A new approach to teaching and learning mechanics

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A new approach to teaching and learning mechanics

Een nieuwe benadering van onderwijzen en leren van mechanica

(met een samenvatting in het Nederlands)

Proefschrift

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door

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geboren op 15 maart 1971, te Amsterdam, Nederland

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Preface

Although my first language is Dutch this thesis is written in English in order to make reaching a potentially larger audience possible. I am aware of the fact that the resulting 'broken English' of this thesis can at times be painful for native English speakers and completely incomprehensible for all nationalities. Misunderstandings because of language difficulties will occur, but my estimate is that these occurrences will be infrequent and certainly less than when people with other nationalities would attempt to read this thesis in Dutch.

Whenever I write about a teacher or student in a general sense I will use the personal pronoun 'she' instead of 'he' or 'he/she'. This is my modest way of making up for centuries of patriarchy. When the context makes it clear that the particular person to whom I refer is male I will of course use the accompanying pronoun.

Throughout this thesis I will speak about 'teaching/learning activities' and 'the teaching/learning process', instead of for instance 'teaching activities' or 'learning process'. The reason for this is that the interest of this research, as in most didactical research, lies in the interrelation of teaching (as descriptive of what a teacher does) and learning (as descriptive of what students do). The 'grain size' of the description of what goes on in the classroom I chose to be large enough so that it would include both teaching and learning. It is to emphasise this interrelation of teaching and learning that I will use the somewhat cumbersome terms 'teaching/learning activities' and 'the teaching/learning process'.

Another term I will frequently use is 'didactics' with which I mean the content-specific interrelation of teaching and learning activities and processes. This usage of the term didactics is quite common in many continental European languages, but differs from the British or North-American usage of the term, which for some seem to carry negative connotations.

In this research I have benefited from the advice of mainly two people: Piet Lijnse and Kees Klaassen. I found it stimulating and humbling to work with these really smart individuals. Educating people is stretching people. However, nobody likes being stretched. I found being stretched by these two gentlemen in the process of educating me unpleasant and I resisted as much as I could. If there has been any increase in my qualities it is therefore completely due to their unrelenting efforts.

Discussions of this research with colleagues were sometimes useful. In this respect I like to offer thanks to Roald Verhoeff and Hanna Westbroek. Without the kind contribution of two teachers the educational design described in this thesis could not have been tested and developed. Warm thanks are therefore due to Felix Metselaar and Michiel Boonzajer.

Since for obvious reasons I could not implement all suggestions for improvement, any mistakes in this thesis are completely my own.

Axel Westra

Chapter 1

Introduction

1. The topic of mechanics

An important aim in teaching and learning of mechanics, I think, is that students come to understand and appreciate mechanics for the right reasons. 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 power and simplicity of Newtonian mechanics makes the heart of many a physicist beat faster. Could students be made to appreciate mechanics for the same reasons? If so they would have truly understood something about mechanics! I think it might be worthwhile to find out to what extent this is possible.

Learning mechanics is notoriously difficult and much research has been devoted in mapping and understanding these difficulties (e.g. (Hake, 1986)). Concerning possible causes of this lack in understanding, the mainstream opinion appears to be that the 'naïve' conceptions of students are very different from the 'expert' Newtonian conceptions and that therefore a transition between those is difficult to achieve. Far less research was directed at remedying these problems, which makes some sense, since one first has to diagnose the disease before trying to apply a cure. Another reason for this lack of remedies is that science education as a field of research is very young. Roughly speaking the history of the sciences shows a development in particular sciences (like for instance biology) from a descriptive level (*what* kind of things are we dealing with) to a explanatory level (*why* are the things doing the things they do) to an applicatory level (*how* can we use the understood behaviour of things). The science of 'science education' is in many respects still in the early stage of description. However, at the same time many people involved in science education are more interested in the applications. This results in rather explorative research, since thoroughly tested didactical theories have not yet been developed. This research too will show the resulting tentative exploring that comes from searching for applications without the aid of a mature didactical theory.

The earlier mentioned metaphor of a disease (with the symptoms of learning difficulties in mechanics) also illustrates another point, namely that the cure one applies depends on the kind of disease that is diagnosed. It will turn out that part of the reason for the first steps towards a cure that I have taken lies in the fact that I tend to diagnose a different disease than many other researchers.

2. Overcoming difficulties in learning mechanics

My diagnosis of the difficulties in learning mechanics and the related approach for remedying these use the basic idea that although there obviously are differences between the Newtonian way of explaining motions and the common sense way, they also have something in common, which may be used productively for teaching/learning mechanics. What they have in common, I think, is what may be called an explanatory scheme. This explanatory scheme consists of the assumptions that a particular kind of motion needs no explanation and that motions that deviate from motion of that kind must be accounted for in terms of influences. I call the assumed motion that needs no explanation an ‘influence free motion’. Newton’s assumption of an influence free motion is motion with uniform velocity. Deviation from such motion is caused by influences, which Newton called forces. Common sense explanations of motion use the same explanatory scheme. 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. In this one can recognise the combined use of an influence free motion (gradually coming to a stop) and an influence (pedalling) that causes a deviation from this kind of motion. The ‘expert’ explanation may aim at theoretical values like broad applicability, simplicity and empirical adequacy, while the aims of a common sense explanation are related to practical usefulness and may depend on the context. That is, I interpret the differences between expert and common sense not so much as differences of belief, but rather as differences of aims and motives.

A common sense explanation of a motion, like that you have to keep pedalling in order to keep speed on a bicycle, is usually straightforward. In comparison, the description of such an explanation in terms of the explanatory scheme for motion, which involves an assumption for an influence free motion in conjunction with an identification of suitable influences that account for deviations from this influence free motion, may appear very difficult or even awkward. Indeed, the scheme’s use is not in the first place of a practical nature, but rather lies in the fact that it allows one to talk *about* explanation of motion. From this theoretical perspective, moreover, its broad applicability can be appreciated, not only in the sense that one can see it as underlying various explanations of motion, but also in the sense that one can begin to wonder whether, perhaps, *any* motion could be explained in this way.

As I just suggested, the differences between naïve and expert conceptions may be much smaller than they appear, in the sense that there are structural similarities between them and that the differences between the expert and the novice are to be found in their respective motives and aims. Of course this does not mean that students already know Newtonian mechanics and even less that they are willing to learn it. In fact, they will have to expand their knowledge considerably, and how they can be made to want this is a big educational problem.

Apart from the explanatory scheme’s possible immediate use in a course in mechanics I would like to suggest that the explanatory scheme also provides a ‘vocabulary’ for clarifying or addressing what students actually say when they later explain motion and for pointing out the differences and similarities between their explanations and the Newtonian ones. In this sense I think that having available this explanation vocabulary can also be of help in discussing, with students, the usual problems in understanding mechanics.

Although this idea might be applied to a complete mechanics course for secondary education, such an endeavour would be too time consuming and unnecessary for exploring how this idea may be made productive. I therefore decided to apply the idea in a design of an *introductory* course of about 10 lessons for upper level pre university students (age 16). In an introduction of any study topic one expects to find what the topic is about and some indication of the importance of studying the topic. In my case this fits in nicely with my first two aims of giving students some sense of how mechanics works and the power and range of mechanics.

3. Research question and method

My research question is how the idea of a common explanatory scheme in common sense and Newtonian mechanics can be made productive in teaching/learning mechanics. How this can be made productive, concrete, in real life education, is still an open question I am going to explore in this thesis. This question concerns both how the explanatory scheme can be used in a design of an introductory course that will lead to my educational aim (of making students appreciate the power and range of mechanics and know how mechanics works) and whether this course will provide the vocabulary to address the usual learning difficulties to be used in the regular course following this introductory course.

Since my research question is a design question, the method followed is a design experiment (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) sometimes also called developmental research (Lijnse, 1995).

A starting-point in my design is the idea that it would be worthwhile if students in each successive learning activity can see the point of doing that activity, how it builds on or makes use of the preceding activity and attributes to and prepares for the next one. All 'local' activities are leading to a 'global' goal students have some perspective on (however vague) and have some reason for achieving. This is sometimes called a problem posing approach (Klaassen, 1995).

This idea together with the idea of the explanatory scheme will be worked into a design, which will be described in a scenario. A scenario is an important instrument in this kind of research. It describes and justifies in considerable detail the learning tasks and their interrelations as well as the actions that students and teacher are expected to perform. It can be seen as a hypothesis, as a prediction and justification of the teaching/learning process that is expected to take place. As such, it also enables the researcher to precisely observe where the actual teaching/learning trajectory deviates from what he expected, and thus to test his hypotheses in a valid and controllable way.

In my scenario a justification will be given for each teaching/learning activity, why this particular activity should take place, what the goals of the activity are and why this activity would be expected to meet these goals. All successive activity goals should of course lead to the course goal of giving students some sense of how mechanics works and some appreciation of its power and range.

Expectations for each teaching/learning activity will be compared to the actual teaching/learning process that takes place. The precise expectation determines what sort of data, e.g. observations, video- and audio recordings, interviews with students and teacher, students' written materials and questionnaires, will be collected. These can then be analysed by qualitative interpretative methods. This will give information to what extent the teaching/learning activity goals are met and this in turn sheds some light on the more general course goals.

4. Content of this thesis

In chapter 2 the context of this research will be described. Some goals for mechanics education, problem analyses of what might be difficult in reaching those goals, approaches of remedying these difficulties, research methods for investigating these approaches and the results they yielded will be presented and critically discussed. After that, chapter 3 continues with a broad description of my own attempt, in the light of the discussed alternative approaches. Here the idea of the explanatory scheme will be extensively presented as a possible means of reaching the desired educational goals. The research question will be further elaborated upon and the method of design experiments will be presented as a useful way of answering the research question. Chapter 4 describes how the test of a first design resulted in ideas for revising it and broadly describes the resulting second design. Also the way in which the teacher was prepared for executing these designs will be addressed there. Chapter 5 zooms in on the (in chapter 4 broadly described) second design. It contains a detailed description of the second design, which includes the revisions that were based on the testing of the first design. Chapter 6 describes the results that were obtained from testing that second design. Finally, in chapter 7 these results are reflected upon, which will result in an answer to the research question and which will point to directions for further research.

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.

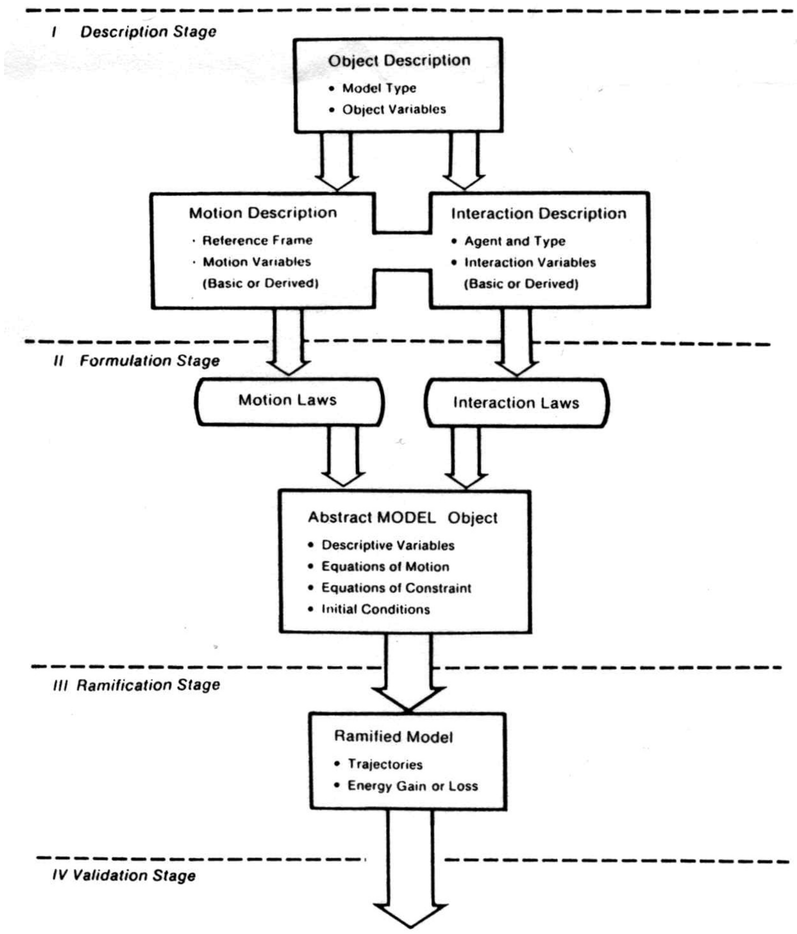


Figure 1: Schematic depiction of model development in mechanics according to Hestenes.

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.

