (on mechanics) before education in mechanics. Depending on one's particular theory concerning the nature of this intuitive mechanics people use different terms, like preconceptions and the rest. If for example one thinks of this intuitive mechanics as consisting of a coherent set of false ideas explaining wrongly the experiences in the world, a word like 'misconceptions' may be used.

It is argued that this intuitive mechanics, even though it differs from Newtonian mechanics, nevertheless may be quite appropriate for the student in making sense of her everyday life. But precisely because this is the case, it cannot be neglected in the transition to Newtonian mechanics. Since in traditional teaching this is neglected, this neglect accounts for the poor results.

Strong agreement within the research community can be found on the point that the intuitive mechanics is not appropriately taken into account in traditional teaching in mechanics. A further analysis as to why this not taking into account of intuitive mechanics leads to poor educational results shows considerable differences in opinion. The question why inadequately taking into account of intuitive mechanics leads to poor result is related to how the nature of the intuitive mechanics is seen, which, as was mentioned before, is reflected in the terms used to describe this intuitive mechanics. Broadly speaking how intuitive mechanics is seen ranges from potentially useful to potentially harmful. If it is seen as harmful the poor results of education can be attributed to failing to do something about this harmful influence. If it is seen as useful the poor results of education can be attributed to failing to make productive use of this potential. Next I will present four further analyses of the nature of intuitive mechanics in order to illustrate the spectrum from useful to harmful.

Intuitive mechanics as an alternative wrong theory of motion

McCloskey (1983) saw intuitive mechanics as a coherent view of the world, an alternative *theory*. He considered this theory to be similar to a pre-Newtonian theory called impetus theory. This alternative theory is considered wrong in the sense that it gives false predictions in a number of situations, for instance the trajectory of a ball dropped by a flying airplane. It is also seen as stable in the sense of resistant to education. Furthermore it is seen as creating learning difficulties by making students misinterpret or distort a presentation of Newtonian mechanics to fit their intuitive mechanics. Intuitive mechanics is therefore clearly considered to be a hindrance. That traditional education does not realise this and take care of this alternative theory is seen as causing its poor results.

Hestenes also sees the problem of disappointing results of education in mechanics in the role intuitive mechanics plays. His characterisation of intuitive mechanics as alternative theory is more elaborate than McCloskey's in the sense that he identifies not only the alternative impetus theory, but also other alternative theories or conceptions. Many different common sense conceptions are mentioned in the literature. A classification can be found in Halloun & Hestenes (1985). The most important in the sense of most often mentioned are: a) Activity implies a force and more activity implies more force (Dekkers & Thijs, 1998). This is a more general description of the 'motion implies force' conception. b) Closely related, but not the same is the 'impetus theory' that states that during an interaction between two objects an amount of impetus is transferred from one to the other, which 'uses it up' during its motion. c) Force as overcoming a resistance and action and reaction forces are not the same size. This is called the *dominance* alternative conception (Hestenes, 1992). These are considered to be too easily dismissed in traditional education. Hestenes too saw strong similarities between intuitive mechanics and mechanics of pre-Newtonian intellectual giants like Aristotle, so intuitive mechanics should be seen as a set of serious and stable alternative hypotheses (Halloun & Hestenes, 1985). The change from intuitive mechanics to Newtonian mechanics for an individual student is seen as of comparable magnitude as is claimed of the historical scientific revolution from pre-Newtonian to Newtonian mechanics. The stability of intuitive mechanics is attributed to a natural human resistance to conceptual change, in order to overcome which Piagetian accommodation by means of cognitive conflict is advised.

> "Traditional physics instruction does not adequately take the intuitions of students into account, so it frequently fails to establish the conditions of cognitive conflict needed to drive a transition from common sense intuitions to the more veridical intuition of a physicist." (Hestenes, 1987).

Furthermore, this stable intuitive mechanics is sometimes inadvertently promoted by instruction.

Intuitive mechanics as containing some useful anchors

Another further analysis of the nature of intuitive mechanics by Clement agrees with the alternative wrong theory analysis in the sense that students' intuitive mechanics poses strong barriers to understanding in physics (Brown, 1994; Clement, Brown, & Zietsman, 1989). It is not further explained how these barriers function, but the usual misconception literature is referred to (Viennot 1979; Clement 1982; McDermott 1984; Halloun and Hestenes 1985 et cetera), so it seems fair to conclude that Clement would agree with the 'intuitive mechanics as an alternative wrong theory' view. However, according to him only certain preconceptions are in conflict with the physicist's point of view whereas others are in agreement and might be productively used in teaching/learning mechanics. Since there might be some good in some preconceptions Clement paints a slightly less gloomy picture of the hindering influence of preconceptions and sees a possibly helpful role in some preconceptions that might function as so-called anchors (see section 2.3.3). Of course failing to make use of these potentially helpful anchors in traditional education would then also account for its poor results.

Intuitive mechanics as knowledge in pieces

DiSessa describes both intuitive mechanics, which he calls an intuitive sense of mechanism, and expert understanding in terms of simple elements abstracted from the different ways in which things and events appear to us. These elements are called 'phenomenological primitives', abbreviated to p-prims. An example is *Ohm's p-prim* which is described as "an agent or causal impetus acts through a resistance or interference to produce a result. It cues and justifies a set of proportionalities, such as 'increased effort or intensity of impetus leads to more result'; 'increased resistance leads to less result.' These effects can compensate each other; for example, increased effort and increased resistance may leave the result unchanged" (diSessa, 1993). Another example is *springiness (spring scale p-prim)*: "objects give under stressing force. The amount of give is proportional to force" (ibid. p. 221).

The difference between intuitive and expert mechanics is seen as largely a matter of degree of organisation of already existing p-prims. In intuitive mechanics these p-prims are so weakly organised that one cannot call intuitive mechanics a theory, in expert mechanics they are systematically organised. "It happens that Newtonian mechanics is, by and large, relatively compatible with the naïve sense of mechanism. This provides a great opportunity to develop expertise by revamping naïve knowledge, both to encode basic laws and to connect those laws to specific situations" (ibid. p. 190). Failing to make productive use of this opportunity accounts for the poor results of traditional education in mechanics.

Intuitive mechanics as compatible with Newtonian mechanics

Dekkers also attributed the well-known learning difficulties concerning the concept of force to the inadequate way students' prior knowledge is taken into account. His research shows a shift in the analysis of the intuitive mechanics as potentially harmful to potentially useful. At first, based on a problem analysis in which the intuitive mechanics was seen as a potentially harmful alternative theory, he used a conflict strategy to replace this alternative theory with the Newtonian one. Students were then seen not to base their answers on either alternative or Newtonian concepts, which led him to question his problem analysis.

Partly based on the work of Klaassen (1995) he concluded that the usual misconceptions like 'motion implies a force' are inadequate representations of the students' beliefs. In his interpretation of the student conception of 'force', "the students believe that a 'force' is needed to start the motion of an object, that a 'force' is needed to keep an object moving, and that a moving object exerts a 'force' on another when it is stopped by that object. […] Note that, in real situations with friction, the given beliefs resemble scientific beliefs about the scientific concept of force. […] Those ideas need refinement, but have the *potential* to become the basis for development of the physics concept of force" (Dekkers & Thijs, 1998). Hence "students do not have beliefs about familiar situations that are incompatible with scientific beliefs", and therefore "[c]onceptual replacement […] is not an adequate strategy to foster conceptual growth for the topic under consideration" (ibid. p. 31). Thus, Dekkers rejected his initial problem analysis and reanalysed the nature of students' intuitive mechanics as compatible with Newtonian mechanics and therefore potentially useful. The difference between novice and expert mechanics Dekkers sees in the different degree of differentiation of the concept of force. "[T]he students do not (feel a need to) differentiate between concepts in the same way a scientist would. […] [T]he students in this study often did not differentiate between "force" and the "something" given to an object at the start of its motion […]" (ibid. p. 41).

2.2.2. Neglect of epistemological[3] commitments in teaching

Hewson adheres to a conceptual change perspective as expressed in the theory of Posner (1982). He tried to show “that it is essential that any student who wishes to learn science should hold strong epistemological commitments to generalizability and internal consistency” (Hewson, 1985). He claimed to have identified several instances in which these epistemological commitments were absent and that therefore learning failed, in the sense that the required conceptual conflict was not recognised by the student.

> “It is important to note how essential the epistemological commitments of the student are to conceptual conflict. Without an epistemological commitment to internal consistency, the conflict will not be recognised. Without an epistemological commitment to generalizability, the conflict will not lead to the rejection of an alternative conception” (ibid. p. 168).

He therefore claims to have identified a necessary but not sufficient condition for conceptual change, which traditional education unjustly assumes can be taken as satisfied.

Hammer and Elby suggest a similar shift in thinking about students’ epistemological notions as in thinking about the nature of intuitive mechanics. As was mentioned earlier a reaction on viewing learning mechanics as replacing the ‘stable alternative wrong theory intuitive mechanics’ was to view it as reorganising the already existing elements of the ‘knowledge in pieces intuitive mechanics’. Hammer and Elby suggest not to view students’ epistemological notions as stable, wrong and to be replaced, and instead adopt the view in which learning productive epistemological notions is seen as reorganising already existing epistemological elements which they call epistemological resources (Hammer & Elby, 2003).

Hammer and Elby identify the problem in mechanics as follows:

> “Students who have difficulties often view physics knowledge as a collection of facts, formulas, and problem solving methods, mostly disconnected from everyday thinking, and they view learning as primarily a matter of memorization. By contrast, successful learners tend to see physics as a coherent system of ideas, the formalism as a means for expressing and working with those ideas, and learning as a matter of reconstructing and refining one’s current understanding” (ibid. p. 54).

These respective ‘views on physics’ reflect different epistemological notions, according to Hammer and Elby. The poor results in traditional mechanics education are attributed to its failure to address students’ notions of knowledge. The key factor they identify in these notions is what they call ‘principled consistency’.

> “Ultimately, success in learning physics requires students to embrace a principled theoretical framework – here Newton’s Laws of Motion. Although

[3] Epistemology is an area of philosophy concerned with the nature and justification of human knowledge.

traditional courses presume that students understand and value principled consistency, evidence shows most do not, at least not in the context of introductory physics" (ibid. p. 71).

Does this mean Hammer and Elby think students are inconsistent? They do think students have the epistemological resources to spot and reconcile inconsistencies. How can and why would they be knowingly inconsistent in physics? Their answer is that "[s]tudents abide inconsistencies in physics class, because, instead of applying those 'reconciliation' resources, they are applying other resources that are useful in other circumstances" (ibid. p. 68). Students would apply other resources because in most problem solving the objective is to arrive at an answer, for which reconciling inconsistencies in one's understanding is not always necessary, so they argue. Problem solving or thinking about questions in physics is for developing coherent understanding, not primarily for arriving at answers. Therefore "[t]he instructional task, on this view, is to look for reconciliation resources elsewhere in students' experience. In what contexts, we ask, might students naturally understand *the need* to reconcile inconsistencies?" (ibid. p. 69; italics ASW)

Although much more research on students' epistemological notions has been done[4], I think it is generally of not much use for the topic of analysing the problem of poor educational results in mechanics.

2.2.3. Lack of attention to process in teaching

Apart from inadequate attention to students' pre-educational notions, be they about mechanical content or about the nature and justification of knowledge of mechanics, another cause for the lack of understanding in mechanics is seen in poor consideration of process knowledge in mechanics education. Process knowledge in mechanics, in contrast to factual knowledge, concerns explicitly the ways of doing mechanics. It consists of strategies and techniques for developing, validating and utilising factual knowledge. Applied generally to research this can be called 'the scientific method' and

[4] There are different reasons for looking into epistemology. I will mention four of them: 1. Driver et al. show how the different arguments for the importance of scientific literacy as an educational goal require an explicit understanding of the nature of science (Driver, Leach, Millar, & Scott, 1996) p. 15-23. 2. Developing an argued epistemology can be considered a worthwhile educational goal in itself. So research into epistemological change or development is useful. This development was studied by e.g. Grosslight (1991) by investigating students' understanding of models. A concrete way of teaching epistemological awareness is described by Meyling (1997). 3. There might be an influence of a particular epistemological stance on cognitive processes. Hewson investigated the connection between epistemological commitment and conceptual change. How epistemological assumptions influence thinking and reasoning processes was studied by Kitchener with a focus on reflective judgement, by Kuhn with a focus on skills of argumentation and by Schommer with a focus on comprehension and cognition for academic tasks (Hofer & Pintrich, 1997) and references therein. 4. Epistemological stances are believed to have an influence on classroom management (Yerrick, Pedersen, & Arnason, 1998). Only the third point about the connection between epistemological stance and conceptual change is related to the problem analysis of lack of understanding in mechanics.

applied more restrictedly to questions or textbook problems it can be called ‘problem solving skills’.