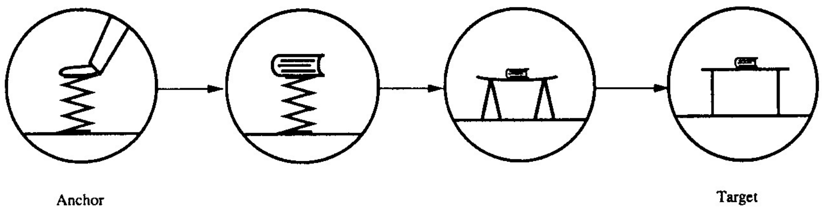


Figure 2: Example of Clement's bridging method

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.

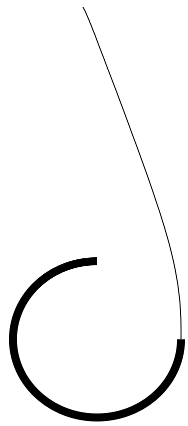


Figure 3: The predicted motion of a ball leaving a curved tube lying flat on a table

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

[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 ¬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.

Chapter 3

Backgrounds of the design

1. Introduction

In chapter 2 some background concerning mechanics was discussed. Notions reported in the literature about the goals for mechanics, the problems in mechanics education, approaches to dealing with these goals and problems, and research methods were presented and discussed from which implicitly (and sometimes explicitly) my own view might have become noticeable. My view concerning these topics will be made more explicit in this chapter. I will start by discussing my goals for mechanics and problem analysis as part of this introduction.

My goals for mechanics are that (1) students come to know how mechanics works and (2) develop some appreciation for its power and range. The first goal is about how explanation of motion works. Understanding mechanics requires integrated understanding, in which concepts are connected to other concepts and familiar phenomena. In order to achieve such understanding an emulation of scientific practice and especially some need for a theoretical way of explaining motion which is part of a scientific practice seems useful. As was seen in chapter 2, sections 2.1 and 3.1 this is not an uncommon goal. The appreciation for the power and range of mechanics I aim for is primarily concerned with *understanding* why it is powerful and far ranging. Although such an appreciation will not readily motivate students to engage in studying mechanics, it can be motivating in an intellectual or theoretical way, not unlike the motivational aim in Advancing Physics discussed in chapter 2, section 3.1. With projects like Harvard Project Physics and Nuffield in mind some modesty seems in order in one's ambitions regarding the extent to which such goals can be reached.

To these two goals I add a third that is related to my problem analysis: providing students with a vocabulary with which the usual learning difficulties can be discussed. This third goal will be discussed in section 2.2 of this chapter.

Turning now to my problem analysis the reader may recall that I think that students' beliefs are basically correct, but that they differ in the meaning they attribute to words as 'force', 'inertia', 'mass' and 'acceleration'. This was expressed in terms of the explanatory scheme as that students have a different specifications of the explanatory scheme than the Newtonian specification (see chapter 2 section 3.2.1), which is understandable since they differ in their aims and interests for explaining motions. In my opinion the educational problem (or challenge) lies in making students change their aims and interests towards the 'theoretical orientation' required to appreciate the experts' aims and interests, which is a prerequisite for adopting the experts' choices for influence free motion and related influences and thereby the experts' meaning of terms like 'force'. What is basically correct in students' way of explaining motion, that is, what is already in agreement with the Newtonian way of explaining motion, is the underlying structure of explaining that I called the explanatory scheme.

The explanatory scheme forms the backbone of this work. It plays a role both in my problem analysis and my educational approach. In the problem analysis it serves a purpose in reinterpreting students' statements that are normally interpreted as alternative conceptions in a way that takes account of the interpretation problem. One could say that it solves the interpretation problem related to students' statements concerning mechanics. This was seen in chapter 2 section 3.2. In the educational approach it serves a purpose in providing a framework, in the sense that the topics of Newtonian mechanics can be introduced and can find their meaning as specifications of the explanatory scheme. Since it plays this central role I will argue for it extensively in the next section and present a first draft of how it may be applied in an introductory course for mechanics.

After that I will be finally able to formulate my research question in section 3, which also describes some specific aspects of the research method, developmental research, that I think are not widely known, leaving a full account of this method to other sources. For answering the research question it will be necessary to design education which is guided by my view on education and earlier (similar) design work, which will both be discussed in section 4.

2. The explanatory scheme

In this section I will argue for the idea of using the explanatory scheme in mechanics education. First, in section 2.1, I will further argue for the explanatory scheme as a backbone of causal explanation of motion. In section 2.2 I will argue for its relevance for education by exploring the question how the explanatory scheme for motion might become useful in contributing to reaching my goals of understanding mechanics, of appreciating its power and range and of providing students with a vocabulary with which the usual learning difficulties can be discussed. The condition sine qua non for appreciating this relevance is of course that the explanatory scheme for motion can be made explicit to students. I will turn in section 2.3 to the question how this condition may be met.

2.1. Causal explanation, in particular of motion

The explanatory scheme for motion was introduced in chapter 2, section 3.2.1, as a structure underlying all causal explanation of motion. In this section I will further elaborate this claim. I begin by bringing forward some simple facts about causal explanation. Subsequently I discuss the explanatory scheme for motion in this light. Because the scheme plays a pivotal role in my research, I close this section with a discussion of the status of this scheme.

What we want in a causal explanation of an event is information about the history of the event, from which it can be inferred that the event to be explained would follow. Two closely related steps are involved here: an appeal to causal laws or other causal lore, and a characterisation of the event to be explained and part of its history such that, thus characterised, the laws are applicable. Consider a simple example: why did this small red headed wooden stick catch fire? Well, that stick is a match and it was struck. What makes this into an explanation, is an (implicit) appeal to a very rough law like: if a dry match is struck sufficiently hard against a properly prepared surface, then, other conditions being favourable, it will light. The law becomes relevant because the object initially characterised as 'small red headed wooden stick' was redescribed as a match.

Obviously, this kind of explanation is not high science, if only because of the (implicit) use of failsafe clauses like ‘sufficiently hard’, ‘properly prepared’ and ‘other conditions being favourable’. Furthermore, if asked what a match is, most people probably cannot do much better than say that it is an object so designed that striking it causes it to light under appropriate circumstances.[1] Nevertheless, appeal to such rules of thumb is not empty either, if only because quite often it sufficiently supports our daily intercourse with events that must be foreseen or understood in the light of our everyday practical purposes.

The above discussion also introduces another main point concerning causal explanation: which laws are appealed to is interest relative, as are the concepts that are used in characterizing the event to be explained and part of its history. It depends on what we or our audience are interested in, on what we are able to deliver, on what we think our audience will be able to understand, and so on. ‘Because the vacuum pump did not function properly’ may well be (part of) the explanation of why a match did light, e.g. by someone who intended to convince his audience that the match would not light when struck in an environment with little oxygen. Furthermore, as already noted, in our daily traffic with events we perforce make use of sketchy summary generalisations involving causal concepts, precisely because they spare us the need to say what it is about, e.g., the match or striking it that explains why it acts as it does. We then simply assume that a vast number of (unspecified and unspecifiable) factors that might have interfered with the history leading up to the event to be explained did not interfere. We short-circuit part of what a fuller explanation would make manifest by appealing to more precise laws: laws that avoid or at least reduce the use of causal concepts, and clauses like ‘other conditions being favourable’ or ‘other things being equal’ (ceteris paribus). In the lighting match example, one may think of laws involving the concepts of friction and heat and laws involving the concepts of phosphorus, sulphur, oxygen (perhaps made explicit in exothermic chemical reaction schemes). It is clear that such concepts, in terms of which the relevant objects and events will have to be characterised in order for the laws to be applicable, only have remote connections with the descriptions under which the objects and events interest us for everyday purposes. Even more so if we were to appeal to laws governing the electromagnetic interactions between charged particles. But, of course, there are other interests than our mundane needs, among them those that are pursued in the various sciences. At the other end of a continuum of explanatory interests, for instance, we find the all-governing concern for maximum generality, for laws that are as precise, explicit, strict and as exceptionless as possible. In a developing physics we can hope to find generalisations whose positive instances give us reason to believe that they could be sharpened indefinitely by drawing upon the same vocabulary. This then points to the form and vocabulary of the finished system of laws, with a theoretical asymptote of perfect coherence with all the evidence and perfect predictability and total explanation under the terms of the system.

To summarize, in giving a causal explanation of an event we normally take for granted a great deal of background, and what we typically want to know is what to add to that

[1] In this sense the concept of a match is a causal concept, i.e. a concept that has the notion of causality irreducibly built into it.

background to make the occurrence of the effect intelligible. In order to achieve this it must prove possible to so characterise the event to be explained and the addition to the background that they fall under a (more or less strict and more or less lawlike) generalisation. What vocabulary and laws we settle on is to some degree a matter of the explanatory interests we happen to have. This I take to be rather uncontroversial facts about causal explanation. There are of course some controversial issues involved here, such as whether it is possible to analyse the notion of cause in terms of necessary and/or sufficient conditions, whether there is a non-question-begging criterion of the lawlike, or whether it is indeed possible, even in a developing physics, to free laws of all ceteris paribus clauses. I do not wish to take a stand on such issues, however, though I will later add an element to the above discussion that may be controversial. Now I first want to point out that the explanatory scheme for motion introduced in chapter 2 does indeed belong to the genus of causal explanation.

The explanatory scheme for motion, it will be remembered, consists in (1) a characterization of an influence free (force free) motion, checked by (2) a characterisation of plausible lawlike statements (force laws) in which deviations from this influence free motion are correlated with properties of the configurations in which those deviations occur. Where in general causal explanations one accounts for a deviation in some background *state* by identifying a cause, this state in the case of explaining motions is an object in influence free *motion*, deviations of which are accounted for by identifying influences. The explanatory scheme still allows for a variety of specific explanations of motion, with different assumptions for an influence free motion, which to some degree reflect the variety of explanatory interests we may happen to have. In everyday life, for instance, we take a strong interest in how to move objects from *A* to *B*, or to move ourselves from *A* to *B* by means of some object. Within this context, it makes good sense to consider as influence free motion the way in which the objects would move without our interference (stand still or gradually come to a stop), given that at the same time we happen to know enough rough laws in which relevant deviations from it (setting in motion, keeping in motion, braking) are satisfactorily correlated to kinds of actions we can perform. Given another goal, e.g. hitting a target with a projectile, another type of motion can be considered as influence free, as long as this is checked by the availability of sufficient rough laws to account for relevant deviations from *that* one. Many of the intuitive rules concerning motion are (related to) rough laws between kinds of actions and deviations from a particular kind of motion, as I have tried to illustrate in chapter 2.

Whereas commonsense explanation of motion is highly pragmatic, with conspicuous ties to action, explanation of motion can also be pursued in a frame of mind in which we want to understand things irrespective of whether we can control them and irrespective of whether such knowledge will advance our mundane goals. In the latter case, explanation of motion, though it may answer to various interests, in itself is not interest relative. *Every* deviation from the assumed influence free motion, whether it is of practical interest or not, has to be accounted for by means of appropriate, ultimately exceptionless force laws. Due to these rather disparate explanatory interests, there is hardly any tension between commonsense and scientific explanation of motion.

But also within one and the same theoretical mood, the explanatory scheme can still be detailed in a variety of ways, both logically and to some extent also historically realised. The explanatory scheme can be seen, for example, as structuring the Newtonian framework. It consists in (1) the specification of a kind of motion that is to count as influence free (uniform rectilinear motion), and (2) interaction theory to account for all deviations from this kind of motion in terms of force laws. Force laws, such as Newton's law of gravitation, are general statements that specify the forces objects exert on each other as a function of their total configuration (Jammer, 1957, chapter 12). Another, and less well known and developed way to detail the explanatory scheme is due to Kepler. It consists in (1) taking *rest* as the influence free motion, and (2) interaction theory to account for the deviations. This leads to a concept of force that differs from the Newtonian one. Keplerian net forces, just to name one difference, are of necessity always in the direction of motion. In order to account for planetary motion, Kepler imagined some kind of spokes emanating from the sun and pushing the planets along their orbits as the sun rotates about its axis (Barbour, 2001, section 6.6; Jammer, 1957, chapter 5). It is possible to make Kepler's idea precise and to formulate more or less plausible Keplerian force laws, which lead to the same predictions of planetary motion as within the Newtonian framework on the basis of a gravitational influence directed to the sun.

Within both the Keplerian and the Newtonian scheme, deviations from the assumed influence free motion provide motives to construct a theory that succeeds in accounting for the deviations. Because there are no guarantees that one will be able to do so, there does arise a rivalry between the two schemes. Their relative merits will have to be evaluated in the light of a shared commitment to the usual epistemic virtues associated with their fundamental aspirations, such as those of strict empirical adequacy and broad applicability. For further discussion of the status of laws of motion I refer to Nagel (1979, section 7.II) and Friedman (1983, section III.7).

I hope the above sufficiently places the explanatory scheme for motion within the realm of causal explanation. I will now close with a more fundamental discussion of the status of the scheme, or rather of causal explanation in general. It is based on the work of Davidson (e.g.: (Davidson, 1995; Davidson, 2001)).[2] I began this section by pointing at the (at least implicit) appeal to laws or lawlike generalisations in explaining why an event occurs. What will now be added to this is the suggestion that the conceptual connections between the notion of event (and other basic ones such as those of change, object, cause, substance and kind) on the one hand, and the notion of generality on the other, may be tighter than that they happen to both occur in causal explanations. What we have taken for granted in the discussion of explaining the occurrence of an event, for example, is what an event *is*, apart from an apparent incentive to provide an explanation. One natural proposal for a definition of an event or change might run as follows: some predicate P is true of an object at a given time t and subsequent to t P is no longer true of that object. This can only be right as a definition, however, if we have

[2] Similar ideas can be found in the work of others, amongst them Spinoza, Kant, and Hamilton, as is e.g. made clear by Heymans' (1890) overview of how the notion of causality functions in the work of philosophers from 17th to the 19th century.

independent means of saying what objects are or which predicates count as state-descriptions. But we do not have such independent means. In fact, the problem what a change or event is, is pretty much the same problem as what an object is or what states it can be in. Davidson's suggestion, as formulated by Ramberg (1999), is that '[w]hat we count as an object and what we count as a state of an object, as well as what we count as a change, is governed by our fundamental interest in construing our environment in terms of generalities. [...] to recognize a change in the state of a physical object just *is* to recognize an event which is susceptible to explanation in terms of empirical law. [...] our identification of objects and the changes they undergo implements and is given point by the explanatory generalizations to which they yield, and by which we manage our dealings with them. […] the observer of physical events cannot but see them as, on the whole, instances of how things generally tend to go. We couldn't fail to discover general relations by which we understand the changes we perceive in the physical world about us, because we are by nature disposed to count as changes and as persistent objects of such changes whatever will yield general patterns allowing us to predict our environment.' This fundamental interest in generality is very clearly encapsulated in the so-called cause-law thesis. It says that if two particular events are related as cause and effect (*a* caused *b*), that then there is a law (a lawlike generalization) to the effect that 'all events similar to *a* will be followed by events similar to *b*'. That is, we have reason to believe the singular causal statement only in so far as we have reason to believe there is such a law (and we may have good reason to believe there is such a law without knowing what the law is). Davidson's suggestion is that the cause-law thesis is built into the very application of the concepts of object, state, change, and so on. Similarly, it is constitutive of the concept of change that like changes will happen under like circumstances; and constitutive of the concept of object, that like objects undergo like changes under like circumstances.

The built in interest in construing our environment in terms of generality pulls together the whole continuum of non-mental sciences from our most primitive concepts of objects and their modifications to advanced physics. Not in the sense, of course, of providing a single all-purpose class containing all and only objects, a single all-purpose class containing all and only changes, and so on. The cause-law thesis and its variants only set *constraints* on what is to count as objects, changes, laws, and so on. They offer a *scheme* into which what we are to count as objects, changes, laws, and so on, must fit: 'events are changes that explain and require such explanations. This is not an empirical fact: nature doesn't care what we call a change, so we decide what counts as a change on the basis of what we want to explain, and what we think available as an explanation. In deciding what counts as a change we also decide what generalizations to count as lawlike. [...] if you can't explain it using one assumption of what counts as a change, adopt new categories that allow a redefinition of change. The history of physics is replete with examples of such adjustments in the choice of properties, thus altering what calls for a causal explanation.' (Davidson, 1995) Furthermore, the application conditions of the terms of the vocabularies of common sense and the various sciences are to varying degrees also constrained by whatever special interests are associated with them, and may thus trace different patterns of events. Still the characterisations they deliver are all, though each in its own way, geared 'to show up the general patterns in the changes that their objects undergo, general patterns the articulation of which amounts to providing a body of laws, or lawlike generalizations.' (Ramberg, 1999)

2.2. Relevance of the explanatory scheme for mechanics teaching

Let us explore the question how the explanatory scheme for motion might become useful for education. The explanatory scheme for motion will be useful for education when it somehow contributes to reaching the goals of understanding mechanics, of appreciating its power and range and, related to my problem analysis, of changing the aims and interest of the students and of providing them with a vocabulary with which the usual learning difficulties can be discussed.

A first basic idea that comes to mind when thinking about the explanatory scheme for motion's relevance is that it is the same in both common sense and Newtonian explanations of motion (as was seen in chapter 2 section 3.2.1 and in the previous section). In reaching an understanding of mechanics it might therefore provide a useful basis to build upon.

A first step in building on students' use of the explanatory scheme for motion would involve making this use explicit. If this first step is taken and students realise that the explanatory scheme for motion describes what they do when they explain motion, a second step can be attempted which involves recognising the explanatory scheme for motion in Newtonian explanations. In a third step the findings from the first two steps can be compared. Students can come to realise that Newton explained motions in a structurally similar way as they do. There are also striking differences in the choices made in specifying the scheme, like Newton's apparently peculiar meaning of 'force' and 'forcefree motion'. Comparing the explanatory scheme for motion in both their own and Newtonian explanation of motion will also point to their difference in terms of differing aims and interests and may therefore be useful in changing the practical aims and interests of the students in theoretical aims and interests of Newtonian mechanics.

However, such a direct comparison of students' and Newtonian explanations in the third step is problematic for two reasons. Firstly, practical explanations of students are already quite complex in Newtonian terms, because they usually involve multiple forces like friction et cetera. Secondly, in order to appreciate the more theoretical aims like strong empirical adequacy and broad applicability of Newtonian explanations some context is required in which a strictly practical explanation alone is unsatisfactory.

An alternative third step that involves mainly theoretical aims and therefore may take the previous objection into account is comparing explanations of Newton and Kepler of the motion of heavenly bodies. Since Kepler can be seen as a spokesman for common sense ideas about mechanics (notably rest as influence free motion and a 'force' always in the direction of motion), comparing Newton to Kepler is almost equivalent to comparing Newton and common sense. It is not essential that Kepler resembles common sense notions. As I will argue later any comparison as such will do, as long as both alternatives have theoretical aims. However, it can be expected that the stronger the students can recognise Kepler as a spokesman for their own opinions, the more committed they will be in the comparison. This alternative third step would also imply an addition to the second step, where the explanatory scheme is not only recognised in Newton but also in Kepler. I will first argue that comparing these two important historical figures might be useful and then that the context of motion of heavenly bodies is promising.

The choice for Kepler and Newton is based on two reasons. It will be remembered that firstly, both Newtonian and Keplerian models can be seen as specifications of the explanatory scheme for motion and can therefore be investigated from the perspective of the scheme and in turn illustrate the scheme. Secondly, both Kepler and Newton had similar aims and interests, namely to arrive at a general theory for the motion of heavenly bodies (and in the case of Newton even all motion). Comparing these alternative kinds of models requires criteria for evaluating (types of) models, that will not surface when comparing for instance a Newtonian explanation of some motion with a common sense explanation of the same motion. I will elaborate on these two reasons by sketching how comparing Kepler and Newton can help to reach the aim of understanding (Newtonian) mechanics and why the required criteria are important for my goal of developing some appreciation for the power and range of mechanics.

Both Keplerian and Newtonian models can be seen as specifications of the explanatory scheme for motion. An assumption for an influence free motion coupled with the identification of influences can be seen in both of them. They differ in the assumptions for the influence free motion (in this case rest and rectilinear motion with constant velocity respectively) and then of course also in the concrete influence laws and how this determines the motion precisely. The latter involves the concept of inertia and a 'second law'. So influence laws, inertia and a 'second law' according to both Kepler and Newton can be studied from the perspective of further specifying the explanatory scheme for motion. That means all of mechanics (with the possible exception of Newton's third law and Kepler's equivalent of Newton's third law[3]) can be introduced using the framework of the explanatory scheme for motion.

Comparison of alternative kinds of models, in this case Keplerian and Newtonian, can serve to find explicit criteria for evaluating these different kinds of models. These criteria provide the reasons for valuing Newtonian mechanics more than Keplerian mechanics. Since one of my main goals is to arrive at some sense of appreciation for (Newtonian) mechanics as an exemplary scientific theory, that is to say a theory that is far reaching or general, empirically adequate and plausible, these criteria are essential. Studying two alternative kinds of models quite naturally raises the question whether one kind of model might be preferable and how one could decide this. So the explanatory scheme for motion is relevant for reaching this educational aim.

I have explained why a comparison of Keplerian and Newtonian models seems useful, but not yet why this comparison might take place in the context of the motions of

[3] Newton's third law might be addressed as part of the interaction theory aspect of mechanics, where it serves as a constraint on force laws. Mechanics can be conceptually divided into an interaction theory consisting of force laws and the third law and a force-motion coupling theory consisting of the second law, kinematics and first law. Implementing a discussion of the third law into this approach seems quite possible, but was not attempted in this research. I will therefore refrain from further speculations regarding the third law.

heavenly bodies. The first reason for this is that explaining and predicting the motion of heavenly bodies is one of the big successes of science in general and mechanics in particular and therefore the historical example par excellence to illustrate its power and range, which was one of my aims. Secondly, these motions seem suitable to promote understanding of mechanics (another aim) since they are relatively simple for they involve only one influence (the complicating factor of friction is not an issue). Furthermore, motions in a curve also show in the Newtonian case more clearly deviations from the assumed influence free motion than do linear motions. One might object that investigating the motion of heavenly bodies introduces the complicating factor of a varying force, since gravity depends on distance and will therefore not be constant. This apparent complicating factor may not be that confusing when all calculations are left to a computer model. It may even prove useful to illustrate the fact that influences are functions of attributes of the configuration. (It's not a bug, it's a feature!) Thirdly, the context of motion of heavenly bodies quite naturally avoids triggering practical aims and interests and seems therefore suitable to instil a theoretical orientation, which was already argued to be important for both the goal of understanding mechanics and appreciating its power and range.

There is yet another reason why the explanatory scheme for motion is relevant for education: It may provide a vocabulary for addressing the usual learning difficulties in mechanics. In the language of the scheme the similarities and differences between common sense and Newtonian explanations of motion can be made explicit, and will strongly resemble the similarities and differences between Keplerian and Newtonian explanations of motion, I expect. Even common sense notions that do not resemble Keplerian notions can now more easily be addressed since criteria for valuing choices in specifications of the explanatory scheme have been established and comparing explanations has been practiced. Hereby students can come to understand why their explanation is unsatisfactory from a particular (scientific) perspective, but completely okay from another (practical) perspective. Also why one would prefer a Newtonian explanation over another, probably more intuitive, explanation given the aims and interests of science.

Take for example the following item from the FCI (item 5):

> A boy throws a steel ball straight up. Disregarding any effects of air resistance, the force(s) acting on the ball until it returns to the ground is (are):
>
> (A) its weight vertically downward along a steadily decreasing upward force.
>
> (B) a steadily decreasing upward force from the moment it leaves the hand until it reaches its highest point beyond which there is a steadily increasing downward force of gravity as the object gets closer to the earth.
>
> (C) a constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point, after which there is only the constant downward force of gravity.
>
> (D) a constant downward force of gravity only.

(E) non of the above, the ball falls back down to earth simply because that is its natural action.

A similar question about identifying influences is likely to occur in any regular course on mechanics. The given alternatives can each be discussed using the vocabulary of the explanatory scheme. For instance the plausibility of the upward force in (A), (B) and (C) can be questioned. Where does it come from? Finding some kind of plausible regularity relating this influence to attributes of the configuration, e.g. the hand, may prove to be very difficult. Also the question can be raised what influence free motion seems to be assumed in the various alternatives. Alternative (E) shows falling down as assumption of an influence free motion that differs from Newton's assumption. This explanation is therefore not Newtonian (Aristotelian in fact), but does account for the downward motion. It does not mention or explain the upward part of the motion. Reasons for preferring a Newtonian explanation to another common sense or Aristotelian explanation can at such a point be recalled (its empirical adequacy, plausibility, range, et cetera). Another question that can be asked is: Why does the identified influence has to be there? Answering this second question is for many students reason to identify an upward influence for the first upward part of the motion. Here can be recalled that in the case of Newtonian explanations it is not necessarily the case that there is always an influence in the direction of the motion. A Newtonian explanation using a single constant downward influence can account for this motion, which can be shown with a computer model or graphical construction.