Hestenes is quite explicit in his problem analysis of traditional education in mechanics. He attributes the unsatisfactory outcome of instruction in physics at least partly to inadequate attention given to procedural knowledge.

> “[T]he usual textbook treatment of procedural knowledge is almost totally inadequate, consisting of little more than platitudes about the power of scientific method and off-hand remarks about problem solving. Students are left to discover essential procedural knowledge for themselves by struggling with practice problems and observing the performance of professors and teaching assistants” (Hestenes, 1987).

Two readily recognisable features of lacking proper procedural knowledge is adopting rote learning and plug-and-chug problem solving. Students can be reinforced in a plug-and-chug approach because it is often successful. Students can get points on an exam by writing down the correct formula, which they sometimes can find just by looking at the variables in a problem[5]. This results in students who have learnt a bunch of unrelated facts in the end.

Another line of argument of Hestenes that can also be found in Raghavan & Glaser is that successful problem solvers (like scientists) “possess a substantial, hierarchically organised knowledge base and typically resort to qualitative model-based reasoning to analyse and explicate real world phenomena” (Raghavan & Glaser, 1995). Model-based reasoning is lacking in traditional education and might therefore account for its poor results.

2.3. Approach

Approaches to overcome the identified problems in mechanics education can be organised in a spectrum ranging from theoretical to practical. Three kinds of approaches (and some variations of each kind) can be distinguished that are expected to be of assistance in overcoming the identified problem. The first kind tries to develop a general theory of conceptual change (diSessa, 1993; Posner et al., 1982), the second kind formulates general implications for education (Hestenes, 1987) and the third kind develops education (Clement, 1993; Dekkers & Thijs, 1998; Hammer & Elby, 2003).

The first kind of approach, developing a general theory of conceptual change, is in itself not a solution to the problem. A theory of conceptual change still needs to be applied, which is very difficult and can also be a topic of research (concerning what a successful application consists of). However, it can inspire people to take this as a starting point for further development or even point in a possibly fruitful direction by giving some general implications for education, which is the second kind of approach.

[5] This observation is probably quite recognisable for anyone who has spent some time in education. A terrible rule in Dutch exams, for instance, is that all given data in a problem must be useful. It is not allowed to toss in a couple of irrelevant variables.

By the second kind of approach, formulating general implications for education, I mean the kind of advice that is sometimes given in the final section in journals on (science) education. Sometimes it consists of a logical extension or first application of the developed theory, like in the case of McCloskey who suggested:

> "Thus, it may be useful […] for physics instructors to discuss with students their naïve beliefs, carefully pointing out what is wrong with these beliefs, and how they differ from the views of classical physics. In this way students may be induced to give up the impetus theory and accept the Newtonian perspective" (McCloskey, 1983).

Although in the best case indications for a solution to the problem are given, in itself it is not a solution.

Sometimes the implications for education are so extensively described and argued for that they are considered to be quite readily applicable to education. For instance the approach developed by Hestenes is considered to be applicable by teachers (after some teacher training in a series of workshops) in their own classrooms.

Finally the third kind of approach, developing education, tries to find a solution to the problem by spelling out concrete education, which is considered to remedy the problem.

In this section I will present some approaches to the problem of lack of understanding in mechanics that try to provide a solution. I will therefore restrict myself to the third kind of approaches but also include the approach of Hestenes that, although it is categorised under the second kind, does claim to provide a solution. I will present the approaches in following order: I start with 'overcoming misconceptions', continue with 'providing adequate attention to process in teaching', then 'building on useful intuitive notions by means of bridging', then 'restructuring potentially useful intuitive notions', and finally 'making productive use of epistemological resources'.

2.3.1. Overcoming misconceptions

Hestenes' problem analysis consists of two elements, the problem of misconceptions and the problem of attention to process, as was seen in section 2.2. Hestenes does not emphasise any relationship between these problems and in his approach of dealing with these problems the elements concerned with either problem can be considered separately, which will be done here.

The Hestenes approach consists of formulated implications for education. It deals with preconceptions by means of a dialectic teaching strategy later called modified Socratic method (Hestenes, 1987). This strategy involves the following elements: 1. Explicit formulation of common sense beliefs, invited by well-chosen problems. 2. Check for external validity: Is the belief consistent with empirical data? 3. Check for internal consistency: Does the belief contradict other beliefs? 4. Comparison with other beliefs including the scientific one. Given his problem analysis described earlier this strategy does seem quite obvious[6]: It makes the difference between the intuitive and Newtonian mechanics explicit and points out why the Newtonian should be preferred (namely

[6] It is of course not obvious how this should be done in detail in real life education.

consistent with observations and other beliefs), thereby providing a cognitive conflict which can be resolved by adopting a recognisably superior alternative.

The question remains how this strategy should be implemented which is not said in the quoted article. One way of implementing it was developed by Wells which I will present here and discuss later in more detail (Wells, Hestenes, & Swackhamer, 1995). Wells used a taxonomy of misconceptions for planning the lessons. He "prepared an agenda of misconceptions to be addressed in connection with each activity. This preparation sensitised him to opportunities for addressing misconceptions in the course of student presentations and discussions" (ibid.)

In his implementation the role of the so-called Socratic teacher is important. This is someone who manages group discussions, corrects student ideas by posing questions and at the same time guards the quality of the learning process and is very unobtrusive. His role is especially important in so-called post-mortems. Although never defined, I think Hestenes uses the term post-mortem for a teacher-guided reflection on an activity, like an experiment or solving a textbook problem, in which the teacher proposes the right Newtonian outcome for consideration by the students. Post-mortems are seen as activities in which the most significant learning can occur. A special moment in post-mortems is when "Students are thrilled when they (…) understand how all the models in mechanics can be generated by a single theory". An important ingredient of the Hestenes - Wells approach is therefore connected to teacher related skills like: being able to choose the right models or problems to work with considering the specific conceptions of the students at that time and being able to conduct a successful post-mortem.

The method used by Wells can be described as cooperative inquiry with modelling. The cooperative inquiry element consists in the method being student-centred, activity oriented and lab-based (70 % of the time). The modelling element is expected to take care of the identified problem of lack of attention to process, to which I will turn now.

2.3.2. Providing adequate attention to process in teaching

Hestenes - Wells' modelling approach consists, I assume, of developed education since Wells taught classes with it. Reported are only implications for education, however. I will therefore treat it as an approach of the second kind, i.e. formulating educational implications. The approach organises the course content around a small number of basic models, like the 'harmonic oscillator' and the 'particle subject to a constant force', that describe basic patterns in physical phenomena. Students apply those in a variety of situations. "Explicit emphasis on basic models focuses student attention on the structure of scientific knowledge as the basis for scientific understanding." Other elements of the approach are use of an explicit definition for the concept of model and theory, an extensive discussion of qualitative reasoning and representational tools like force diagrams and motion maps, and making use of a modelling cycle which characterises specific modelling stages and thereby makes explicit some procedural knowledge. The teacher sets the stage for each new question "to be asked of nature". Students collaborate in small groups in planning and conducting experiments and later present their conclusions and evaluate their models by comparison with data. These exchanges result in post-mortems in which the Socratic teacher plays an important part.

The building of models follows a procedure which makes use of Hestenes' modelling theory (Hestenes, 1987). This describes four stages in modelling: description, formulation, ramification and validation, see Figure 1.

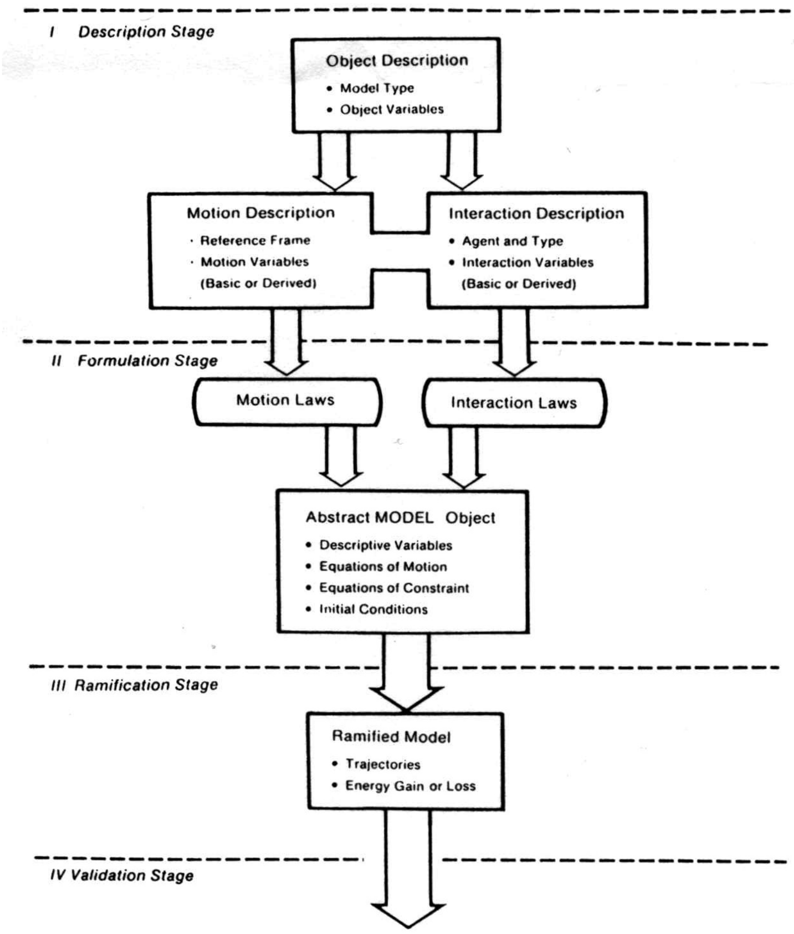

Figure 1: Schematic depiction of model development in mechanics according to Hestenes.

In the description stage the object, motion and interaction is described. Other tools like motion maps or force-diagrams are also explicitly used here. In the formulation stage the relations between the variables is put into mathematical equations. Specific calculations with these equations lead in the ramification stage to certain outcomes. The ramified model is then validated in the validation stage.

> "It is the whole model that needs to be evaluated when a solution is checked. As long as students regard the solution as a mere number or formula, the only way they have to check it is by comparison with an answer key. The approach I am advocating here is aptly characterised by the slogan THE MODEL IS THE MESSAGE" (ibid. p. 446).

For problem solving this modelling strategy is supplemented by some additional procedural knowledge in the form of a model deployment strategy: develop a suitable model of the situation specified by the problem and then ramify the model to generate the desired information. This strategy is further elaborated in deployment tactics as (among other things): extracting information, representing information in a schematic form, formulating the goal, determining relevant theory, selecting model types and checking results.

In this way procedural knowledge is made explicit in several ways. Application of the basic models is guided by a model deployment strategy. Also the general model specification (the definition of the concept of model) and the representational tools can be seen as explicating procedural knowledge. The type of questioning by the Socratic teacher also emphasises the procedural aspects. It remains unclear to me, however, how these ‘tools’ (deployment strategy, deployment tactics, model specification and representational tools) were put to use in the classroom. The articles do not mention it and I was unable to find further clues. Even teaching materials on the internet (http://modeling.la.asu.edu/modeling.html) only show the tools and not how they were used.

2.3.3. Building on useful intuitive notions by means of ‘bridging’

Clement (1993) developed education in which he tries to take account of intuitive mechanics by identifying several correct intuitive notions which he calls ‘anchors’ and builds from those to scientific notions which he calls ‘targets’. For the step from anchor to target to be made successfully by the student, it is necessary to make one or more steps in between anchor and target. This is called ‘bridging’. See for an example from Brown (1994) Figure 2.