Until now I have argued in this section for the relevance of the explanatory scheme for motion in teaching mechanics. The condition sine qua non for this relevance was that use of the explanatory scheme for motion by students could be made explicit to students (step 1). Then use of the explanatory scheme for motion by Newton could be made explicit (step 2). I also argued that comparison of Newton's use to Kepler's use is preferable to a direct comparison to the students' common sense use. In the next section I will turn to the question how the first condition of triggering and explicating the explanatory scheme may be met.

2.3. Triggering and explicating the explanatory scheme

It is important to note that the idea that causal explanations of motion can be interpreted from the perspective of the explanatory scheme for motion itself is not a hypothesis to be tested. I take it to be given for this research. Of course, it is not given as a matter of fact and I have given arguments for it in section 2.1. But, as argued there, the status of the explanatory scheme is so basic and constitutive for how one understands the world that it is among the last things I would give up. The question I am interested in here is not whether students make use of the scheme, but *if* and *how* this use could be made explicit to students as a first step in making the explanatory scheme productive in teaching/learning mechanics. Although students make implicit use of the explanatory scheme for motion they most likely are unaware of this. This can be compared to people almost all the time making correct implicit use of logical rules in their conversations, but without formal training in logic they will be unable to explicate any of these rules.

Since I expect to be able to recognise the explanatory scheme for motion in all explanations of motion, a first idea to implement this idea in a course on mechanics could be to get students to explain motions, so that their use of the scheme could be pointed out to them in these explanations they themselves have given. But how can such explanations be triggered? With 'triggering the explanatory scheme' I simply mean making students explain motions. They do not have to realise themselves that what they are doing is 'explaining' a motion, as long as *I* can recognise an explanation in what they say. Furthermore, when students come up with explanations of motion, can the explanatory scheme for motion be explicated? And how? With 'explicating the explanatory scheme' I mean pointing out the scheme in their explanations in a way that students can understand. This understanding can vary from merely being able to follow what is said when the scheme is explicated, to being able to fill in elements of the scheme when asked (e.g. a correct response to 'what influence did you identify?'), to pointing out the scheme themselves without prompting questions (e.g. a correct response to 'how is the scheme used in this explanation?'). This last level I do not expect to be easily reachable. The extent to what they will be able to use the scheme themselves is uncertain.

Without a proper introduction of the explanatory scheme it will not be able to function as a guide for the rest of the introductory course and I would have fallen at the first fence. Since the start of the course has this importance and it was uncertain how the scheme could be properly explicated I decided to explore a particular idea of involving students in explaining motion in a pilot study, which I will describe shortly.

In this pilot study I tried to trigger the explanatory scheme for motion by showing (after one trial run) three pairs of 15 year old high ability students[4], which resembled the target group for the introductory course (see chapter 2, section 1)[5], video fragments of different motions:

1. a bicycle rider riding with constant speed
2. a bicycle rider not pedalling and coming to a stop
3. a tired ice-skater who continues to glide after a race
4. a basketball player taking a penalty shot
5. a race car taking a turn
6. a ball in a circle with gap.

Each fragment was paused after a couple of seconds and then the students were asked 'How will this motion continue?' and 'Why will this motion continue in this way?' The latter question is expected to trigger an explanation of motion. After having answered

[4] These students had already received some education in mechanics in the lower grades, but this can be considered irrelevant for our purposes.

[5] Although the target group consists of fourth grade (16 year) pre-university students before the regular mechanics course, these third grade (15 year) students were considered similar enough. In fact, since this pilot occurred shortly before the summer vacation, these students were only 3 months away from matching the target group perfectly.

these two questions the fragment continued and the students could see if their prediction was right. From these conversations about motions I then tried to explicate the explanatory scheme. Why in this way?

The first three fragments were meant to trigger the mentioning of two types of influences: personal influences, something a person does or does not do to change a motion (like pedalling and braking) and non-personal influences, something the environment does which changes the motion (like slipperiness and resistance). The division of influences in these two types was meant to make the concept of an influence free motion easier by first considering only personal influences to be absent, which was expected to be easier because students have a plausible interaction theory available to explain deviations from the influence free motion. Students have experience with or can easily imagine what will happen with or without some personal influence, whereas they do not with non-personal influences. The plan was that after considering only the personal influences then the more difficult step can be taken of considering all influences to be absent. I would then explicate the scheme by pointing out that there is a certain way in which they, the students, explain these motions. They have all identified influences on the motion, I expect mentioning of e.g. pedalling, braking and 'being slippery' or 'resistance' or whatever the students put forward. In their explanations of some motions the identification of influences must, at least implicitly, have been accompanied by an assumption of what would happen with the motion when these influences were absent. I would then try to give an example from the answers of one or two students. I did not expect students to grasp completely the idea of the explanatory scheme for motion at this stage. I did expect them to find the categorisation into personal and non-personal influences straightforward. Three more fragments were shown and discussed to identify some more influences, to practice with the explanatory scheme for motion and to notice what one might assume for influence free motion.

Data gathering, analysis and presentation

I have chosen interviews with pairs because then the students can interact with each other and the interview may be perceived as less frightening than when students are alone. When there are more than two students in a group managing problems may make it more difficult to flexibly react to what happens. Since this pilot study only aimed to get some grip on and feeling for the triggering and explicating of the explanatory scheme few interviews were thought to suffice. The interviews were audio taped and transcribed. The analysis of the interviews consisted of a comparison of the actual conversation with the expected one, which was described in an extensive interview plan. Expectations were made explicit for this reason (enabling the analysis) and also to facilitate the actual interview. My interpretation of all three interviews was discussed with a second researcher, who read the interview protocols. Most of the time agreement about a particular interpretation was reached. Only those instances of agreement were used to base conclusions on.

In the presented fragments the teacher will be indicated with 'T', the students with the first letter of their first name, except when this could be confusing in which case the first three or four letters of their first name will be used and the researcher or interviewer with 'I', throughout this thesis. Pauses are indicated in parentheses by their length in seconds, e.g. '(3s)' means a pause of three seconds. Dialogue written in parentheses means that I could not hear that part very well. Statements written in square parentheses are comments from me. The fragments were stylised in two ways. Firstly literal repetitions and humming were deleted. Secondly spoken language was transformed in 'written spoken language' by deleting stutters, too many ahs and ehms, not functional repetitions and adjusting the grammar.

Results

The first three video fragments sufficed in triggering examples of personal and non-personal influences. Comparing fragments showed the need for another influence like friction or resistance. There are clear examples of students' use of the explanatory scheme in all interviews, so this way of triggering the scheme worked as expected. The following is a representative example of this use of the explanatory scheme in which a bicycle rider not pedalling and a tired ice-skater who continues to glide after a race are compared:

1. I: When you compare this [fragment] now with that bicycle rider gradually coming to a stop, are there any differences?
2. B: Yes, she is standing on her own legs. The girl on the bicycle is again something else. She can control herself with her legs, so she does not start to wobble.
3. E: The one on the bike also falls when she stops, because she is standing on one thing. That skater will not fall, for she has two irons.
4. I: Other differences?
5. E: The girl on the bicycle also has to pull on and turn her steering wheel to keep on end.
6. I: Imagine that the ice skater never brakes nor will be forced to go to the side because of a next race, what will happen then? Will she continue riding rounds?
7. B: No, she will go slower and at a time come to a stop.
8. I: But how does this come about?
9. E: Because she has no more speed. She does not make any new speed and the speed she had at the beginning will be exhausted.
10. I: Can you also say such a thing with the bicycle rider: She has a certain speed and that will be exhausted?
11. B/E: Yes.
12. I: But how does it come about that the bicycle rider comes to a stop much more quickly?
13. E: More resistance of the tires and the surface of the road.
14. B: Yes, ice is more slippery.

There is an unexpected focus on another than the expected non-personal influence, namely balancing. The ice skater can balance by using both legs (2, 3). The bicycle rider balances by pulling and turning her steering wheel (5). In this an unexpected use of the explanatory scheme for motion can be found: The identified influence (balancing) causes a deviation, in a way which is known to be effective, from what would have happened without that influence, namely falling. After the interviewer tried to shift the focus of attention to the decelerating (6), another (and more expected) form of the explanatory scheme for motion was found (7, 9). She will go slower and at one time stop, because she does not *make any new speed* (=influence) and the speed she had will have been exhausted. The influence free motion in this case is a 'depleting speed' or deceleration. The third fragment as such did not trigger new influences, as expected. By comparing the fragments students could readily name a non-personal influence, resistance (13, 14), which was the purpose of the comparison. In order to be able to give such an answer it is essential to have a plausible regularity available relating resistance to more quickly coming to a stop, like 'more resistance results in more quickly coming to a stop' or 'slipperiness results in less quickly coming to a stop'.

The students agreed on what would happen with a motion when all personal influences are left out of consideration. This setting aside of personal influences was in the three video fragments not perceived as a strange thing to do. The next step, setting aside *all* influences was after that still difficult but at least not a strange thing to do. The students were willing and able to think along in these terms of the explanatory scheme, that were therefore to some extent clearly explicated for them. As expected, the result of what would happen with the motion in that case was not so clear and students simply did not know or had no clear ideas about this influence free motion and therefore neither about an interaction theory. This however concerned the specification of the scheme. The main point here is that they were able to consider what these concrete specifications might be. Take to illustrate this point the following explanations of two students about what would happen with the motion of a thrown basketball after setting aside all influences.

Question: What would happen with the motion when we set aside all influences?

1. E: It will remain floating. At some time.
2. I: Do you also think that?
3. R: Yes, it will just continue according to me.
4. I: How should I see that?
5. R: It will keep the direction in which it is thrown, I think.
6. I: E, you said that it would remain floating.
7. E: Yes, at some time it stands still.
8. I: Immediately? Or how should I see that?
9. E: Immediately. I think it stands still immediately. The [basketball] player did not provide it with any force.

The students could fairly easily be let to consider what would happen when these influences were absent. They did not show signs of misunderstanding the point or meaning of the question, but instead offered different speculations for a choice for influence free motion. E assumed rest (7, 9) and R assumed rectilinear motion (3, 5).

One exceptional student, Roland, could even apply the practiced way of explaining motions to the example of a race car taking a turn, which was used in one of the try-outs of these interviews:

1. I: How will it continue?
2. [E: It will take the turn.]
3. R: It will just continue.
4. I: Ok. I have asked you several times before. Now try to explain this all by yourself, like we did with the other examples. You start (Roland).

5. R: Eh, according to me, with resistance it will normally continue, but then you have to keep applying force. When there is no force left, it will eventually come to a rest. When there would be no resistance, it would continue indefinitely.
6. I: Ok, but who is applying force?
7. R: Ehm, yes, the engine is, rather.

The motion that is explained is not the turning of the car, which was intended with this fragment, but the continuation of the car (3). Roland identifies two influences: a ‘force’, he later attributes to the engine (7), and resistance. He sets aside first the ‘force’, leading, resistance still being there, to the car eventually coming to a rest. Secondly he sets aside resistance too, leading to the car continuing indefinitely (5). That he is able to correctly apply the scheme indicates that he must recognise its logic.

In conclusion can be said that the triggering of the scheme went according to plan and it was rather easy. The extent to which the scheme could be explicated in the course of one interview can be described in the following way. Students were not particularly surprised or confused with my account of the explanatory scheme and they could be led to consider questions like ‘which influences are working’ and ‘what would happen when all influences would be absent’ in a quite natural way. This indicates that they had some understanding of the meaning of the scheme.

3. Research question and method

In section 2.1 I discussed the explanatory scheme and its status. I have indicated the didactical possibilities of this scheme in section 2.2 and presented some indications that it can be triggered in and explicated to students in section 2.3 to continue on this path. The remaining question I would like to explore is whether and how this can be made productive, concrete, in real life education.

My research question is how the idea of a common explanatory scheme for motion in common sense and Newtonian mechanics can be made productive in teaching/learning mechanics.

Although the idea of the explanatory scheme for motion might be applied to a complete mechanics course for secondary education, such an endeavour would be unnecessary for exploring how this idea may be made productive. I therefore decided to apply the idea in a design of an *introductory* course. Normally in an introduction of any study topic one expects to find what the topic is about and some indication of the importance of studying the topic. In my case this fits in nicely with my aims of giving students some sense of how mechanics works and the power and range of mechanics. This introduction does not replace the normal course in mechanics students receive, but is simply something extra at the beginning. To distinguish between the introductory course I designed as a means for answering my research question and the regular course that follows this introduction I shall henceforth call the former ‘introductory course’ and the latter ‘regular course’.