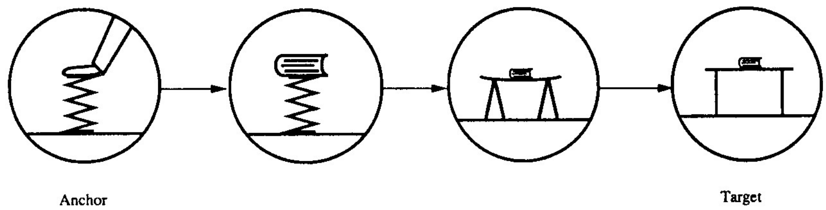

Figure 2: Example of Clement’s bridging method

The ‘target’ is the notion that a table exerts an upward force on a book lying on it. This target is reached by starting from an ‘anchor’ situation in which a hand pushes down on a spring, which pushes back on the hand, via several bridging situations like a book on a spring and a book on a flexible board resting on two sawhorses. The final argument is that “the table is composed of molecules which are connected to other molecules by bonds which are ‘springy’ ”. Therefore the table reacts very much like a spring to the book and does therefore exert a force upwards on the book.

Besides use of anchors, bridges and targets other general features of the lesson series developed by Clement were that open discussions about beliefs about a physical situation were encouraged, beliefs were also voiced by regular voting and empirical demonstrations "were used occasionally to disequilibrate students' alternative conceptions or to support an aspect of the analogue model".

2.3.4. Restructuring potentially useful intuitive notions

Dekkers also developed education. He shifted from a potentially harmful to a potentially useful perspective on intuitive mechanics, as was mentioned in section 2.2. The corresponding education he designed expresses this shift. Before the shift he designed a lab experiment using a pulled trolley. By measuring the forward and backward forces on the trolley students can find out that they are equal irrespective of the constant speed at which the trolley moves. This was expected to conflict with the alternative conception of 'motion implies a force', which would be resolved by students' adopting the Newtonian concept. This resolution was seen not to occur.

> "[T]he students do not (feel a need to) differentiate between concepts in the same way scientists would. [T]he students in this study often did not differentiate between "force" and the "something" given to an object at the start of its motion according to physics. […] [I]f these concepts are not differentiated, a confrontation between them is neither possible nor meaningful" (Dekkers & Thijs, 1998).

After his shift in perspective Dekkers designed activities that preceded the lab experiment and intended to provide the means for students to resolve the conflict when they did the lab experiment later. In these activities three conditions for establishing the presence of a force were introduced, namely the presence of force requires an interaction between two objects, the potential to exert force is not itself a force, and if a force exists, its magnitude can be measured and is not zero. If students have accepted these conditions as their own before experiencing the conflict they can resolve it in the intended way. The revised teaching sequence consists of the following topics:

- The word 'force' refers to a multitude of real things, but in physics forces need to be measurable.
- There is no 'force of motion' as illustrated by motion without (observable) friction.
- Forces require interaction. Illustrated with magnet and piece of iron. Hand as first instrument to detect forces.
- Analogy of handshake for principle of interaction.
- Quantify forces by using spring-balances.
- Trolley lab experiment.

> "[T]he educator's main challenge is not to make students aware that they have incorrect ideas, but to make them aware of the context dependence of their statements and create in them a need for conceptual differentiation. To perceive

the "alternativeness" of their conceptions *and* to resolve the dissonance they experience, students need the very same conceptual "tools". Therefore, students should be provided with the means to resolve dissonance *before* that dissonance occurs. Analysis of students' conceptions shows that these means were implicitly available in their existing knowledge", namely "the students' life-world knowledge that, in certain contexts, the presence of a force requires two objects, each exerting a force on the other" (ibid.).

Dekkers' approach aimed at restructuring the 'already implicitly available means' in the sense of refining them and making them applicable to a wider range of contexts.

2.3.5. Making productive use of epistemological resources

Hammer developed an introductory course in physics to help students understand and approach learning science as a 'refinement of everyday thinking'. The basic idea is that students already have epistemological resources (the epistemological equivalent of p-prims) concerning the source of knowledge (like knowledge as propagated stuff or knowledge as fabricated stuff), concerning epistemological activities (like checking), concerning epistemological forms (like rules, facts or games) and concerning epistemological stances (like acceptance, understanding or puzzlement). In physics some resources are considered to be more productive than others. For instance, students who think of learning physics as absorbing information from authority use the resource 'knowledge as propagated stuff' when 'knowledge as fabricated stuff' would be more productive. The educational challenge in this example lies in promoting use of the resource 'knowledge as fabricated stuff' *these students also have, but use in different contexts*, in learning physics as well.

The course starts by teaching students to write essays on some problems following the structure argument, counter-argument and response to the counter-argument. It then follows with three successive main topics:

1. Developing an awareness of everyday thinking.
2. Learning to refine everyday thinking.
3. Developing and committing to a principled framework.

Students' intuitions are triggered in a number of inventive ways and used in explaining motions. By writing essays and discussions on these explanations these intuitions are not discarded but reconciled with other intuitions, but not yet with the Newtonian explanation.

2.4. Method and results

Most of the projects mentioned in the preceding sections were evaluated, although sometimes only a selection of the initially stated goals was assessed. Research methods used for these evaluations can be divided in two groups. The first group is primarily concerned with either cognitive or affective outcomes of a course and follows a pre-post test model in which mostly quantitative data in the form of questionnaires before and after the intervention (the course) is collected. The second group is primarily concerned with what goes on during the intervention and collects mostly qualitative data in the form of observations, interviews, worksheets, et cetera.

In this section I will present the research method and results of the projects that were presented in the preceding sections. These will be critically discussed in section 3.4. This presentation is organised around the goals for mechanics mentioned in section 2.1. I will start with the common goal in all projects, namely that of understanding the conceptual structure of mechanics, and describe how this goal was evaluated in PSSC, HPP, Nuffield, PLON, the Hestenes – Wells approach, bridging approach and restructuring approach. Secondly the evaluation of the additional goal of illustrating the humanistic enterprise of physics in HPP, PSSC and Nuffield will be described. Thirdly I will present the evaluation of the goal of raising the motivation for mechanics in PLON. The evaluation of the additional goal of illustrating 'science at its best' in HPP cannot be described, since it did not take place to my knowledge.

Evaluation of the goal of understanding the conceptual structure of mechanics

I start by describing the evaluation of the goal of understanding the conceptual structure of mechanics and will first turn to PSSC, HPP and Nuffield.

PSSC, HPP and Nuffield

What the three main curriculum projects from the sixties and seventies, PSSC, HPP and Nuffield, have in common is that they were all primarily suited for the academically inclined students. They were courses of 'physicists' physics' (Bounds & Nicholls, 1988) and for this group not particularly successful or unsuccessful. For instance Welch (1973) reported in a review of about 60 articles on the evaluation of HPP that "no significant differences [between HPP and comparison groups; ASW] were found on the three cognitive measures of the study". These cognitive measures were three pre- post tests: a physics achievement test, 'Test on Understanding Science' and the 'Welch Science Process Inventory' (Welch, 1973).

Another outcome of the evaluation of these projects was a growing interest in what the learning difficulties in physics in general and mechanics in particular were. This can be seen as one of the triggers of the extensive investigation of conceptual problems in the 'alternative conceptions' research wave at the end of the seventies, the eighties and beginning of the nineties. (An overview of the historical developments in physics curricula can be found in Lijnse (1997).)

PLON

As was the case with PSSC, HPP and Nuffield, also the PLON mechanics course did not result in better or worse conventional physics learning-outcomes than a control group. This was established by means of a pre- post test design using a physics test, learning reports and a text construction test (Wierstra, 1990).

Hestenes – Wells approach

Comparisons on Mechanics Diagnostic and a problem solving test[7] scores between Wells' modelling method (which includes cooperative inquiry elements), cooperative inquiry and traditional education show considerable improvement of the modelling method over cooperative inquiry, which suggests that the cooperative inquiry elements included in the modelling method are not the important factors, and traditional education. The modelling method results are the best by far. Wells' (experimental) high school group showed increases of 36% on the Force Concept Inventory and performed better on the Mechanics Baseline than university students (Wells et al., 1995). The 'Force Concept Inventory' (FCI) is a 29 items multiple-choice questionnaire mostly on identifying and estimating forces (force A is bigger/smaller/… than force B et cetera) and contains also some questions on kinematics. It was developed to measure which 'alternative conceptions' were held by the tested person in the domain of mechanics (Hestenes, 1992). The 'Mechanics Baseline' (MB) test is a 26 items multiple choice questionnaire that can be considered as a rather normal (though quite difficult) mechanics problem solving test (Hestenes & Wells, 1992). No systematic classroom research was done. Some classroom observations are presented for illustrative purposes. The emphasis lies on the learning outcomes as measured by the FCI and MB, which were used in the pre- post test.

Bridging approach

The experimental group in Clements bridging approach showed 28% larger gains (post-test score minus pre-test score) than the control group on the test used (Clement, 1993). Observations showed that "some students changed their minds toward the physicist's view during each major section of the lesson, e.g. after the anchor, bridge, model, and demonstration sections, leading us to hypothesise that each technique was helpful to some subset of students".

Clement stated quite specific content and process goals for his teaching strategy. These can be seen as elaborations of the general goal of understanding the conceptual structure of mechanics. Observations were made to establish to what extent these goals were reached, but only conclusions from these observations were reported. For instance one of the goals stated for the developed course was that students actively participate in intellectual discussions. Another goal was that students generate analogies and explanatory models. Observations from video tape showed that "students generated several types of interesting arguments during discussion, such as: generation of analogies and extreme cases of their own; explanations via a microscopic model; giving a concrete example of a principle; arguments by contradiction from lack of a causal effect; generation of new scientific questions related to the lesson; and even spontaneous generation of bridging analogies. This last observation gives us reason to believe that even though the lessons were designed primarily with content understanding goals in mind, some process goals were also being achieved as an important outcome" (Clement, 1993). Apparently Clement is satisfied that both goals

[7] Mechanics Diagnostic was a precursor of the FCI and the problem solving test was a precursor of the Mechanics Baseline test.

(that were given as example above) were reached. In the cited article the pre- post test results and method are more extensively discussed than the observations.

Restructuring approach

Students did seem to have learned the interaction aspect of the force concept:

> "In the 1993 classes, where the initial sequence was used, all arguments against a 'force of motion' based on the absence of interaction were forwarded by the teacher. Students did not remember these arguments in interviews conducted later. Our assumption that these arguments could be developed by the students *from* or *after* the conflict experience turned out to be erroneous. In all classes using the revised sequence, however, students forwarded such arguments by themselves. Most students did remember these arguments in later interviews (Dekkers, 1997). The quality of the discussions had substantially improved in the 1994 period of research [with the revised sequence; ASW], even when debates were still heated and students still had many conceptual problems" (Dekkers & Thijs, 1998, p.46).

Apart from observations also a pre- post test was used. This test consisted of 11 test items (of which 3 were multiple choice) on identifying and comparing forces acting on uniformly moving objects or on projectiles. Test scores showed a 41% increase after the practical and 65% increase two months later. Answer patters showed consistent use of one, namely the Newtonian, concept.

Dekkers used and reported qualitative data besides his pre- post test to a much further extent than the previously mentioned researchers. Apart from learning outcomes Dekkers was interested in the process of conceptual development for which classroom and small group observations, interviews, collected homework assignments, worksheets and audio recordings of salient discussions were used. One of his aims for instance was to provide cognitive dissonance with the trolley practical and he describes the qualitative data to show that this cognitive dissonance did in fact occur.

Evaluation of the goal of illustrating the humanistic enterprise of physics

I will turn now to the evaluation of the goal of illustrating the humanistic enterprise of physics. The humanistic nature of physics can be seen in its history, changing nature or development and emphasis on inquiry. The first two elements seem to be recognised by students. For instance Welch (1973) reported that: "Students in HPP find the course more satisfying, diverse, historical, philosophical, humanitarian, and social" (p. 375). This was found by identifying variables that discriminate between HPP and other courses and using those variables to assess the effects of the course.

The element of inquiry was harder to get across. One of the reasons was the unfamiliarity of teachers with this element. "Courses such as PSSC and HPP, which emphasise open inquiry and the provisional character of scientific knowledge, place greater demands on teachers than does a more traditional course, and this too has taken its toll" (French, 1986). The toll was taken in the form of teaching the course in ways that were not intended. Another reason, mentioned in relation to the Nuffield project, was that the usual assessment of practical work did not promote inquiry, but emphasised the *product* of practical work instead of the process (Bounds & Nicholls, 1988).

Evaluation of the goal of raising motivation

Finally I turn to the evaluation of the goal of raising motivation. When asked to compare and rank the different PLON topics (on traffic (=mechanics), electronics, music, weather changes and others), students appreciated the lessons on mechanics more than the other PLON topics. Teachers that taught the PLON courses indicated in a questionnaire that students found the topic of mechanics interesting and not too technical. Remarks of some students that were asked to keep a logbook during the course gave some indications of appreciation (Genderen, 1989). A comparative study of the PLON mechanics course and a 'traditional' course indicated that the PLON aim of raising motivation by showing the relevance of mechanics for the daily life of the students was not met. Students do consider the PLON lessons to be more concerned with daily life and participated more in the lessons. However, this stronger emphasis on daily life and participation did not result in more appreciation of the lessons in mechanics. As was the case with the goal of understanding mechanics, this was established by means of a pre- post test design using a physics test, learning report and a text construction test (Wierstra, 1990).

The other way of raising motivation by emphasising the theoretical challenge of mechanics used in Advancing Physics is not yet systematically evaluated at the time of writing.

3. Critical discussion

In this section relevant research that was presented in section 2 will be critically discussed around the same four focal points: goals, problem analysis, approach and method & results.

3.1. Goals

In this section I return to the spectrum of goals that were aimed at in several curriculum development projects. The goal of 'understanding mechanics' is so obvious that it is sometimes considered to be unnecessary to mention it. What is precisely meant by understanding can of course differ and one can find different emphases in different projects.

Harvard Project Physics' goal of illustrating science at its best with mechanics is from a physicist's point of view quite appropriate. Newtonian mechanics has been one of the great successes of physics or science in general. It can be seen as a prototypical example of capturing natural phenomena in quantitative expressions that have such a wide applicability that they can be called universal laws. The process of capturing natural phenomena consists in the case of Newtonian mechanics in finding appropriate force laws to plug into his second law. By suggesting a force law for gravitation Newton has very successfully implemented this scheme in accounting for the motions of the planets in the solar system. The power and simplicity (one could fit Newton's laws on the back of a bar mat) of this ‘programme’ makes the heart of many a physicist beat faster. Since mechanics is in this sense indeed an example of science at its best, it seems a worthy goal to try to get this message across to students. Although there may be ways to reach this goal for all students, it appears to be more suited for the academically inclined brighter students. A similar estimation also involves the humanistic goal, since elements like inquiry, history and development of mechanics or the specific emphasis on the discipline seem to require inquiring minds interested in experiments, that appreciate the historical development of mechanics, or are attracted by the scientific context: academically inclined minds. What these projects also showed is that some modesty is in order in what one can expect of the extent to which such goals can be reached, even with academically inclined students.

In section 2.1 I mentioned two attempts to increase motivation: showing the relevance of mechanics for daily life and showing its theoretical challenge. The second approach seems to me more promising. Of course Newtonian mechanics led to all sorts of practically relevant things, but these things are as a rule either much to complicated to illustrate the Newtonian basic structure or can be explained without this structure. An example of the latter is the estimation of the magnitude of the force in car collisions in the PLON course by means of the rule $F \cdot \Delta t = m \cdot \Delta v$. By calculating the average force in a collision and measuring the maximum force they can exert by pressing scales students come to the conclusion that safety belts are needed because a person would be unable to stop herself from slamming into the dashboard by muscle force alone. This is an interesting and practical example related to daily life, but does not require the basic Newtonian structure to explain. The mentioned rule suffices. There is no need for students to derive this rule from more basic principles. The force concept itself does not have to be elaborated. A notion of ‘force’ as a measure of ‘muscle force’ suffices. One can of course be content when students are able to apply some derived rules like the one mentioned without knowing their background and argue that for some students this would be the maximum that can be achieved, but such a result cannot be called ‘understanding mechanics’ in the sense of knowing how explaining motion works.

The goal of raising motivation by emphasising the theoretical challenge is more in line with what mechanics really is. One can even argue that this theoretical orientation towards mechanics is more relevant for the daily life of academically inclined students than the practical orientation discussed above. When asked to select physics topics they want to know more about from a list of topics, including some that are not part of standard curricula, quite some students would choose quantum mechanics, special relativity and astronomy. This choice should not be surprising because these subjects are frequently talked about on television and in magazines. In this sense they are more part of those students’ daily life than learning about traffic (to name one practical topic). The unknown, like quantum mechanics, sounds considerably more appealing to learn about than the known, like traffic.

3.2. Problem analysis

In this section I will critically discuss the three problem analyses presented in section 2.2, neglect of intuitive mechanics, epistemological commitments and explicit attention to process in teaching. The first of the three kinds of these problem analyses stated that students' notions on mechanics are inadequately taken into account. There were differences in opinion as to whether these notions were potentially useful or a hindrance. Before such differences can be settled, however, first the following question must be answered: What is the content of students' notions and on what ground is this concluded? A central point in my discussion of the problem analyses will be that this question is not satisfactorily answered, because of a neglect of what I call the interpretation problem. This interpretation problem is about the difficulty to determine what someone believes based on what she says (or writes) when one can not assume that all words are understood in the same way by the interpreter and the person who uttered the words. This problem occurs always in communication, but most of the times is easily solved. In the case of talk using the word 'force' solving this problem takes somewhat more care. I will now elaborate on the interpretation problem in the context of mechanics to further explain what the problem is about. My account is based on Klaassen (2003). See also (Dekkers, 1997; Dekkers & Thijs, 1998; Klaassen, 1995; Klaassen & Lijnse, 1996; Klaassen, 2003)

Neglect of the interpretation problem

The conclusions of studies concerning children's pre-instructional theories of motion, like the ones discussed in section 2.2 by McCloskey (1983) or Hestenes (1985) or others like Clement (1982) or Gunstone (1985) are well known. It is reported that children (or, more generally, lay people) seem to operate with basic intuitive notions such as:

- A force is needed in order to set an object in motion.
- Sustained motion needs a continuous force.
- Force and motion are proportional to one another. More force has to be exerted in order to set an object in a faster motion or to sustain a faster motion.
- If an object is in motion, it has a force in the direction of its motion.
- If there is no continuous supply of force, the force of an object wears out.
- Forces can be imparted by agents and transferred from one object to another.

Perhaps it is worthwhile to give a few examples of what children or lay people actually say, in order to see in what sense they say can be said to hold this intuitive theory. Here are some examples of what children in the age group 11-14 say (I have taken the quotes from the paper by Gunstone & Watts).

> 'If he wanted to keep moving along ... he would have to keep pushing, otherwise he'll run out of force and just stop.'
>
> 'To keep going steadily you need a steady push. If you don't force something to move it's not going to go along is it?'
>
> 'Why do they [things rolling along the floor] stop? It's just they always stop. After you push it they go as far as the push ... how hard it was, and after that wears off it just goes back like it used to be.'

Note that those children do not always frame their ideas in the exact words of the above intuitive theory. The step, however, from ‘If he wanted to keep moving along he would have to keep pushing’ or ‘To keep going steadily you need a steady push’ to ‘Sustained motion needs a continuous force’ seems a very small one. So it is plausible to assume that they themselves might as well have expressed their idea by an utterance of the latter sentence, or at least have assented to an utterance of it. Similarly, they might as well have said: ‘Force and motion are proportional to one another,’ instead of, or as a generalisation of: ‘After you push it they go as far as the push ... how hard it was.’ There are also cases in which their wording (e.g., ‘he’ll run out of force’ or ‘[the push] wears off’) is already pretty close to the above intuitive theory (‘the force of an object wears out’). Another familiar case (cf. Clement, 1982) is that students, when asked to draw the forces that are present when a tossed coin is in its upward motion, draw an upward force which they call, e.g., ‘the force I’m giving it’ or ‘the force of throwing the coin up.’ This comes pretty close to ‘if an object is in motion, then it has a force in the direction of its motion’ and ‘forces can be imparted by agents’.

So although children do not always frame their ideas in the exact words of the above intuitive theory, they can be said to hold the above intuitive theory in the sense that they either do express their ideas in pretty much the wording of the intuitive rules, or else might at least have done so. What follows from this? In particular, can it be concluded whether or not the intuitive theory is at variance with the principles of Newtonian mechanics? Of course, I agree that a statement such as ‘Sustained motion needs a continuous force’ seems to be contradictory to Newton’s first law, and that in Newtonian mechanics an expression like ‘to have a force’ is meaningless. But does it follow from this that the intuitive theory contradicts Newtonian mechanics? I think not. Consider the target sentence:

S. Sustained motion needs a continuous force.

Children and lay people would assent, we have assumed, to (S) and Newton would dissent from it. This would only imply that they contradict one another, however, if all parties understood (S) in the same way, i.e. if there was identity of meaning. But *does* students’ pre-instructional conception of force, in particular, match the mature Newtonian concept? Most researchers probably hold that it does not, and I agree. But most researchers leave unsettled what students’ pre-instructional conception of force is. As a consequence they also leave unsettled what children and lay people believe when they assent to (S). As long as all of this is unsettled, the question whether their belief contradicts any of Newton’s beliefs is premature. First the interpretation problem must be solved.

The problem of interpretation, despite quite common implicit recognition that it is a problem that obviously needs to be solved, is hardly ever explicitly mentioned, let alone properly solved. Reports in which children’s or lay people’s intuitive theories are formulated in scientific terms cannot be expected to have solved the problem. At best such reports are to be read as stating the problem. They merely bring out that the way in which some scientific word is used by children or lay people is not in accordance with how the word is used in science, and *therefore*, I would add, most likely is not to be interpreted in accordance with that scientific usage.

Before looking in more detail into the earlier presented problem analyses, which, I think, do not solve the interpretation problem, it may be useful to first formulate some alternative intuitive rules in which the word 'force' is omitted. I think this is not too difficult. For when I read what children say about familiar situations in which some object was in motion, usually after it had been kicked, pushed, thrown, etc, by some agent, I have the feeling that I understand perfectly well what they are trying to tell about them. When riding my bike I have to keep pedalling to keep moving; if I were to stop pedalling, I would come to a stop; the harder I throw something, the farther it gets, etc. Put in somewhat more general terms, I would give the following as some basic intuitive rules that all of us (not just children or lay people) operate by.

- Agents can make an effort to cause something to happen, for instance set things in motion (throw a ball, ride a bike, …).
- The more effort you make, the more effect you beget (throw the ball further away, ride the bike faster, …).
- To keep things in motion you have to keep making an effort (keep pedalling, keep pushing, …), otherwise they will, eventually, come to a stop (if I stop pedalling me and my bike will come to a stop, …).
- The motion of an object can also cause something to happen (the motion of a ball can cause the breakage of a window, the motion of another ball, ...).
- A faster motion of an object can cause an increased effect (a very fast motion of the ball may cause the breakage of several windows, a faster motion of the other ball, ...).

Note that such rules are *common ground* for students, lay people and physicists. A physicist does agree, for example, that when riding a bike on a flat road one has to keep pedalling in order to keep going steadily, and that otherwise one would come to a stop. Without pretending to now have solved the problem of interpretation regarding the conception of force, the above reformulation may already cast some doubt on the alternativeness of students' conceptions. This discussion of the interpretation problem also served as a discussion of the problem analysis of 'intuitive mechanics as an alternative wrong theory of motion'. The other problem analyses will be discussed in the next section.

3.2.1. Neglect of intuitive mechanics

Let us continue with a discussion of the remaining problem analyses that were presented in section 2.2.1. I will start with the problem analyses of 'intuitive mechanics as compatible with Newtonian mechanics' and 'intuitive mechanics as containing some useful anchors' and argue that they do not solve the interpretation problem. I will then continue with an interpretation of my own which can be seen as a solution to the interpretation problem concerning the force concept. This reinterpretation will be in terms of a so-called 'explanatory scheme' that will be introduced and illustrated. I will then use this explanatory scheme in a discussion of the remaining problem analysis of 'intuitive mechanics as knowledge in pieces'.

Intuitive mechanics as compatible with Newtonian mechanics or as containing some useful anchors

In some contexts[8] students use the word ‘force’ where also a physicist would, in other contexts not. In the approach of Dekkers contexts in which the word ‘force’ are used similarly by physicists and students are ‘expanded’ to include more situations. This, however, does not solve the interpretation problem as long as it is not made clear what it is about some contexts, but not others, that make students hold the word ‘force’ applicable. Evidently it is not the physicist’s criteria for holding the word ‘force’ applicable even though in some contexts both his criteria and those of the student are satisfied. So the question remains: what are the criteria of the student? Answering this question is essential for solving the interpretation problem.

The problem analysis which sees potential use in ‘anchors’, raises the same serious question concerning the treatment of the interpretation problem. In this case: What is the anchoring intuition that the students already possess? For instance in the example of a bridging strategy from section 2.3.3 of the upward force exerted by a table on a book the anchoring intuition is that “the spring exerts an upward force on the hand”. But which belief is expressed in this statement? Which criterion for application of the word ‘force’ is used? This is left unsettled and thereby the interpretation problem is left unsolved.