In the regular course productive use of the introductory course could be made by placing the details of the regular course in the bigger picture provided for by the introductory course and by using the vocabulary of explanation to address alternative explanations of motions that inevitably will occur. This will require some slight additions or adaptations in how the regular course is executed. Indications for the teacher as to how the introductory course could be used in the regular course will be part of my design. Whether this use will turn out to be productive is part of the research question. The research question concerns therefore both how the scheme can be used in a design of an introductory course that will lead to my educational aim of making students appreciate the power and range of mechanics and know how mechanics works and whether this course will provide the vocabulary to address the usual learning difficulties reported in literature to be used in the regular course following this introductory course. There is of course the possibility that the scheme cannot be made productive at all. For this to conclude many attempts of putting it to work would have to have been made, and this can therefore not be an outcome of my research[6]. I *can* come to the conclusion that *my* attempt of making the scheme productive failed, of course.

Design research

I will attempt to answer the research question by means of a design experiment. I will not say much about the general features of and rationale behind design experiments (also called design-based research or developmental research). That has been done extensively elsewhere (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003); (Design-Based_Research_Collective, 2002); (Lijnse, 1995); (Lijnse, 2003). Suffice it here to say that trying to make the explanatory scheme productive in teaching/learning mechanics is quite a novel idea of which it is unclear how it can be done. By designing and testing some prototype of designed education and then revising the prototype and testing it again and so on in a cyclic process one can come to grips with this question of how it can be done. Such a design can be expected to suffer from many growing pains. Enough of these will surface in one trial with one class taught by one teacher. One such trial will result in a plethora of indications for revisions in the design[7], which, after being revised, can be put to the test again. Such a second trial can be expected to still suffer from growing pains, albeit hopefully less so than in the first trial or at least differently.

Testing a design raises some important methodological points that need to be taken into account when applying this research method. Firstly, the didactical quality of the design has to be object of study. When a domain specific didactical theory is the aim, all the aspects of the teaching/learning process, like the teacher's role, the learning activities or just 'what happened in the classroom', and their interrelatedness should be studied. "Didactics concerns the organisation of the content to be learned both in a sequence of successive learning activities and in supportive teaching activities, in such a way that it supports the learning process of the students and the learning goals are sufficiently met" (Westbroek, 2005, p. 51). Secondly, expectations need to be formulated, thereby making it clear to understand why the design was designed in the way it was. Behind a

[6] How many trials are needed before one concludes that something cannot be done? If one is stubborn enough one can always say: 'try harder'. Perhaps the deciding factor is the availability of a better alternative.

[7] Anyone with some experience in any kind of design knows that the first prototypes will not work as intended. Earlier experiences in designing education, e.g. (Knippels, Waarlo, & Boersma, 2001; Kortland, 2001; Verhoeff, 2003; Vollebregt, 1998) indicate the same finding.

design ought to lie some justification of why this design is expected to do what it must do. These expectations are then subject to empirical testing, resulting in further improvement of the design and to a domain specific didactical theory as result.

An important tool for ensuring or helping that the just mentioned methodological issues are addressed is the *scenario*. It describes and justifies in considerable detail the learning tasks and their interrelations as well as the actions that students and teacher are expected to perform. It can be seen as a hypothesis, as a prediction and a justification of the teaching/learning process that is expected to take place. As such, it also enables the researcher to precisely observe where the actual teaching/learning trajectory deviates from what she expected, and thus to test her hypotheses in a valid and controllable way.

In the scenario a justification is given for each teaching/learning activity, of why this particular activity should take place, what the local goals of the activity are and why this activity would be expected to meet these goals. All successive local goals should of course lead to the global goal of giving students some sense of how mechanics works and some appreciation of its power and range. Such an explicit description allows for the didactical quality of the design to be object of study. More details on the scenario will follow when I present my scenario for the introductory course in chapter 5.

There are some practical considerations that influence this research. Time restrictions allowed two consecutive trials. The lesson time available for trials was ten 50 minute lessons for the first trial and twelve 65 minute lessons for the second trial. The choice for the length of the course is based on the following considerations: The length is restricted by the number of lessons a teacher is willing to spent on such a course instead of the regular program and by the amount of data the researcher is capable of handling in the course of a 4 year research project. Of course also a minimum amount of lessons is needed to develop the basic idea.

The choice for the target group, upper level pre-university students (age 16), is based on my expectation that the required ‘theoretical mood’ (see section 1 in this chapter) can more easily be developed in academically inclined pre-university students. Also at this stage students start with mechanics in the Dutch educational system[8], making an introductory course appropriate.

4. Theoretical guidelines for the design

In chapter 2 approaches contributing to solve the problem of lack of understanding in mechanics were divided in three categories: theories about the problem (that might be used by others in application to education), guidelines for teaching, and spelled out education (in the form of learning materials, teacher guides et cetera). It may be clear from the previous section that I opt for the third category. Only in a developmental

[8] In earlier grades students studied mechanics as well, but this background I consider to be irrelevant for my purposes. The fact that mechanics in upper level secondary school effectively starts all over again points to a similar lack of confidence in students’ knowledge and skills concerning mechanics acquired in lower level secondary education by teachers and schoolbook writers.

process of designing and redesigning concrete real-life education can the question how the idea of an explanatory scheme for motion be used productively in teaching and learning mechanics be answered. The devil is in the details. In my opinion the task of applying educational guidelines based on research of some particular kind is difficult and time consuming and is therefore not solely the job of teachers. In order to improve education in mechanics one should come up with something more explicit than guidelines for teaching, that is to say, concrete developed education.

Developing some course will show to some extent the views on teaching and learning of the developer. These views can be seen as guiding the design and are important to be made explicit, which will be done in the next section, section 4.1. Other guidelines can in this particular case be found in earlier work that had similar views on education. This earlier work of Kortland and Vollebregt resulted in so-called didactical structures within a problem posing approach. (Both terms, didactical structure and problem posing, will be discussed extensively later.) Their didactical structures can be seen as designing aids for future similar approaches and were used as such in my design, which will be described in section 4.2.

4.1. View on teaching and learning

A view on teaching and learning to which I adhere, its relation to constructivism concerning both similarities and differences and the specific emphasis on problem posing has been described before (Vollebregt, 1998); (Kortland, 2001). For presenting my view in this thesis I will rely on an excerpt from an article from IJSE (2004) by Lijnse and Klaassen which I think puts the same matter clearly.

> "For the design of teaching sequences, e.g., in principle it may make a difference whether one starts from a receptive, behaviouristic, discovery or information-processing view on learning, to name just a few influential views from the recent past (Duit and Treagust 1998). Even though such differences may, in didactical practice, turn out to be much smaller than expected. Regarding views on learning, much attention has been drawn recently by constructivism. To our opinion, the didactical relevance of that view boils down to the rather trivial phrase that 'new knowledge is constructed on the basis of already existing knowledge' (Ogborn 1997). As such, this view does not relate directly to a view on teaching as the construction process of the learner takes always place, irrespective of how it is being taught. However, if one wants to prevent a learning process that results too quickly in a *forced* concept development full of misconceptions, or, in other words, if one adopts the view that teaching should result in something like real understanding, it seems necessary to allow students ample freedom to use and make their constructions explicit, e.g., by means of social interactions with the teacher and/or peers (freedom from below), and at the same time to carefully guide their construction process in such a way that it results in the aims that one wants to reach (guidance from above).
>
> Finding an adequate balance between this necessary freedom from below and the equally necessary guidance from above lies at the heart of our didactical research. It means that one tries to guide students in a *bottom-up*

teaching/learning process, starting from *common ground* (i.e. starting from shared, and known to be shared, ways of thinking about the world), by designing teaching activities that are to gradually create places in students' conceptual apparatus for the concepts and skills one wants to teach to occupy. In that sense, we can give content to the phrase 'construct new knowledge on the basis of already existing knowledge'.

At first sight, this view seems to represent nothing new, as is clear from many reports about 'constructivist science teaching' (Scott, Asoko and Driver 1992; Leach and Scott 2002). In our work, however, we differ in two major aspects from these reports. Though we take 'educational constructivism' in the above sense as a first starting point, we do not adhere to the 'alternative framework' movement. In our view, students' beliefs about their experiential world are, in general, largely correct, which implies that, if properly interpreted, we can always find common ground to start from in our teaching process (Klaassen 1995; Klaassen and Lijnse 1996). As far as cognitive learning is concerned, we think it best to think of science learning as a process in which students, by drawing on their existing conceptual resources, experiential base and belief system, come to *add* to those (with accompanying changes of meaning).

What we think needs to be added to this picture, as a second starting point, is that if this process is to make sense to them, students must also be made to *want* to add to those. Or, in other words, students should at any time during the process of teaching and learning see *the point* of what they are doing[9]. If that is the case, the process of teaching and learning will probably make (more) sense to them and it then becomes more probable that they will construct or accommodate new knowledge on grounds that they themselves understand. An approach to science education that explicitly aims at this, we call *problem posing*. The emphasis of a problem posing approach is thus on bringing students in such a position that they themselves come to see the *point* of extending their existing conceptual knowledge, experiences and belief system in a certain

[9] The following quotation, as reported by Gunstone (1992), shows that this is not a self-evident condition.

"In the following typical example, the student (P) has been asked by the interviewer (O) about the purpose of the activity they have just completed.

P: *He talked about it……..That's about all…..*

O: *What have you decided it [the activity] is all about?*

P: *I dunno, I never really thought about it …. just doing it – doing what it says … its 8.5 …. just got to do different numbers and the next one we have to do is this [points in text to 8.6]."*

In addition Gunstone (1992) writes: "This problem of students not knowing the purpose(s) of what they are doing, even when they have been told, is perfectly familiar to any of us who have spent time teaching. The real issue is why the problem is so common and why it is very hard to avoid". As a remedy, much emphasis has been laid on fostering students' general meta-cognitive knowledge and skills. Students should learn to learn. Without wanting to argue about the value of this emphasis, in our approach we adopt the additional view that it should also be clear to students on content-related grounds why and what they are doing.

direction. Thus formulated, also the second starting point seems rather trivial, and indeed it is. Since in themselves both starting points do not give any further detailed didactical guidance, the real *non-trivial* didactical challenge lies, as already mentioned, in the quality with which they can be put into practice. The more so as such an approach asks for a considerable change in didactical contract (Tiberghien 2000) as compared to what teachers and students are mostly used to.

In correspondence to this and in analogy to what Freudenthal (1991) writes about mathematics, we may say that we see science as a human activity and that, consequently, science teaching should guide students in '*scientificalising*' their world, instead of trying to transfer scientific knowledge as a ready made product. Freudenthal speaks in this context about a process of *guided re*invention that students have to participate in, adding that for its design it might be quite inspiring to look into the history of invention.

Our point of view of developing a problem posing teaching-learning approach along these lines thus asks for a thorough didactical analysis of common sense and scientific knowledge, as well as of their relation. How can we design a conceptual teaching pathway that is divided in such steps that, in a teaching situation, students are meaningfully able and willing to take them, building productively on what they already know and are able to? Can we make students ask or value questions that on the one hand make sense to them and that, on the other, ask for the development of (possibly adapted) new ideas and scientific concepts to be taught that provide an answer to their questions?

That means that, for them, the concepts to be reinvented will function for a particular purpose, and that the reasons for their construction and acceptance are directly derived from that functioning. In doing so, apart from being guided, knowledge construction within this problem posing approach is, in a sense, similar to the process of professional knowledge construction within science itself. Knowledge is (guidedly) constructed for a certain purpose. And it is accepted by those who construct it to the extent that it functions productively for that purpose" (Lijnse & Klaassen, 2004).

4.2. Use of earlier problem posing designs

Since it is my aim to develop a problem posing educational design it seems worthwhile to explore earlier designs with the same aim and see how these might become useful. The work of Vollebregt (1998) involved designing a problem posing course in an initial particle model. Since this topic is quite similar to mechanics in the respect that both aim for quite theoretical goals this seems a promising starting point to explore its possible use for designing a problem posing course on mechanics. It will turn out that this leads to the identification of four main themes in my design. I will first describe how these themes surfaced and then turn to some other use earlier problem posing designs had.

Four main themes

First main theme

One of the problems that need to be solved in a problem posing approach concerns the introduction of the topic. In my opinion each introduction should give students some sense of the importance and of the content of the subject to be learned. In other words an introduction should answer two questions: 'what is the topic about?' and 'why would I engage in it?' Taking this function of an introduction of any theoretical topic seriously results in a paradox[10]. How can one meaningfully indicate what a topic is about before starting it? One could of course take the introductory function not seriously and simply state what the topic is about, without considering whether this could be understood. For instance the topic of mechanics can be introduced by stating that 'mechanics is very important, it is about the three laws of Newton, the concept of force and mass et cetera'. Such an introduction does not give any understandable clue what mechanics is about to someone who does not know what the three laws of Newton are and what mass or force is. At the most it indicates which new words can be expected to get some meaning along the way. From a problem posing perspective this way of (not) dealing with the paradox is undesirable, for it does not provide the students with a motive or reason to engage in the topic and does not give any direction in what the problem with explaining motion might be, or how it might be solved, answered or explored. In terms of a problem posing approach dealing with this paradox can be expressed as finding a broad motive. This is particularly hard for theoretical topics, since the goal of understanding a particular theoretical topic (to the extent that it can provide some direction in how to engage in it) is more difficult to imagine at the start than a more practical goal (see also the last footnote). Vollebregt encountered this difficulty when she indicated that she did not succeed well enough in establishing an answer to the why- and what-questions in the introduction of her course on particle models.