The explanatory scheme

This type of criticism is quite easy and can be continued for more alternative conceptions research. Let me now take a more constructive route and give a shot at interpreting students’ explanations of motion. What makes students think the word ‘force’ is applicable in some contexts and not in others? Take for example the explanation that for keeping speed on one’s bicycle one needs to keep pedalling, because otherwise one would come to a stop. The ‘because otherwise’ indicates an important clue for applying the word ‘force’ or in this case ‘pedalling’. The situation ‘otherwise’ indicates a motion that is well known. In this case coming to a stop is what always happens when a person stops pedalling in practical circumstances when bicycling is used as a means of transport. In this case the actual motion differs from the ‘otherwise’ situation, that is to say keeping speed differs from coming to a stop. It is precisely this difference that calls for an explanation, which is given by identifying a cause in the form of an influence or force, which in this case is the readily available action of the person riding the bike, namely pedalling. Pedalling is a very plausible cause, because one can see where it comes from, namely a person, and one knows it to influence the speed of the bicycle. One has experienced the rule that the harder one pedals, the faster one goes, which is a very strong indication that pedalling influences motion of the bicycle. This example is illustrative for what happens in more (in fact all) explanations of motion. Let me recap in more general terms: What is explained in an explanation of a particular motion by identifying one or more causes (or influences or forces) is a deviation from a motion without these influences, which can be called *influence free motion*. Causes are identified when they are plausible, which means that one has some clue as to where they come from, how they influence the object that

[8] Context is here used in the sense of ‘situation’ as also Dekkers uses it.

deviates from the influence free motion and how they depend on attributes of the configuration in which the motion to be explained takes place.

Whenever a cause for a motion is identified two questions are implicitly answered. Why has there have to be this particular cause? And where does this cause come from? The first question can be answered based on the observed motion and one's assumption for an influence free motion. Take for example three alternative explanations for the (almost) circular motion of the moon around the earth by Aristotle, Kepler and Newton[9]:

> Newton: "A circular motion deviates from rectilinear motion with constant speed (which is the assumed influence free motion). There has to be a force in the direction of the deviation, that is towards the earth. That force is gravity (the identified influence), which pulls on the moon and depends on or is a function of the configuration (i.e. mass of the earth, mass of the moon and distance between earth and moon)".
>
> Kepler: "A circular motion deviates from rest (which is the assumed influence free motion). There has to be a force in the direction of the deviation, that is in the direction of the velocity. That force is some kind of sweeping drag of the earth because of the earth's rotation. This can be thought of as invisible spokes protruding from the earth and dragging the moon along. It depends on or is a function of the configuration (i.e. rotation speed of the earth and distance between earth and moon)".
>
> Aristotle: "A circular motion is the natural motion for heavenly bodies (the assumed influence free motion) and does therefore not need any further explanation".

These explanations illustrate that there is a need to identify an influence whenever a motion deviates from the assumed influence free motion. This does not mean that one is free to choose an influence free motion to one's liking and start from that. One has also to be able to find plausible influences, which was expressed in the second question (where does this cause come from?). For instance the nowadays accepted explanation of Newton was in his time forcibly debated precisely because the notion of an influence that operated from a distance was considered implausible. An inability to identify a plausible influence bears on one's choice for influence free motion. One cannot stick to 'motion with constant velocity' as influence free motion if one were repeatedly to fail in finding some plausible attraction from the earth on the moon. In this way all the elements in an explanation of motion are related. This structure in explanations of motion I call *explanatory scheme* and can be described as an assumption for an influence free motion together with an assumption that deviations from this motion

[9] For the moment it is unimportant if these historical figures really did give such an explanation. Although I think that there are good grounds to claim that they can be interpreted in the mentioned way, here these explanations are simply used to illustrate the common structure in different explanations. If the reader feels more comfortable by attributing these explanations to Tom, Dick and Harry, that is fine by me.

must be accountable in terms of influences that are a function of attributes of the configuration.

Within the boundaries of being able to find a plausible influence free motion and related plausible influences one can make several choices, as was illustrated in the different explanations of the almost circular motion of the moon. Another example concerns the different choices of the student and the physicist and the resulting different (but non-conflicting) explanations for keeping speed on one's bike. The 'expert' explanation of the physicist may aim at theoretical values like generalizability, simplicity and exactness, while the aims of a common sense explanation of the student are related to practical usefulness and may depend on the context. In this way the differences between expert and common sense explanations of motion are seen not so much as differences of belief, but rather as differences of aims and motives.

The examples shown so far were deliberately constructed to highlight the explanatory scheme I think lies behind explanations of motion[10]. Let us now look to some real life examples with this scheme in mind and see how it functions. The following explanations of motions are usually interpreted as alternative conceptions. I will show that they can be reinterpreted as instances of use of the explanatory scheme. This will illustrate the explanatory scheme itself, it will show that an alternative (and better) interpretation is possible and thereby add weight to the earlier criticism of some problem analyses and it will provide a solution to the interpretation problem.

The first two examples are from a paper by Gunstone and Watts (1985) and were already mentioned before. Children in the age group 11-14 say:

> 'If he wanted to keep moving along ... he would have to keep pushing, otherwise he'll run out of force and just stop.'

The identified influence is 'pushing'. This is plausible since it is clear where it comes from, that it influences the motion and that it depends on the configuration (in this case the person, how strong he is and how hard he pushes). Without this influence 'he'll run out of force and just stop', therefore the influence free motion in this case is 'comes to a stop', which is quite plausible for this kind of motions. Experience tells us that after pushing an object it either directly stops (when it is very heavy and pushed on a rough surface) or continues for a little while and gradually comes to a stop (when it is light or pushed on a slippery surface). For everyday aims and interests it makes a lot of sense to assume as influence free motion those motions that objects have when *people* as agents do not influence them. The observed deviation from this influence free motion, 'to keep moving along', is connected to the child's identification of an influence.

A second example is:

> 'To keep going steadily you need a steady push. If you don't force something to move it's not going to go along is it?'

[10] Although I think that the explanatory scheme lies behind all explanations of motion, this does not mean that explication of this thought is original. In chapter 3 I will trace the explication of this thought to the nineteenth century. It might perhaps be traced back even further.

The identified influence is ‘push’. Again very plausible. Without this influence ‘it’s not going along’, therefore the influence free motion could be ‘rest’ or ‘coming to a stop’. In this example also a sense of degree can be found (implicit) in ‘steady’ push. This implies that a not steady (e.g. increasing) push would result in a bigger result.

The third example is from the paper by McCloskey (1983).

> One subject, who had never taken a physics course, explained a curved trajectory drawn for a ball shot through a curved tube in the following way: ‘The momentum from the curve [of the tube] gives it [the ball] the arc… The force that the ball picks up from the curve eventually dissipates and it will follow a normal straight line.’

This situation is depicted in Figure 3.

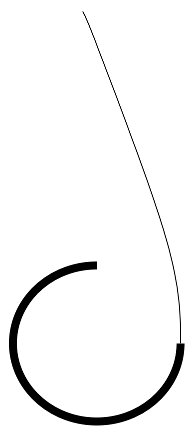

Figure 3: The predicted motion of a ball leaving a curved tube lying flat on a table

Note that the explained motion is not observed, but predicted and drawn or maybe selected from several drawn alternatives. The identified influence is ‘the momentum or force from the curve [of the tube]’. Without this influence ‘it will follow a normal straight line’. For a rolling ball following a straight line is a normal thing to do as everyone has experienced numerous times. This choice for influence free motion seems therefore quite plausible. The subject does not say whether the ball gradually slows down, because the most noticeable part of the motion to be explained is the perhaps mysterious continuation of the curve after leaving the tube. Given the motion that is to be explained and given the need to identify an influence it is not a strange thing to attribute the influence to the tube even after the ball leaves it. Even though the plausibility of this influence is in question, because it attributes a kind of aftereffect to the tube, it can still be argued for. Its agent, the tube, is easily identifiable. Tubes can influence the motion of balls and this influence depends on the configuration like the curvature of the tube for one thing. The difficult part is, as mentioned before, how this influence can still function after the ball has lost contact with the tube. In this way the explanatory scheme can be seen to work in an explanation of a motion that does not occur, but is thought to occur.

Given the somewhat implausible influence and therefore slightly awkward explanation I imagine that this subject finds it quite easy to change its explanation when shown the real motion of the ball. The only part that needs changing to account for the real motion is that the already identified influence of the tube no longer exhibits an aftereffect. After such a revision the same use is still made of the explanatory scheme, namely the same assumption for an influence free motion and the same identification of an influence that account for a deviation from this influence free motion.

Later more examples will be encountered, but these three will suffice for now. In what way does this solve the interpretation problem? The explanatory scheme makes the conceptual relation explicit between deviations from an influence free motion and explanations of these deviations in terms of influences that are functions of characteristics of the configuration. My attribution of this notion of an explanatory scheme to students and experts alike is similar to the impetus theory in the sense that both attribute some kind of *theory* to students. Although I disagree with the specific impetus theory of McCloskey, that does not mean that I am against attributing any coherent set of notions concerning motion and the explanation of motion to students. DiSessa, on the other hand, argues that “intuitive physics is nothing much like a theory. […] Instead, intuitive physics is a fragmented collection of ideas, loosely connected and reinforcing, having none of the commitment or systematicity that one attributes to theories” (diSessa, 1988, p. 50). In this respect diSessa’s view appears to be in quite sharp contrast, not only to McCloskey’s, but also to my own. The next section is devoted to a discussion of diSessa’s knowledge in pieces account.

Intuitive mechanics as knowledge in pieces

Students’ explanations of motion can be interpreted in terms of p-prims. “[P]-prims can be understood as simple abstractions from common experiences that are taken as relatively primitive in the sense that they generally need no explanation; they simply happen” (ibid. p. 52). Explaining a particular motion consists therefore in reducing the motion to one or more p-prims that are triggered by certain attributes of the motion to be explained. This describes what can be called a psychological process.

Take for example the explanation of a coin toss. This is an example of a reinterpretation by diSessa of what McCloskey would call a prototypical instance of use of the impetus theory in terms of several p-prims. DiSessa’s point was to show how a ‘knowledge in pieces’ account like the one he gave using p-prims could provide a better interpretation of an intuitive mechanics explanation for the coin toss than an impetus theory account (diSessa, 1993, p. 195-201).

> “In students’ descriptions of a vertical toss students will frequently declare that the tossed object rises because of the force imparted to it by the tosser. The impetus (subjects almost always use the term *force*), however, gradually dies away. At the peak of the trajectory, the impetus is exactly balanced by gravity. Gravity then overcomes the upward impetus, causing the object to fall downward”(p. 195).

DiSessa recognises several p-prims in this account. The following is a paraphrase of his explanation:

The p-prim *force as a mover* describes the hand-in-contact throw part. Here also the p-prim *overcoming* in the sense of the hand overcoming gravity is recognised. The problem in explaining the toss is posed by the p-prim *continuous force* and lies in the conflict that the ball goes up for a while whereas gravity would cause it to go down. Students need to explain how the object can act as an independent agent that, in its upward motion, overcomes gravity. They know that this agency has come from the tosser, so that fact is expressed as a transfer or communication of some form or other. The top of the toss shows some *equilibrium* or *balancing* of the impetus or internal force and gravity. In the weakening of the impetus from throw to apex the *dying away* p-prim can be seen. (ibid. p. 197)

In this way the coin toss is explained by reducing it to elements that each do not require any explanation (at least for the one who is doing the explaining). One can imagine someone for whom the coin toss itself is unproblematic and does not need any explanation. In such a case use of the p-prim *vertical toss*[11] can be attributed to this person. According to diSessa p-prims are loosely coupled and sometimes overlapping which accounts for the flexibility of this knowledge in pieces account. ('It's a feature, not a bug!') Slightly varying contexts can trigger completely different p-prims. For instance, slight variations in situations that all expressed the same problem of what would happen when a circular motion is aborted by removing the circumstances causing it resulted in widely differing answers and justifications. A circular impetus theory cannot account for these differences, whereas a p-prim account can. Lack of flexibility is not necessarily a feature of any theory, albeit it is one of the (circular) impetus theory.

I claim that the same flexibility is also provided for by the explanatory scheme. To back this claim let us look into the p-prims used in the coin toss example and see how they can be understood in terms of the explanatory scheme. I will discuss the mentioned p-prims in turn.

Force as a mover (also *force as deflector*, *continuous force* and *force as a spinner*). "Pushing an object from rest causes it to move in the direction of the push. The p-prim abstracted from that behaviour, at that level of detail, I call force as a mover" (diSessa, 1993). When a change in a motion is observed, like a change from rest to moving with a particular speed, one feels the need to find a plausible influence (normally called 'force') that accounts for this change. This need for a plausible influence is not merely a psychological need in the sense of only descriptive of peoples behaviour, but underlying it is a logical need. Our view on causality dictates it. Without this influence the motion would not have changed and the object would have remained at rest, which is a plausible influence free motion in the context of everyday life in which one is mainly interested in how one can *personally* influence motions. So when an object starts to move or changes its movement a plausible influence needs to be identified, when an object starts to spin or changes its spin a plausible influence needs to be identified, when it is deflected et cetera. It depends on the situation and one's knowledge if such an

[11] This p-prim is not in diSessa's list, but it might be added for those people that do not consider gravity to be an influence, because in that case there is no *balancing* or *overcoming* in this example.

influence can be found, but *that* an influence needs to be found in order to explain the motion can not be escaped.

It can also be the case that an influence is obvious although the result in the form of a change of motion like changing from rest to moving with a particular speed is not. Take for example someone pushing with all his might a heavy car that barely moves. In that case other p-prims might be triggered like *resistance, balancing* or *overcoming*. In the latter case two obvious[12] influences ('forces'), that each on their own might change the motion of an object, are identified and are working at the same time and can balance each other (*dynamic balancing*, *cancelling*). If the object starts moving or the motion of the object changes this can be explained with *overcoming* by assuming that one of these influences overpowers the other. For *continuous force* the same can be said as for *force as a mover* but now the identified influence can be assumed or seen to work uninterruptedly. So far these p-prims indicate situations in which a need is felt to identify plausible influences. The p-prim *dying away* indicates an influence free motion. When this p-prim is triggered in some situation no need is felt to identify an influence. An example of such a situation was already discussed, namely the example of gradually coming to a stop when one stops pedalling when riding a bicycle.

So underlying all these p-prims (and I can extend this discussion in a similar vein to include others) the same explanatory scheme can be found, which is therefore flexible enough to accommodate them. The explanatory scheme can be seen as a mould in which quite different content can be put and which results in explanations that are different in detail, but the same in structure. The point I am trying to make here is that the explanatory scheme underlies each explanation of motion as well as diSessa's p-prims and is therefore another, more fundamental, description of what takes place in explaining motions.

The transition from novice to expert in mechanics diSessa sees as "building a new and deeper systematicity" of the set of already existing p-prims. Increasing systematicity involves increasing the priority of more basic p-prims, for instance those that encode basic laws. In terms of the explanatory scheme, building systematicity would involve having students assume as influence free motion one that *allows* identification of plausible influences as functions of attributes of the configuration by means of which it becomes possible to explain a very large range of motions (ideally all motions) very precisely. Assumptions for influence free motions and related influences that depend on the particular situation would instead result in piecemeal and imprecise explanations. In this sense I understand generalizability and precision to be important parts of systematicity. The educational challenge lies in my view in making students want to be able to explain motion in a general, precise or systematic way. For this a theoretical orientation in the student is required.

[12] Or one obvious influence. Take the same example of someone pushing a car with all his might with as a result that the car starts to move very slowly. One influence, pushing, is obvious. The p-prim force as a mover might dictate a bigger result in the form of a faster motion. The tiny result could be explained by using *Ohms p-prim*, *resistance* or *overcoming*. When using *overcoming* the need is felt to identify another influence that is overcome by the obvious pushing influence.

DiSessa's account of the structure of intuitive mechanics shows an alternative for the, at that time, dominant misconceptions account. I think his attempt at developing this knowledge in pieces theory can best be understood as a reaction to the older and very influential misconceptions view. His claim was that his theory accounts for the same observations as the misconceptions theory did. His emphasis was not on how his theory might become useful in designing education that counters the stated problems (as was also not the case in the misconceptions theory). Instead he opened the door to more productive use of intuitive notions as an alternative for the conflict strategies to which the misconceptions view seemed to lead. In arguing for more constructive use of intuitive notions one would have a stronger case when an alternative and feasible theoretical account for the nature of these intuitive notions is available. In his reaction to the misconceptions view diSessa went to the other extreme of an anti-theoretical attitude and an overstatement of knowledge in pieces. The explanatory scheme binds those pieces of knowledge coherently together.

Concluding remark: What the intuitive mechanics as theory movement has shown is that students do give non-Newtonian answers to specific questions, i.e. utter non-Newtonian statements, and that in those answers patters can be identified. Students do have opinions on the matter of explaining motions. I disagree with the hindrance perspective on these intuitive notions, since this is based on a misinterpretation of what students actually say and write and is unproductive for developing (constructive) education. Given their basically correct intuitive notions on the matter, something constructive/productive has to be done with them in education. And this *can* be done (in principle) since the explanatory scheme underlying the students' common sense explanations of motion also underlies Newton's way of explaining motion. In Newtonian mechanics the explanatory scheme is implemented by accounting for motion in terms of plausible force laws (such as Newton's law of gravitation), in conjunction with an assumption as to how forces combine and produce accelerations (Newton's second law), where accelerations are just the deviations from moving with constant velocity (the influence free motion according to Newton's first law). In the words of Maxwell: "The first law tells us under what conditions there is no external force; in every case in which we find an alteration of motion of a body [that is a deviation from the influence free motion; ASW], we can trace this alteration to some action between that body and another, that is to say, to an external force". So when students' intuitive notions are understood in terms of the explanatory scheme underlying both their and Newtonian explanations of motion, this gives tremendous hope for using these intuitive notions constructively. How this can be done in practice remains to be seen and is the main topic of this thesis.

3.2.2. Neglect of epistemology

Other notions students have before education in mechanics that are considered to be inadequately taken into account in traditional education involve their epistemology. Here also one should take care of the interpretation problem. The first questions concerning epistemic notions are what these notions precisely are and how these were established. Some so-called epistemic notions appear to be better labelled as meta-cognitive strategies. Hammer and Elby (Hammer & Elby, 2003) for instance mention the strategy that students give different explanations for different motions just to come up with an answer to a teacher question[13]. Another notion that is mentioned in the literature is the epistemic notion of generalizability. According to Hewson (1985) this, together with internal consistency[14], is lacking in students. Generalizability can also be found in Hammer and Elby who talk about consistency, which I interpret as meaning the same as generalizability.

A point of critique on both Hewson and Hammer & Elby involves the basis on which they attribute epistemic notions to students. Many classes of epistemic notions are attributed to students by Hammer and Elby like the notion 'knowledge as propagated stuff'. An example of a statement which expresses this notion given by them is that children can understand the question 'How do you know we're having soup for dinner' by responding 'Because mommy told me'. I think that attributing an epistemic notion to students on the sole basis of such a statement is not justified. The earlier mentioned epistemic notion of generalizability, however, does merit the name, since it plays a part in the justification of knowledge, for instance when choosing between an Aristotelian or Newtonian model for the motion of heavenly bodies.

Hammer and Elby saw as educational challenge increasing students' valuing of generalizability, for which they tried to trigger those resources that already involve generalizability in other contexts. This approach still leaves the question unanswered *why* students should apply their already existing resources of generalizability to mechanics. To illustrate this argument let us consider what it would take to teach Aristotle Newtonian mechanics in this way. First of all it would not be productive to try to convince him of being inconsistent when he claims different natural motions for heavenly bodies (circular) than for earthly bodies (falling), because he is not[15]. We, as scientists, realise that one important criterion for adopting a Newtonian perspective is its

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[13] They seem to connect this strategy to what they call the lack of (epistemic) commitment to principled consistency, but it is unclear in what respect this is different from meta-cognition. They themselves seem at a loss to indicate the difference (Hammer & Elby, 2003, note 3).

[14] Some care should be taken in interpreting what Hewson means by internal consistency. Surely he cannot mean that students belief proposition p and its negation $\neg$p at the same time. That would fail to attribute the most common aspect of rationality to students, and thereby make it impossible to interpret anything they say. In interpreting someone else the assumption that the other is a rational being is necessary. Perhaps Hewson means internally inconsistent *from the Newtonian point of view*. From this perspective Aristotle's different accounts for the circular motion of heavenly bodies and the falling towards earth motion of earthly bodies would be considered inconsistent. Different 'natural motions' are attributed to objects in different contexts. This lacks the consistency of a Newtonian account in which only one 'natural motion' is needed. This single natural motion, rectilinear motion with constant velocity, can be generalised to al contexts, which is a common criterion for choosing between scientific theories. Its greater generalizability is therefore one indication for the superiority of Newton's account. In this interpretation of Hewson commitment to internal consistency would be the same thing as a commitment to generalizability, which cannot be right for Hewson specifically distinguishes these two. At this point I am at a loss as to what Hewson could possibly mean by internal consistency.

[15] As he would not fail to point out. Most students however can perhaps more easily be intimidated, but in their case the message would not stick, and rightly so!

greater generalizability. We therefore try to trigger this same epistemic commitment to generalizability that Aristotle already has in a different context than mechanics. This is the approach of Hammer and Elby. This is also where their approach stops. A subsequent step that should be taken, however, is to show in what way Newtonian mechanics is more general than Aristotelian mechanics.

The problem is not that students lack commitment to generalizability in certain contexts and not in others, or have an excess in some contexts[16] for that matter. I think most students appreciate generalizability as an epistemic virtue for scientific aims and interests. At least research has not shown this to be otherwise. There is nothing wrong with triggering commitment to generalizability, because this is an important criterion for choosing between alternative theories. The main question is, however, in what sense one theory is more general than an alternative one.

3.2.3. Neglect of process

Analysing the problem with mechanics as neglect of process knowledge seems to put the finger on a sore spot.

The identification of the problem as a neglect of process knowledge seems similar to the problem analysis of a neglect of epistemic notions. Both in the neglect of epistemology and in the neglect of process knowledge the same argument can be found. As was shown before both analyses noticed the more coherent and systematic way an expert solves (mechanics) problems. In traditional teaching the novice views mechanics formulas, facts, phenomena et cetera as disconnected from each other and from everyday thinking. A further analysis resulted in the case of neglect of epistemology in the claim that students lack the (epistemological) commitment to generalizability, which means that students do not see the value or the importance in a more general way of explaining motion over several different local (context dependent) explanations of motions. In the case of neglect of process knowledge the problem was further analysed as students' inability to pick up the implicit problem solving skills displayed by the teacher. Making these problem solving skills explicit Hestenes came up with a modelling method, using several procedural tools. Another aspect in making problem solving skills explicit can be seen in explicating the expert's commitment to generalizability, which is implicitly contained in this modelling approach. Modelling is applying theory, which has as one of its characteristics that it is general. I think, therefore, that although Hestenes made no explicit reference whatsoever to epistemic considerations (or epistemological literature), he would not object to seeing and explicating the importance of a commitment to generalizability. The difference between these two problem analyses lies in my view in the emphasis they put on what aspect of problem solving skills is considered most important: modelling as such (in which criteria as generalizability, exactness and simplicity play a part), or specifically one aspect of modelling, namely the commitment to generalizability.

[16] An example of overgeneralization is that the notion that the temperature of water rises when heat is added is also applied in the situation when water starts to boil.

Since the problem analysis of lack of attention to process knowledge is in this sense quite similar to the earlier discussed problem analysis of epistemology, the same point as was made there can be made here: The main question is *in what sense* the model that is being constructed (developed, validated, ramified) is more general, exact and simple.

3.3. Approach

Let us look once again at some different approaches to solving the problem of student's lack of understanding and/or motivation. This time with the aim to specify what is useful and what not in the different approaches and provide an onset for an approach of our own to overcoming this problem. I will discuss the approaches presented in section 2.3 of this chapter starting with 'overcoming misconceptions' and 'providing adequate attention to process knowledge by modelling', then 'building on useful intuitive notions by means of bridging' and finally 'restructuring potentially useful intuitive notions'. 'Making productive use of epistemological resources' was already discussed in the discussion of its problem analysis in section 3.2.2 of this chapter.