Let us look in slightly more detail to Vollebregt's ideas about the why- and what-questions, since these served as inspirations for the design of my introductory course on mechanics.

Vollebregt identified the importance of addressing the why-question and attempted to do that by appealing to an assumed intrinsic theoretical curiosity in pre-university students and showing that it can be worthwhile to pursue knowledge of an ever more general kind. "This more general knowledge may allow for understanding why previous (less general) regularities are as they are and, moreover, may be used to explain and predict more events in a better way" (Vollebregt, 1998). However, she was not content with this part of her design. "[A] real motive for the introduction of a specific particle model is still missing, and therefore initial activities cannot sufficiently induce a theoretical orientation." This expectation was later, in the test of the design, observed to be true. In the discussion of her findings she suggests that a possibly more fruitful approach may lie in a general introduction consisting of a historical account of famous

[10] In the case of practical topics there need not result a paradox. Take for instance the practical topic of learning to drive a car. Here the student can envisage right at the beginning a pretty clear picture of what it is she is going to learn, without knowing how to drive at that stage.

scientists, "in order to show that people have always thought about the origin of everything around them, have tried to classify matter and have tried to figure out how it all works and what it consists of. […] In this way, the teacher shows in general terms what is going to be the issue of the next lessons [i.e. answers the what-question; ASW] and meanwhile builds on a possibly existing curiosity of some of the pupils [i.e. answers the why-question; ASW]" (Vollebregt, 1998). In the case of my design for the introductory mechanics course this idea of a historical account to show the importance of explaining motion seems also useful.

Answering the what-question in Vollebregt's design took place in a procedural way: looking for better understanding of already established generalisations by searching for even more wide-ranging generalisations. In retrospect she was not fully content with this and would have liked to include a more content related answer to the what-question. For this she suggested that "pupils' attention needs to be focussed, from the start, […] on giving explanations in terms of the behaviour of constituting elements, which differs from the behaviour of the system as a whole," that is to say functional explanations. My research originated in the idea to appeal to basic intuitions in order to suggest a content related direction to answer the what-question. The explanatory scheme for motion may, for the topic of mechanics, provide for this.

Second main theme

Next Vollebregt introduced in her course an initial particle model that was right away acceptable to students since it could immediately explain some phenomena, although it was not motivated from a content related perspective (see above). Students then extended their knowledge by refining and adapting this initial model in order to explain even more phenomena. This part of the design did what it supposed to do and was therefore quite successful in that respect. A similar idea may be used in the case of the design of the mechanics course by letting students look for concrete explanations of motions as 'refinings' and applications (or specifications) of the explanatory scheme. Both Keplerian and Newtonian mechanics can be seen as particular specifications of the explanatory scheme as was seen in section 2.

Third main theme

In the design of Vollebregt students were expected to reflect on the nature of particle explanations and the process of modelling during and after the development of the model. For this the comparison of alternative explanatory frameworks (one in which the temperature is related to the speed of the particles and another in which the particles themselves become warmer or colder) was useful, because it triggered a discussion of the fruitfulness of these alternatives in which the nature of particle explanations naturally was addressed. Both the need for a reflection and the way to bring it about by comparison of alternative frameworks seem useful to adopt in the mechanics course. In my case, alternative 'refinings' or specifications of the explanatory scheme for motion.

Fourth main theme

Vollebregt made the structure in particle explanations explicit in order to facilitate subsequent study of particle models in topics or subjects like electricity, nuclear physics, chemistry et cetera. Her design ends with an outlook on subsequent particle models. She did not indicate how in these later topics use could be made of her course. In my case I will give some indications of how use can be made of the introductory course in the regular course in mechanics, since it aims to be *introductory*, that is, it should have some use for the regular course.

Recapitulating it can be said that the work of Vollebregt suggests three successive themes that need to be addressed in a problem posing design for my introductory course:

- The *why* and *how* of introducing the topic. The explanatory scheme for motion plays a role in the 'how'.
- Extending students' knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining motion.
- Reflection on the knowledge developed so far and the method of working. This consists of an evaluation of models and *types* of models in the light of achieving broader applicability.

To these three themes I like to add a fourth:

- Preparation of and embedding in the regular course.

This last theme has understandably little emphasis in Vollebregt's work since her course was not designed to be an introduction.

Earlier didactical structures guiding the design

Apart from (in a way) prescribing successive themes a problem posing design should address, the work of Vollebregt was useful for my design in another respect. Use of so-called didactical structures had implications for thinking about my design. I will first say something about what didactical structures are and then indicate what implications these structures had for my design.

A didactical structure of a topic is a functional description of the main steps in teaching/learning the topic. Both the work of Vollebregt and the not further discussed work of Kortland (2001) resulted in didactical structures. To make clearer what is meant by didactical structure let us take as an example the graphically represented didactical structure of the education designed by Vollebregt, see Figure 1. The point I want to make here is the use of structural elements, not the precise content of these elements in her course.

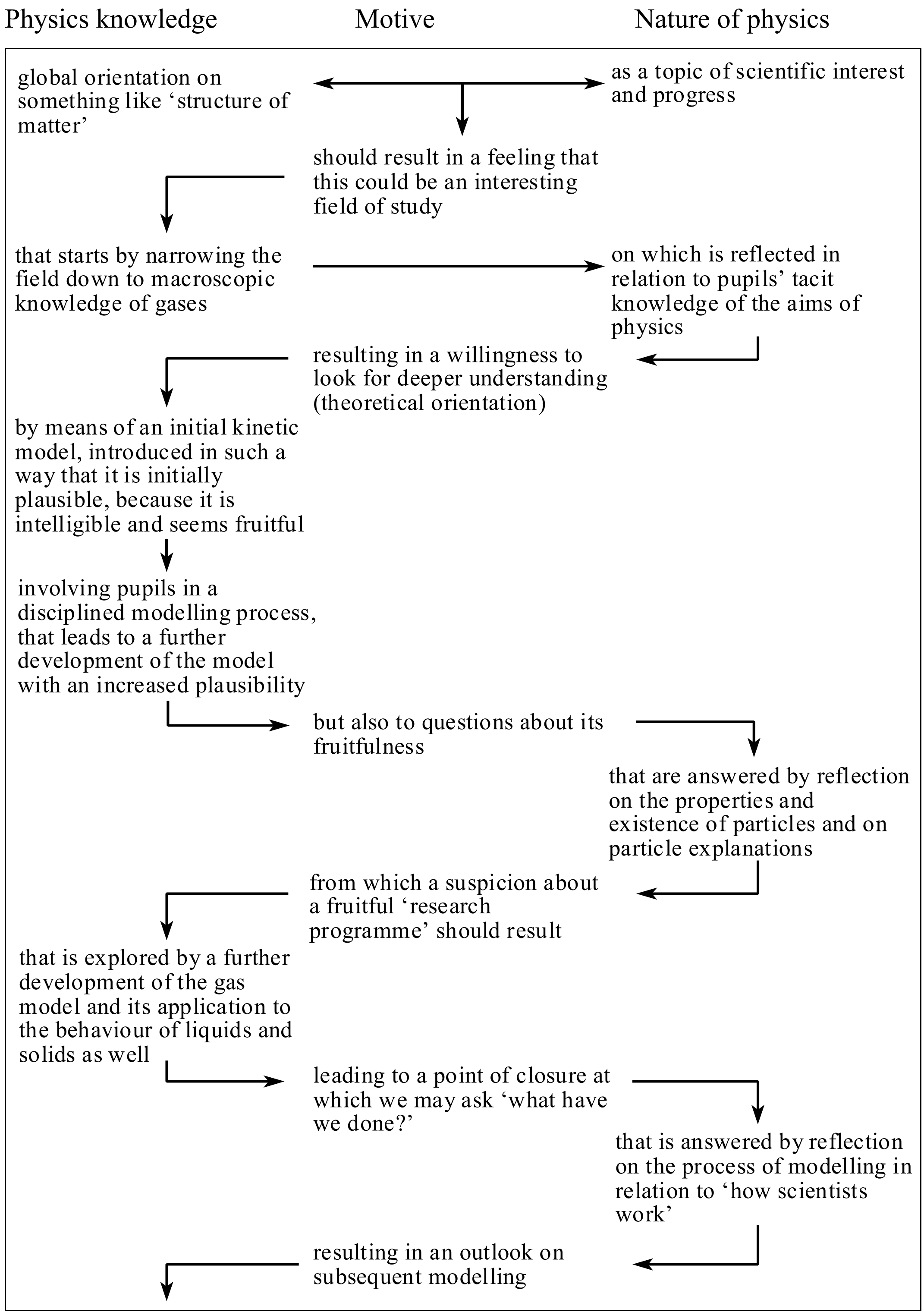


Figure 1: A didactical structure for a problem posing approach to the introduction of a particle model.

This figure shows a sequence of steps each with a specific didactical function that is organised in three columns. In the column on the left those steps mainly related to the educational goal of learning about particle models can be found. On the right one finds the steps related to a second educational goal about learning about the nature of particle models. These two goals were the main goals in this course. The column in the middle explicitly mentions the motives for the subsequent steps. One can see in a glance how each step is supposed to result in a (local) motive for the students to engage in the next step, which in turn results in a new motive et cetera. This figure also shows that aiming for two educational goals at once can become useful, for taking a step in the direction of one goal can provide for a motive to continue with the second goal and vice versa.

This kind of didactical structure had two implications for my design. Firstly thinking about the didactical structure was helpful because it made clearer what the main learning processes of the designed course were and secondly it forced me to make motives explicit. Let me explain. In thinking about the didactical structure of my design, with the example of Vollebregt's at hand, two questions were raised and answered. Firstly, what are the column headings in the depiction of the didactical structure? This question sounds trivial but behind it lies an important point, namely what the main learning processes related to the main educational goals are. In my case it was difficult to determine exactly which processes were coupled, if any. One candidate was (perhaps inspired by the didactical structure of Kortland) content vs. skill. Content could be regarded to consist of knowledge about the explanatory scheme and Newton's laws. Skills involved could be modelling and, arguably, applying the explanatory scheme. Another candidate was a coupling of physics and history. Historical topics about philosophy of change and movement, the study of heavenly bodies and historical persons like Kepler and Newton are used to get the physics across. However, it seemed more natural to view the history only as a context for the physics than as two separate and coupled learning processes. The third candidate was content vs. meta-content. In this case the content is knowledge about Newton's laws. Meta-content is thinking about the knowledge about Newton's laws, which includes the explanatory scheme. This last candidate was the most promising because it captured more fully the learning processes leading to the two educational aims of understanding (the conceptual structure of) mechanics and developing some appreciation for its power and range. The modelling mentioned in the first candidate seemed to be more of a secondary nature.

A second question raised by thinking about the didactical structure concerned the motives in between the successive didactical functions. Dividing the course in successive didactical functions forces one to think what the functional units are and if and how they logically (i.e. meaningfully for students) follow one another. A strong indication for the latter is whether explicit motives can be identified. Filling in a figure depicting the didactical structure can serve as a check for possible omissions in the design. If a particular motive is absent in the design, some justification for its absence is required.

In the next chapter the results of this thought process are presented in the form of a didactical structure and further description of the first design.

5. Summary

In this chapter backgrounds of the design of an introductory course in mechanics were addressed: the explanatory scheme, theoretical guidelines for the design and how the design will be developed which is expressed in the research method. The first included an extensive discussion of the explanatory scheme in which it was argued that this scheme underlying both Newtonian and common sense explanations of motion is a special case of causal explanation in general, which was meant to provide it with a solid backbone[11]. It was then argued that the explanatory scheme might function in mechanics teaching for which two necessary conditions were identified: (1) Students' use of the scheme needed to be triggered and explicated and (2) Newton's use of the scheme needed to be made explicit. Since the first condition was surrounded by much uncertainty as to how this might be done, a pilot study was undertaken to explore this question. This resulted in a feasible approach using video fragments to trigger explanations of motions in which students' use of the explanatory scheme could then be pointed out to them in a way that seemed quite natural to them.

After the notion of an explanatory scheme for motion had been firmly put on the map in this way the research question could be formulated as: 'How can the idea of a common explanatory scheme for motion in common sense and Newtonian mechanics be made productive in teaching/learning mechanics.'

This design question will be explored using the method of a 'design experiment', which involves a cyclic process of designing, testing and revising a prototype. In order to make the didactical quality of the prototype object of study detailed qualitative data of the actual teaching/learning process need to be collected and compared with an equally detailed description and justification of the expected teaching/learning process in the scenario.