3.3.1. Overcoming misconceptions

Since I disagree with the problem analysis on which this approach of overcoming misconceptions is based, I will not discuss the approach in detail. I will show how the approach suffers from the same neglect of the interpretation problem as the problem analysis did and end with two remarks on difficulties that can be expected in any design (including mine). Let us first turn to the suggested strategy of 1. explicit formulation of common sense beliefs, invited by well-chosen problems, 2. check for external validity, 3. check for internal consistency, 4. Comparison with other beliefs including the scientific one. Apparently students' beliefs were established in step 1, after which they were changed in step 2, 3 and 4. However, step 2, 3 and 4 are important points to consider when establishing students' beliefs. In establishing those beliefs it is necessary to check for external validity (2), to check for internal consistency (3) and to some extent compare them with other beliefs including the scientific one (4). Given such a way of interpretation of students' beliefs, which takes the interpretation problem seriously, this strategy is no longer valid.

A comparison with other beliefs including the scientific one seems very useful, but also quite difficult. A comparison of common sense and scientific beliefs can show differences and similarities. A difference is the superiority of the scientific belief for scientific aims and interests, which lies in its generalizability, exactness, predictive power et cetera. Similar is the fact that both are ways of explaining motions that are useful given particular aims and interests and show the same underlying structure, as was discussed in section 3.2. Discussing these differences and similarities in a for students understandable way seems quite difficult. Hestenes paper does not give any clues as to how to go about this topic. An assumption in this approach to overcome misconceptions seems to be that a comparison of common sense and Newtonian explanations of motion will automatically lead to the adoption of the latter. I think that for this to occur students need to adopt or at least appreciate the scientific aims and interests first.

An important element identified in this method is the role of the Socratic teacher. Wells, as an example of someone successfully adopting this role, does succeed in getting students to appreciate theory qua theory. The many qualities such a teacher should have that were mentioned make this role a difficult one.

3.3.2. Providing adequate attention to process in teaching

The modelling approach of Hestenes and Wells provides a thorough training in problem solving. Students are given quite a number of useful guidelines in how to go about in attacking a problem in the form of the mentioned procedural tools. All these tools seem to express what expert problem solvers in fact do when solving problems. I do not think that any expert would be surprised when shown these tools. This is not to downplay these tools. It is quite an achievement to make this skill operational in this way. This assumed recognition of experts only underlines this usefulness.

Learning outcomes (discussed in section 3.4) indicate that students in fact pick up these problem solving skills. Apparently students recognise the usefulness of the procedural tools to the extent of willing to adopt them. The description of the course does not suggest some kind of drill instruction. It remains unclear to me how students are led to recognise this usefulness. To be more concrete this modelling approach leaves unanswered the following questions:

- The course content is centred on a few basic models, but how do students recognise these as being 'basic'?
- How are the representational tools used?
- The modelling cycle is kicked off by the teacher who introduces some question to ask of nature and an experimental set-up to do that, but how can students know the importance of the question and see the use of the set-up? This is known by the teacher who "has a definite agenda and specific objectives for every class activity, including concepts and terminology to be introduced, conclusions to be reached, issues to be raised and misconceptions to be addressed" (Wells et al., 1995). It is unclear how the students can find this out. It appears to be that only in retrospect in the so-called post-mortems that students realise what the bigger picture of what they were doing has been. I do not want to downplay the importance of these post-mortems. I agree that post-mortems can be seen as activities in which the most significant learning can occur. This kind of reflection is a big improvement on traditional education in which this is almost totally lacking. However it would seem to be even better when students see the point of what they are doing *all the time*, so that significant learning not only occurs in post-mortems but also in 'pre-mortems'.

3.3.3. Building on useful intuitive notions by means of 'bridging'

Clement's intermediate position between viewing intuitive mechanics as potentially harmful or potentially useful in his problem analysis can also be seen in the education he designed. On the one hand useful notions in the form of 'anchors' are sought and used by means of bridging to reach the ‘targets’. On the other hand after the bridging activity misconceptions that still remain for some students who did not see the connections between anchor, bridge and target are confronted by a ‘conflicting’ experiment.

The approach raises a number of questions related to the problem analysis that, as we saw in the example of a bridging strategy by Brown in section 3.2, did not solve the interpretation problem. Let me illustrate some of these questions by means of the mentioned example. This example was discussed by Klaassen (2001) whom I will follow below. In this example students’ statements are discussed, not their beliefs. The effect of the bridging-strategy is that a student without following the strategy would say something (or assent to a statement) like ‘the table does not exert a force on the book’ and after following the strategy that ‘the table exerts a force on the book’. But what happens to her beliefs? What for instance is the anchoring intuition that the students already possesses, that is: which belief is expressed with ‘the table does not exert a force on the book’? Which criterion for application of the word ‘force’ is used? What changes as a consequence of the strategy? Her conception of force, her criterion for application of the word ‘force’, both, neither, something else? Has the student explicitly become aware of such a change? Has the student primarily learned that a table can be considered to be made up of tiny springs and therefore can be considered to behave as a spring, or has she also learned something concerning the physical conception of force, and what this has to do with a spring? What should be done with a student who does *not* say that ‘the table does not exert a force on the book’ in the anchor situation? Would that be indicative for yet another conception of force and/or another criterion for application of the word ‘force’? Only when questions as these are addressed can one say something about students’ (deep seated) beliefs that may, when correctly taken into account, have a positive influence on their learning.

I think that this example of a bridging strategy can be understood in terms of a similar explanatory scheme as the explanatory scheme for motion, that is an explanatory scheme based on change of form instead of change of motion. This explanatory scheme consists of a characterisation of a normal form of certain objects, i.e. a form that does not require any explanation, coupled with the identification of influences that relate, in a lawlike manner, deviations of this normal form to attributes of the configuration. Without any of these influences an object would return to its normal form. Each spring for example has its normal length. When the length of a spring deviates from its normal length, this deviation must be attributed to some influence on the spring (that is a function of attributes of the configuration). When this influence ceases, the spring would return eventually to its normal length.

The anchoring intuition in the discussed example can be understood in light of this explanatory scheme for form. What happens in the bridging strategy is that the mentioned way of explaining is triggered with the spring, which is a prototypical instance of this explanatory scheme, and made applicable to the table by presenting the table as a collection of small springs that also changes form, although this is almost invisible. Both the explanatory scheme for motion and the explanatory scheme for form are aspects of the conception of force. A force can change the motion and/or the form of an object. Both explanatory schemes are the same for common sense and expert explanations and did not (and did not have to) change in the bridging strategy. Even the specific characterisation of a normal form of the table did not have to change. The only thing that changed as a consequence of the strategy is that students now think that after all the table did deviate from its normal form. So nothing much happened with students' conception of force in this bridging strategy, especially if nothing of this explanatory process is made explicit to students.

Let me end this discussion of the bridging strategy with a more general remark. What makes a particular anchor useful? There is a similarity between anchor and target that is clear for the expert but hidden for the novice. A bridge between anchor and target is a situation, which is sufficiently similar to the anchor so that the novice recognises the similarity. For both cases, the expert recognising the similarity between anchor and target and the novice recognising the similarity between anchor and bridge (and bridge and target), the same process is involved. For this process to work anchor, bridge and target must have a common underlying feature, which Clement or Brown leave unmentioned, but which can be seen in the explanatory scheme.

3.3.4. Restructuring potentially useful intuitive notions

The restructuring approach of Dekkers tried to make productive use of intuitive notions of students in teaching the force concept. After misinterpreting students' statements as misconceptions a reinterpretation resulted in the notion that students' intuitive notions need to be further differentiated for which the important factor is that students have to feel the need for such a differentiation. An important differentiation was that the concept 'Newtonian force' is only used when there is an interaction, whereas the intuitive conception 'force' does not have interaction as an explicit criterion (there are contexts in which the intuitive conception of force is applicable and in which there is interaction). This is an example of an analysis of both intuitive and Newtonian mechanics, which gives important guidelines for the design of the course. In this case that 'interaction' ought to precede the trolley lab experiment, because otherwise no resolution of conflict would occur. This kind of analysis seems indispensable for designing good education and Dekkers for one takes some time to make his analysis clear to the reader. Surprisingly this is not always the case when designed education is presented in the literature.

This approach raises some questions, however:

- Is the intended conflict in the trolley lab experiment really resolved? The strategy of context expansion involves adding situations in which force is used in the Newtonian sense. Three conditions for application of the word 'force' are introduced and worked with in a number of situations. When these conditions are applied to the situation of the trolley lab experiment students were observed to be in conflict. The inability to point to an interaction between two objects and to measure a forward force makes students conclude that there is no forward force in this situation, which is in conflict with their pre-educational notion that a 'force' is needed to keep an object moving. This conflict is considered to be resolved when students adopt the mentioned conditions for application. In my opinion this is not resolving at all. For resolving the similarities and differences between the old and new conception have to be clear and the reason for the differences understood, which is not the case. Otherwise the old notion is simply overruled or dismissed as incorrect or not in agreement with how physicists talk about motions.

- How has the force conception changed as a consequence of the approach? What students have learned in this strategy are conditions for application of the word force, not the reasons for the existence of these conditions. This is already quite an achievement, but it would be preferable to give students insight in the reasons for this particular use of the word force.
- The importance for a need for differentiation of the intuitive force conception is identified, but how is it incorporated in the design? I cannot recognise it.
- In the beginning of the course motion without (observable) friction illustrates that there is no ‘force of motion’. How can this be understood without the subsequent interaction and trolley lab experiment activities? It seems to me that the goal of the trolley is the same as the goal of this activity, namely to illustrate that there is no force of motion.

3.4. Method and results

In this section I will critically discuss most of the evaluations described in section 2.4. The evaluation of the additional goal of illustrating the humanistic enterprise of physics and the additional goal of raising the motivation for mechanics will not be further discussed. A proper discussion of the former would distract from my main point for this section, which is that either important goals were not reached, or when they seem to have been reached some questions remain regarding how they were reached. A discussion of the latter would not add much to what had already been said in section 2.4. The emphasis lies in this section on a discussion of the method and results of the Hestenes – Wells approach. The reason for this is that in the discussion of the problem analysis and approach of Dekkers and particularly Clement already some remarks were made on their method and results that will not be repeated here. Some arguments do not always fall neatly in the used categories of goals, problem analysis, approach and method & results. It seemed clearer not to interrupt the flow of the argument in those sections.

Evaluation of the goal of understanding the conceptual structure of mechanics

The lack of success in PSSC, HPP, Nuffield and PLON in reaching the common goal of understanding the conceptual structure of mechanics should not come as a surprise since these projects did nothing to specifically address the problem in understanding mechanics, but simply tried to explain mechanics as well as possible. They cannot be blamed for that, of course, because they simply predated the awareness that there lies a persistent problem in understanding mechanics. In fact it can be seen as quite an accomplishment to aim at additional goals on top of the common goal without faring worse on the common goal. Only later, and partly because of this lack of success, a wave of research devoted to identifying learning difficulties took place. Unfortunately most of this research can be categorised as ‘alternative conceptions’ research, that is to say that it was concerned with identifying alternative conceptions students were thought to have. That was unfortunate because it still did not address the real problem. (What the real problem is in my view was discussed in section 3.2 of this chapter and will be further elaborated in chapter 3). The positive side of it is that it put learning difficulties in mechanics prominently on the agenda and gave insight in what these learning difficulties are.

The later Hestenes –Wells approach, bridging approach and restructuring approach were aware of the learning difficulties, analysed them (in different ways) and tried to remedy them. They all claimed success. Does this mean that the problem of lack of understanding in mechanics is solved? I don't think so, because they tried to solve the wrong problem, as I argued in section 3.2. But how can these claims of increased understanding be understood? I will discuss the three mentioned approaches in succession with this question in mind, starting with the Hestenes – Wells approach.

Hestenes – Wells approach

My discussion of the Hestenes – Wells approach is organised around three main points. Firstly I will criticise the FCI and to a lesser extent the MB as instruments to measure shifts from alternative to correct understanding of mechanics. This criticism is based on my problem analysis, which also indicates how FCI results should be interpreted. Secondly I will criticise the research method that uses solely the FCI and MB. Thirdly I will discuss the results of this approach in light of the criticism on the used method.