Theoretical guidelines for the design were expressed in my view on teaching and learning, which involves the notion of problem posing education, and use of earlier designs starting from a similar perspective. Here the work of Vollebregt served as an important inspiration both in suggesting several main themes in my design and providing for the designing aid of 'didactical structures'.

[11] The criticaster that denies that the scheme functions in explanations of motion would now have to account for how causal explanations must be understood, since her denial of the explanatory scheme implicitly denies widespread notions about how causal explanations work.

Chapter 4

Development from first to second design

"Failure is the pillar of success, if you learn from it"

- Saying, popular in Sikkim on signs along the road

1. Introduction

Aims of this chapter are to present the second design on a broad level and to show (on this broad level) how the first design contributed to the second design. The latter illustrates the method of design experiments and provides for some empirical justification of (parts of) the second design. Although the first design turned out to be unsuccessful in many respects, still some important ideas developed from the first trial that were incorporated in the second design. For understanding these ideas a broad description of the development in the design suffices. In fact a more detailed description and analysis of the first trial would not be useful given the numerous flaws in that design.

The design can be viewed from several perspectives ranging from more broad to more detailed. The broadest perspective concerns the four main themes already introduced in chapter 3:

- The why and how of explaining motion. The explanatory scheme plays a role in the ‘how’.
- Extending students’ knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining planetary motion.
- Evaluation of models and types of model in the light of achieving broader applicability.
- Embedding in the regular mechanics course.

Zooming in, each main theme can be divided in several episodes. An episode is a sequence of connected activities related to a particular goal. An episode forms a coherent unit in a lesson in the sense that it requires an introduction, after which some activities addressing some central question follow, and is finally evaluated in light of the introduction. Its size ranges from 30 - 80 minutes.

The most detailed perspective on the designed course is a description of its activities, like answering questions, reading texts or listening to an explanation by the teacher, in which the description concerns the actual questions, texts or formulation of the explanation. Perhaps a time frame may make this distinction clearer, see Table 1:

Zoom size	Describes	Time frame	Relevant sections
Broad	Main themes	lessons	chapter 4, section 2
Intermediary	Episodes	30 - 80 minutes	chapter 5, section 2
Detailed	Activities	1 - 10 minutes	chapter 5, section 3 - 5

Table 1: Different levels of description

The content of the first design, the development in the content from first to second design and the second design will be described on a broad level for the first three main themes in section 2. In this description sometimes some details are mentioned for the sake of clarifying the description on the broad level. The fourth main theme will be addressed slightly differently because it was not put to the test to the same extent as were the first three main themes. It will be described on a broad level and will not include a discussion of how results from the first trial led to revisions in the design of the second.

The development in the teacher preparation from the first to the second design will be described in section 3. The preparation of the teacher in the first trial led to the idea of using interaction structures for the preparation of the second teacher. What this idea entails and how it was put to the test will be the topic of this section.

This chapter will give the reader a rather general view of the revised design. In chapter 5 I will further zoom in on the design by first presenting an overview of the related episodes and then describing the episodes in detail, that is on an activity level.

Let me begin with some remarks concerning the research method used in the first trial. In the first trial one teacher and one pre-university level class of 27 sixteen year old students (Dutch: 4 VWO) participated. This teacher agreed to spent ten 50-minute lessons on this experiment, which consisted of about one quarter of the time he would see this class in that year. The willingness of the teacher to participate in this project, which was also due to that he was a former colleague of mine, was the main criterion for selection. It was an ordinary class in an ordinary school with an ordinary teacher. Teacher explanations to the whole class were video taped. Group discussions were audio taped. I selected four different groups each lesson. Groups ranged in size from two to five students depending on the activity. The teacher and researcher carried a tape recorder all the time, recording all interactions. Students' written materials were photocopied after each lesson.

Based on data obtained in these ways I compared the intended teaching/learning process to the actual one. This analysis did not delve very deep, since the findings at a more superficial (or broader) level already indicated some shortcomings and already suggested ways of improvement. This is a rather normal feature of this kind of research where, although one spends considerable time and thought on the first prototype from behind one's desk, it still shows considerable design flaws when put to the test. Fortunately such a test also gives ideas for improvement. I will present here only the design and results from its test on a broad level, which should suffice to understand and follow the changes made in the second design.

2. The content from first to second design

In this section I will describe the development from the first design I tested to the second design, and organise this description around the four main themes. The development within each theme will be addressed in the four following subsections, starting with the first: The *how* and *why* of explaining motions. This includes a description of the first design, the main results that led to revisions in this design and a description of the resultant second design. The fourth main theme will be described slightly differently, as was already mentioned in section 1.

2.1. The *how* and *why* of explaining motions.

I will first describe, in section 2.1.1, how the first design was expected to implement the functions of the first main theme. Then, in section 2.1.2, I will present some results of testing this design that lead to revising this first design. Finally, in section 2.1.3, I will describe the second design in light of these results. (This procedure is then two times repeated for the second and third main theme in the subsequent sections.)

2.1.1. First design

In the first main theme I tried to develop a theoretical orientation towards explaining motion. This main theme is concerned with the questions '*why* study the topic of explaining motions' and '*how* are motions explained'. In the first design this was implemented in a way that is depicted in Figure 1.

Physics	Motive	Reflection on physics
Orienting and evoking a broad interest in and motive for a study of change as a phenomenon and philosophical theme. Orientation on the course.		
	Should result in the notion that this is an important and interesting theme worth knowing more about	
starting with movements and their causes		on which by reflection an underlying scheme is found and made explicit, in relation to history
	resulting in a willingness to look for deeper understanding (theoretical orientation)	

Figure 1: Didactical structure of the first main theme in the first design.

The question '*why* study explaining motions' could be answered by pointing out its importance as an essential part of understanding the larger theme of change as a phenomenon and philosophical idea. After starting with the big theme 'change' as broad motive, the plan was to narrow it down to the more specific motive of understanding motion by the argument that understanding motion is an important part of understanding change. The theme 'change' could be introduced by means of several philosophers expressing, each in their particular way, how they understood change in terms of the motion and interaction of particles. These positions could then be illustrated with the example of how they would explain the freezing of water. The role of the teacher in this was crucial for instilling a sense of wonder and curiosity. I expected that not so much what was said, but the enthusiasm with which it was said would trigger student's dormant curiosity.

The plan was to answer the question *how* motions are explained with the explanatory scheme, that for that reason needed to be triggered and explicated. Students should come to notice that different explanations of various motions have something in common, namely that influences can be identified and that those influences cause deviations from influence free motions. In order to appreciate the explanatory scheme students need to be oriented towards its theoretical use for understanding all explanations of all motions. This theoretical orientation in a student is an attitude that abandons specific practical aims and interests in explaining a motion and should result in a willingness to look for deeper understanding.

I expected that the recognition of plausible influences and a particular type of motion as influence free is easiest in relation to the ways we ourselves influence motion, see also chapter 3 section 2.1. That is, if standing still or gradually coming to a stop are taken as influence free, various kinds of actions we can perform can be related to kinds of deviations from the assumed influence free motion. In chapter 3 section 2.3 I called these actions ‘personal influences’. In other cases involving ‘non-personal influences’, these influences are less easily recognised precisely because an assumption for an influence free motion in combination with a plausible interaction theory to account for deviations from it is lacking. With ‘interaction theory’ I mean notions concerning the causes and effects of influences that can range from vague (or even implicit) regularities between causal factors and their effects on the motion to precise (and explicit) force laws like Newton’s law of gravitation.

In order to trigger and explicate the explanatory scheme the plan was to examine some explanations of motion in which use of the scheme could be pointed out. A way of triggering explanations of motion used in the first design was using video fragments of motions that were stopped after which the students had to predict and explain the continuation of the interrupted motions. This approach was tested in a pilot study that was described in chapter 3 section 2.3, which started with motions involving only personal influences and later including also non-personal influences. In that pilot it was seen that in the explanations of the motions students watched they mentioned things that I would call influences on the motion. These influences had to be operating because otherwise the object would move differently, namely according to its assumed influence free motion. This general argument of the explanatory scheme, also used (implicitly) by the students was then pointed out to them.

The role of the teacher in triggering and explicating the explanatory scheme is a difficult one. He has to use the diverse student responses recognisably, ensure that the details of the explanatory scheme surface clearly while retaining perspective on the purpose of arriving at an understanding of what explaining motion is about.

This was the first general plan for evoking a broad motive (understanding change) and narrowing this down to a content specific motive (understanding explaining motions) for which students need to adopt a theoretical orientation. This plan was further worked into a concrete design and tested in the first test round. This first main theme took about two 50-minute lessons. I will now discuss some results from this test that lead to revisions of the design.

2.1.2. Results leading to revision of the first design

The execution of the design deviated from the plan in the sense that the supposedly enthusiastic introduction was simply read out and contained irrelevant mentioning of the September 11th disaster, which did raise interest, but for the wrong reasons and the evaluation of the assignments from which the explanatory scheme should have been clearly explicated was almost completely lacking. Although this made it more difficult to draw conclusions about the effectiveness of the design, still some points worth mentioning surfaced.

The first introductory function of answering the question ‘*why* study mechanics’ did not work well enough. The problem was that although the notion of building blocks of matter was caught on to, the essential next step that change can be understood in terms of the motion and interaction of these building blocks was not. A possible cause might have been the following. The chosen example (of freezing of water) and terms that were used could have invoked an image of a ‘static change’. That is to say some state before, then a change and finally a state after, where the dominant aspects are the state before and after and the importance of the change in the middle remains unclear. For instance when asked to write down some similarities and differences between the studied philosophers a student wrote down:

> "Similarities: Changes are achieved by arrangement of matter. In arranging the particles are mixed. After the arranging the particles returned in another way.
>
> Differences: Other notion on how particles were arranged."

The word ‘arrangement’ was used in the student material, which was unfortunate since it has a static connotation.

That students did not see the function of the start concerning the ‘change as motion’ theme was confirmed later in the course. Students drew conclusions in the third main theme in an essay assignment (assignment 26, which will be described in section 2.3.1). They made an effort in writing these essays, which can be considered to reflect what students thought were the salient parts of the introductory course, as well as what they have understood from it.

Let me begin by summarising the findings from these essays and then present a complete account of all relevant statements from the essays related to how motion is explained. Students mentioned those elements from the course they considered to be necessary for predicting (or explaining) motion. They varied in amount and type of elements that were mentioned. Although only two students (Els and Michael) explicitly mentioned the explanatory scheme, all students implicitly made use of the scheme in explaining motion. What is interesting and also in a way reassuring is the diversity in elements that were mentioned. Apparently all the necessary ingredients for an explanation of motion can be recognised by students in the course. There were some who have understood, at least to the extent of finding it important enough to mention it in a recapitulating essay, the importance of an influence law, some the rule deviation = influence/laziness and some the assumption for an influence free motion. Students were not asked to write (elements of) the explanatory scheme down. They were asked to write what explaining motion is about. That they did mention these elements indicates their viability, which I find reassuring.

When writing about how motions are explained some students expressed elements of the explanatory scheme or sometimes tried a general description like the one from the student booklet.

> Els: Explanatory scheme for motion:
> 1. An assumption for the influence free motion.
> 2. Deviations from that influence free motion can be explained by identifying suitable infleunces.

This does not necessarily mean Els has understood it, but at least she considered it important enough to include it in her essay.

Sometimes students mentioned the three elements of the scheme identified in the following figure from the student booklet (§1.6.2, p. 16), which was copied by two students (Rachel, Stan) or described in words by three others (Abe, Tara, Koen)

Kepler	Newton
- Influence free motion is rest	- Influence free motion is straight motion with constant velocity
- deviation = influence / laziness	- deviation = influence / laziness
- Deviations can perhaps be explained by a dragging influence of the rotating sun (spoke explanation).	- Deviations can perhaps be explained by an attracting influence between all heavenly bodies amongst which the sun (gravitation).

Some only mentioned a single element from the scheme, namely the rule deviation = influence / laziness, but did not mention anything about influence laws (Bertine, Mathilde, Mark, Niek, Bashel, Iwan). Take for example Bertine and Iwan:

> Bertine: I have used the formula deviation = influence / laziness a lot.

> Iwan: To predict a motion one needs three things according to Kepler and Newton. Using these two things, the third is calculated. The first two one needs are influence and laziness. By dividing the influence by the laziness one gets the third. The third is deviation which shows how an object will move.

Six others did not mention this rule, but talked about the need for influence laws.

> Lisanne: I think you first have to know that [whether there are influences], in order to determine the motion of an object. One also has to make a formula or influence law. Then one can predict the motion of among others heavenly bodies.