Now starting with the first point about what FCI and MB measure: FCI items were based on student interviews on predicting and explaining motions. The recurrent statements of students were categorised into a number of patterns which were called alternative conceptions, e.g. motion implies force, impetus dissipation et cetera. I do not deny the patterns in student responses, but disagree with their interpretation, as mentioned before. Questions that reliably elicit these patterns were used in the FCI. What the FCI therefore shows is recurrent patterns in student responses. Why is it wrong to interpret these patterns in answers as alternative conceptions that differ from the Newtonian answers? Let me first make a distinction between the questions about a prediction of motion (FCI items 1, 3, 4, 6, 10, 16, 19, 23, 24, 26 and arguably 7, 25 and 27) and the other questions that concern some explanation or make use of the word 'force'. The latter category can only be interpreted as in contrast with Newtonian explanations if one is certain that the word force is used in the same way by the student and the interpreter, which can not be concluded from the test. The former category seems impervious to this line of critique. Surely there can be no way of misinterpretation of a predicted motion? Here at least patterns in student responses that differ from the Newtonian ones must indicate alternative concepts. No, they don't. First note that all questions about prediction of motions concern motions students are not familiar with. It is hard to imagine a student failing to correctly predict a motion she actually has experienced. The questions in the FCI concern two dropped metal balls of different size, a ball on a string swung in a circular way after which the string breaks, a short kick on an ice puck, a fired cannonball, a dropped bowling ball from an airplane and a rocket moving sideways in space after which the motor is turned on. Most people have no experience with these motions and it is again hard to believe someone who has got experience for instance with hitting an ice puck to wrongly predict the motion. In fact the experience people do have with motions that come close to the motions just mentioned could even trigger false predictions. The predicted motion is unknown to the students, which was necessary to elicit an *explanation* in the mind of the student.

In predicting an unknown motion students are forced to extend their explanations of known motions to these other situations for which they were not intended which can result in false predictions. What this shows is that students do not have an understanding of Newtonian mechanics, applicable to any motion. It does not show that they have an alternative theory for these unfamiliar cases. Their theory for familiar cases, which was quite suitable given their aims and interests and gave correct predictions (maybe not as exact as a scientist would want, but exact enough for the student) was extended to situations for which it was not intended, because they were asked to do so. In interviews students normally respond to this type of questions by first expressing uncertainty: "Well I don't really know, but since you ask, I will give it a shot and say …". This first bit of their answers gets lost in tests like the FCI. I am therefore not convinced that these false predictions of motions indicate alternative concepts.

The MB test is a partly quantitative problem solving test, "though its main intent is to assess qualitative understanding" (Hestenes & Wells, 1992). What does a high score on this test mean? I think it is fair to say that students with a high score know how to solve mechanics problems that are usually encountered in most textbooks. Whether students have understood anything about the relation between Newtonian mechanics and common sense is a different matter. It is quite possible to solve the usual textbook mechanics problems without understanding why this is a good way to solve them.

The second point is whether the used pre- post test research method with the FCI and MB can shed light on the usefulness of the approach. I already argued against part of Hestenes' problem analysis concerning the identification of alternative conceptions and the related method that aimed at remedying them. I did not object to the other part of his problem analysis concerning the lack of attention to process knowledge. Perhaps his research provides additional arguments for either part of the problem analysis? I will look at both parts in turn.

An argument Hestenes may put forward in defence of the alternative conceptions hypothesis is that his approach that identified these alternative concepts as causing the problem of lack of understanding and tried to remedy them was very successful in improving this understanding of mechanics as compared to a control group. 'Understanding mechanics' is here used in the already mentioned sense of knowing how to solve the usual textbook problems. For this argument to be true, two related conditions have to be the case: First the elements of the approach that tried to remedy the alternative concepts must be the only factor in which the experimental group differs from the control group. Secondly some plausible account must be given of how the elements of the approach in fact try to remedy the alternative concepts. These conditions are related because given the messiness of educational situations the first condition can never be guaranteed. One can say that the differences between control group and experimental group are many. Therefore an account of why the elements that are incorporated in the design to remedy the alternative concepts are expected to do just that would be needed in order to accept the claim that these alternative conceptions were in fact causing the problem. Such an account is not given. In his conclusions Hestenes does not reflect on the hypothesis that alternative concepts cause the problem of lack of understanding, which suggests that he did not see this as a hypothesis but as an accepted fact. In my opinion this method cannot corroborate this hypothesis/fact.

A similar argument holds for the second part of Hestenes' problem analysis concerning the lack of attention to process knowledge. So, just as was the case in my discussion of the FCI, here too I think that the MB results *as such* do not corroborate the corresponding problem analysis. There are however other reasons for adhering to this problem analysis. For one thing in this case a feasible account can be given, and was given by Hestenes (see sections 2.3.2 and 3.3.2 of this chapter) as to why this modelling approach is expected to contribute to problem solving skills, namely by using explicit procedural tools that express what expert problem solvers in fact do when solving problems. This provides for what I called the second condition in my discussion of the meaning of FCI scores: a plausible account of how the elements of the approach in fact try to remedy the problem. Because of this additional argument more weight can be attributed to the fact that students score well on the MB. This means in my opinion that the hypothesis that lack of attention to process knowledge was in fact partly causing the problem in mechanics is thereby supported.

Additional information possibly corroborating this hypothesis would be whether or not the students who followed the Hestenes – Wells approach showed less rote learning and plug-and-chug behaviour. Plug-and-chugging is quite useless in answering the MB (it was designed that way), but how do these students go about answering regular textbook questions and problems? This was not researched (or at least not reported). When these questions are answered more can be said about the hypothesis that the problem in teaching/learning mechanics is partly caused by lack of attention to process knowledge.

Finally the third point about the results of the approach. The Hestenes – Wells approach was undeniably successful in increasing FCI and MB scores. Although one part of the problem analysis was incorrect, students did learn a lot. What they learned was how to solve the usual textbook problems, which is a common and worthy goal. The Hestenes – Wells approach reached impressive results in this respect. Apparently a lot of practice in the usual textbook problems with attention to the 'mistakes', from the Newtonian perspective, that students make *and/or* explicit attention to process knowledge does help. Provided that it is correctly done, of course. Further narrowing down to see which of these two elements (attention to misconceptions or process) accounts for this success is not possible with the available information. My guess would be that the process element accounts mostly for the success since it is based on a valid problem analysis.

What the students do not learn is the relation between the Newtonian and common sense way of explaining motion, and therefore the reason *why* the Newtonian way is the one they have to adopt. Since this is an aspect I want to focus on in my introductory course, I will not further use the Hestenes – Wells approach. Explicit attention for and practice with solving textbook problems can be incorporated in the *regular* course following my introductory course. The attention to process knowledge and the usual mistakes students make in applying Newtonian mechanics in these problems can be organised around the then introduced explanatory scheme that provides for a vocabulary to discuss those mistakes. In this way Hestenes' general advice of paying explicit attention to process is followed, albeit not the specific implementation of the Hestenes – Wells approach. The importance of this explicit and systematic attention to these problems and how to solve them is something that can be learned from the work of Hestenes and co-workers.

Bridging approach

Clement also claimed some success in understanding mechanics for his bridging approach. The high score on the post test by students who followed the bridging approach raises the same question as in the discussed Hestenes – Wells approach, namely what does this say about the used approach? Apparently something went well, but how can this be attributed to elements of the used approach? And to what elements? These questions are not answered by Clement. I took a shot at answering these questions by means of the explanatory scheme in section 3.3.3.

Clement indicated that observations pointed to increased understanding after each step from anchor, bridge, target to conflicting experiment, see section 2.4. This seems to be in contrast to the assumed working of the strategy for which only after seeing the similarity between anchor and bridge and bridge and target understanding can rise. Perhaps what is meant is that some students immediately recognised the similarity between anchor and target after introduction of the anchor. This interpretation is supported by Clements' claim that 'spontaneous generation of bridging analogies' was observed. What also puzzles me is that some students did not understand the problem after the anchor-bridge-target strategy, but did when presented with the demonstration experiment that was designed to provide cognitive conflict. Does this mean that some people are more sensitive for a bridging strategy whereas others react more to conflict strategies? Why did the bridging strategy fail in some students? Did they not share the anchor intuition? If so, why did the conflict strategy seem to work? What really happened with students' beliefs in this bridging approach is still unclear, as was earlier pointed out in the discussion of problem analyses in section 3.2. In order to answer these questions more should be known about what students beliefs are, what Clement meant by 'understanding' the problem, and how this was observed.

Another methodological point is that Clement rightly checked whether he reached his stated goals by observations, instead of trying to infer that from the pre- post test. How else could one check the goals 'that students actively participate in intellectual discussions' or that 'students generate analogies and explanatory models' than by means of qualitative data? However, since Clement reported only his conclusions from these data (which in the case of checking the goal about participation in discussions seems quite sufficient, but is insufficient for the goal about generating models) the question is raised of how these conclusions were reached. Concluding that students generate analogies and explanatory models is not something easily observed, but apparently inferred from (several?) qualitative data, which is not a trivial matter at all.

So although some success is claimed for this approach it is unclear what kind of understanding the students have acquired.

Restructuring approach

Turning now to the restructuring approach of Dekkers and estimating how students fared on the goal of understanding mechanics one can say that Dekkers showed that they learned the interaction aspect of the force concept and learned three application criteria for use of the word 'force'. Although this is quite an achievement it also leaves something to be desired, for the complete force concept involves more (as can be expressed with the explanatory scheme).

The research method used by Dekkers allowed him to evaluate and change his problem analysis. His initial hypothesis was actually *seen* not to work, which is a strong feature of his method.

In conclusion can be said that the common goal of understanding mechanics and the additional goal of illustrating science at its best are not reached to the extent that is desirable or possible. Although some progress has been made, and in the case of the Hestenes – Wells approach for the common goal remarkable progress, I have pointed out in this section that there is still work to do in the field of understanding learning difficulties, finding ways to remedy them and thereby improving education in the direction of the mentioned goals. This research project aims to contribute to that work.

4. Summary

In this chapter my research was positioned in the field of relevant other research. This other research was presented in section 2 and discussed in section 3 focusing on the main points of goals, problem analysis, approach and method & results.

In addition to the common goal of understanding mechanics three additional goals emerged from a global account of several influential curriculum projects of the past 40 years: Mechanics as illustrating 'science at its best', mechanics as illustrating science as a humanistic enterprise (that was characterised by its focus on history, development and inquiry) and finally mechanics as raising the motivation of students for physics. These additions all capture important aspects of mechanics and are therefore worthy goals, although they are mostly fit for academically inclined minds and some modesty in one's expectations for the extent in which these goals can be reached is in order.

Three types of analyses of the problems in mechanics education were identified: (1) neglect of intuitive mechanics, in which some find this intuitive mechanics potentially helpful and others harmful for learning, (2) neglect of epistemological commitments and (3) lack of attention to process in teaching. The first two types were criticised on grounds of their neglect of solving the interpretation problem. Before changing, bridging, restructuring, confronting or building on students' beliefs, it is important to know what these beliefs are, which is in many cases not properly established. An alternative interpretation of students' beliefs was given in terms of the explanatory scheme which was described as an assumption for an influence free motion coupled to an assumption that deviations from this motion must be accountable in terms of influences that are a function of attributes of the configuration. This scheme underlies both common sense and Newtonian explanations of motion and might therefore become useful in teaching and learning mechanics. The third analysis was considered valid, although an important point was lacking, namely how can be made clear to students why explicit attention to process expresses epistemic virtues like generalizability, exactness, predictive power et cetera.

Five approaches to overcoming the identified problems in mechanics education that developed education were presented and discussed. ‘Making productive use of epistemological resources’ pointed out the importance of students’ appreciation of generalizability and was seen to be missing an important last step which addresses why one model would be more general than another. Discussing ‘overcoming misconceptions’ had lost a lot of its relevance after the severe criticism of the problem analysis on which this approach was based. ‘Providing adequate attention to process in teaching’ seemed a valid approach given its aims and besides a similar objection as in the epistemological approach, only raised some questions concerning the precise execution. ‘Building on useful intuitive notions by means of bridging’ raised a lot of questions because it had not solved the interpretation problem. Interpreted from the perspective of the explanatory scheme what happens with students’ conception of force in this approach was very little. Finally ‘restructuring potential useful intuitive notions’ raised but did not solve the interpretation problem. It taught one important aspect of the force concept, namely interaction, but not other aspects. And some questions remained, most notably in what way students’ force conception changed.

The emphasis in the discussion of the method & results of the approaches lay on those that claimed success, notably the Hestenes – Wells approach. By means of a discussion of what the FCI and MB tests measure and the pre – post test design was shown that what students have learned in this approach is how to solve standard textbook problems, but that they did not see the relation between common sense and Newtonian mechanics.

In this chapter I have tried to show that there is still some work to do in mechanics education by mainly presenting and discussing the work of others. In the next chapter the topic is how I intend to do this work.