> Emma D.: I found it difficult to correctly predict a motion, because I did not know which forces how strongly were operating on the object. I still don’t know that, which I think is a pity.

> Emma D. did not know which forces were operating and how strongly they affected the object. Apparently she does know that one should know these things, i.e. an influence law, in order to predict a motion.

> Nicky / Emma N.: In order to predict a motion one has to know how it originated, what is causing its progress, one also has to know the circumstances and which forces are 'busy'.

Although Nicky and Emma N. do not mention influence laws, knowing which forces are 'busy' implicitly signifies the same thing.

> Bertine: One could say one has completely understood a motion when one has made a prediction of how the motion will continue, and that turns out to be true. [...] One needs an influence law to predict a motion.

> Joffrey: To predict a motion one needs all properties that are required. One needs a formula. In that formula one has to fill in all those properties.

With properties Joffrey means influence-affecting factors, I think.

Some students mention the elements of influence (law) and rule. This was found in the essays of two students:

> Mathilde: When you want to predict a motion of an object, it is important to know the influences (like gravity), then you can predict the motion of the object. With the formula of Kepler and Newton.

> Els: I have learned how motion can be predicted using influence and the law of Newton and Kepler.

With 'the formula or law of Kepler and Newton' Mathilde and Els mean the rule deviation = influence / laziness, I think.

The most complete accounts of how motion is explained were given by Michael and Sophie.

> Michael: By this I learned what to do first in order to explain motion. Namely that you first ask yourself what would happen when there are no influences to be identified. This is called the influence free motion. In case deviations on the influence free motion occur, than that is caused by other influences. With these data an explanatory scheme was formulated. This was used in the notions of Kepler and Newton. They each had their own notion of the deviation from the influence free motion. This is also summarised in a scheme and an influence law according to Kepler and Newton was formulated. And with the help of that law I could predict motion.

Michael mentions all elements of the explanatory scheme, except the rule. Only the connection between the elements remains unclear.

> Sophie: According to the models of Kepler and Newton we can now predict the motion of objects and planets. By using the influence law one can determine the position of an object or planet when there is a particular influence working on it. The formula for this is: deviation = influence / laziness. Kepler says that with the influence free motion is rest. According to Newton the object without influence will go straight on with constant speed.

Sophie mentions all elements, but also in this example without their connection. This ends my presentation of these essays and I will return now to the functions of the introduction.

The second introductory function of answering the question *how* explaining motions work, expressed by the explanatory scheme took place too late and ineffectively.

It was too late in the sense that in the whole first lesson students had to discuss philosophers' ideas about change, without any sight of what this had to do with mechanics. For instance, some remarks students wrote down in response to the evaluative questionnaire after the whole introductory course indicated some confusion what this beginning had to do with anything.

> Niek: "In the beginning I really thought: What is this?";
> Tara: " In the beginning I did not understand well what the purpose of the course was, ...";
> Rachel: "In the beginning I found it difficult, and we did not go into the assignments that much in the lesson, the first part I did not understand entirely."

The second introductory function was ineffective in the sense that the video fragments triggered the expected type of responses, but pointing out the explanatory scheme in them in the intended way, that is in close connection to the student input, while managing a class discussion proved very difficult. The teacher had to manage a kind of class discussion (only student - teacher interaction, no student - student), check that sufficient responses were elicited, remember those responses and abstract those in terms of the explanatory scheme. That is a very difficult task that took me practice in several interviews before I could pull it off in interviews involving only 2 students. Let alone the difficulties involved in doing it in a class of 27 students without any practice! This would require a kind of preparation that did not occur. (How the teacher was prepared will be discussed in section 3.)

What could be seen in the explanations of the various video fragments was that personal influences were easily identified and their role in accounting for the motion was quite clear. Non-personal influences like gravity or friction could be triggered e.g. by comparing fragments and careful questioning, but making clear the function of these influences in accounting for the motion was more difficult. Without having already some interaction theory (however primitive) students found it difficult to identify an influence solely on the basis of accounting for the observed motion. Why was this so difficult? Explaining an observed motion in terms of a deviation from an assumed influence free motion, caused by some to be identified influence, can be compared with trying to solve two variables from one equation. The equation, which stands for the observed motion, is clear. However, when students are uncertain about what influence free motion to assume (one variable) and have almost no clue what influence (the second variable) may cause the deviation from such an influence free motion, this task will prove very difficult indeed. For instance, in the case of a ball moving in a circle with a gap none mentioned an influence of the tube on the ball, which I expected to happen for those students that predicted something else than a continuation of the circular motion when the ball reaches the gap. (If they did it that would have indicated an assumption of circular motion as influence free motion.) Discussing some influence for which they have no name (like 'influence of the tube' or 'centripetal influence') solely on the basis of the notion that some influence has to be there because the observed motion deviates from the assumed influence free motion was at this stage a 'bridge too far'. Even when they can name an influence its role in the explanatory scheme is hard to make explicit when they lack a sufficiently precise interaction theory. Recapitulating, it can be said that the difficulty lies in that students were asked to apply the explanatory scheme that had been explicated from their explanations of motions involving only personal influences directly to motions including also non-personal influences.

2.1.3. Second design

The problems that arose in performing the function of the introduction, discussed in section 2.1.2, resulted in two revisions of the design. Firstly explaining in general will be used as a stepping-stone for explaining motion. Secondly the course will start with the topic of motion directly, instead of introducing it as a special case of change. I will now discuss what these revisions entail and how they are supposed to remedy the problems of the first design.

Improving the design by means of a general explanatory scheme

In the first design I attempted to show what explaining motions in a general way is by explicating the way students already explain motions involving only personal influences and by letting them apply this to motions involving also non-personal influences. However, this proved to be difficult and did not succeed well enough, as was seen in the previous section. A solution to this problem may be found in the idea that explanation of motion is a special case of causal explanation (see chapter 3, section 2). If it is possible to trigger the structure in causal explanation in general, this structure (or general explanatory scheme) can be used as a stepping-stone to the explanatory scheme of motion. The idea is that the general explanatory scheme can be expected to be quite easily triggered, e.g. in the way described shortly. The explanatory scheme for motion could then be introduced as a special case of the general explanatory scheme. Next it could be applied to motions involving mainly personal influences, which is expected to be easy as results from the test of the first design indicated. Explaining motions can then be explicated as filling in the explanatory scheme. This filling in of the explanatory scheme can then be applied to the more difficult motions involving also non-personal influences. I did not know to what extent students were able to take this last step, which is one of the reasons to try this out in a second pilot study, which took place after the first trial and before the second trial (see Table 2). In the first trial the explanatory scheme for motion was explicated on the basis of motions involving personal influences and applied (which failed) to other motions. In the suggested revision the explanatory scheme for motion is already explicated by means of the general explanatory scheme and applied (which is expected to be successful) to motions involving personal influences.

Research activity	When?	What about?
Pilot 1	Summer 2001	Triggering and explicating the explanatory scheme for motion by means of video fragments
Trial 1	Winter 2001	Test of first design
Pilot 2	Winter 2002	Triggering and explicating the explanatory scheme for motion by using the general explanatory scheme as stepping-stone
Trial 2	Spring 2003	Test of second design

Table 2: Sequence of research activities

How can the structure in causal explanation as presented in chapter 3 section 2.1 be made productive? In chapter 3 we saw that in giving a causal explanation of an event we normally take for granted a great deal of background, and what we typically want to know is what to add to that background to make the occurrence of the event intelligible. This can be made clear to students by explicitly comparing the event and the assumed background. The following depiction of an explanation of sugar slowly dissolving in tea, 'the sugar dissolved slowly in the tea, because the tea was not stirred' can be helpful for this comparison (see Figure 2).

Situation A Slowly dissolving	Situation B Quickly dissolving

- No stirring	- Stirring
- Tea	- Tea
- Sugar lump	- Sugar lump
- Temperature T	- Temperature T

Regularity: Always when tea is stirred, sugar dissolves more quickly then when it is not stirred, all other things being equal

Figure 2: General explanatory scheme applied to the example of dissolving sugar in tea

This figure shows a completed or filled in depiction of this explanation. In this case the sugar is considered to be slowly dissolving because the tea was not stirred. The event to be explained, depicted on the left, is mentally compared to the background, which is a situation in which the sugar dissolves more quickly, because in that case the tea is stirred, depicted on the right. What needs to be added to this background to make the occurrence of the event intelligible is the absence of stirring, which is a somewhat awkward way of saying that the stirring needs to be taken away from the background to account for the event of slowly dissolving sugar. The background can be characterised by numerous factors like the amount and sort of tea, the amount and shape of the sugar lump, the kind of sugar, the temperature et cetera, that are the same for both situations.

Furthermore in chapter 3 we saw that it must prove possible to so characterise the event to be explained and the addition to the background that they fall under a (more or less strict and more or less lawlike) generalisation. In the given example the explanation makes implicit use of the regularity or lawlike generalisation ‘always when tea is stirred, sugar dissolves more quickly than when it is not stirred, all other things being equal’. In this way such depictions can become a useful tool to talk about the general structure in causal explanations in a way that is not as abstract as the discussion in chapter 3, but is expected to be concrete and easily recognisable for students. As indicated in chapter 3, section 2.3, with respect to the explanatory scheme for motion, I also assume with respect to the general explanatory scheme that students, like everybody else, make implicit use of it. The serious problem is how to make them recognise and explicitly use the structure in their causal explanations.

Students may be guided by several questions in filling in such figures themselves. With the help of this depiction the general structure in one explanation could be pointed out. Students can then be asked to fill in elements of depictions of other explanations, but with almost all text left out, to see if they understand the different elements of the general explanatory scheme and how they are related.

It can then be pointed out that explanations of motion can be seen in a similar way. For instance students could be asked to identify several elements of an explanation of a particular motion involving only personal influences with the help of a similar depiction as the sugar dissolution explanations, see Figure 3.

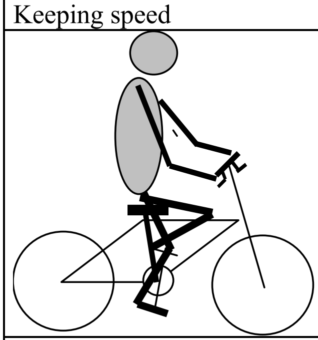
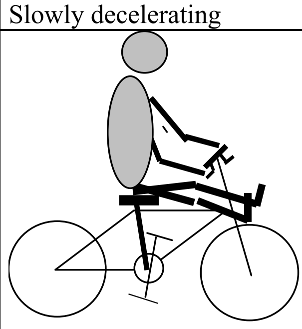
Keeping speed	Slowly decelerating
	
- - -	- - -
Regularity: …	

Figure 3: Comparison bicycle riders 1

Here also two situations differ in one relevant factor. In this case the influence pedalling can be identified, while many factors that characterise the background are the same: the person cycling, the bike, the surface, the tension in the tires et cetera. The pedalling can be related to the phenomenon of keeping speed by the regularity 'always when one (steadily) pedals, one is keeping speed, all other things being equal'. From this the explanatory scheme for motion can be explicated as a special case of the general explanatory scheme. The students can then be asked to apply this scheme in explaining another motion involving also non-personal influences, to see to what extent they had understood it.

This way of depicting the explanatory scheme for motion was inspired by the similar way of depicting the general explanatory scheme. The obvious similarities in presentation are expected to help students see the similarities between both schemes themselves.

A concrete implementation of the idea of using the general explanatory scheme as stepping-stone was tested in a second pilot study to see whether such an introduction was in fact easier. Another question in this study was whether the students recognise the similarities between the general explanatory scheme and the explanatory scheme of motion. Seeing the similarities is an important prerequisite for this idea to work. The similarities can be emphasised[1] by addressing and using both schemes in the same way, e.g. by using the same kind of depictions of the scheme. I will now describe the method and results of this second pilot study and then return to the main point of the first part of this section, improving the design by using the general explanatory scheme as a stepping-stone, in the discussion of the results of this pilot.

<u>Method of the second pilot study</u>

The idea of a general explanatory scheme was worked into an educational design. Students were presented with several explanations of sugar dissolving in tea, one of which was depicted in the manner of Figure 2. This design was tested in a quasi-educational setting with the researcher as teacher and two students as class, which can also be seen as a structured interview. The research method of the second pilot study was similar to the first pilot study described in chapter 3 section 2.3. The first couple of interviews (about four) served as try-out for the interview scheme, which during this phase was adjusted until it seemed 'good enough'. The subsequent interviews all followed the same interview scheme and were for data gathering. Saturation effects determined the amount of interviews held. If new interviews were no longer surprising it was time to stop (which happened after about 8 interviews, including the try-outs).

The interview was described in a scenario-like interview scheme, together with a description of the intended teaching/learning process with argued expectations and how this is supposed to contribute to answering the research questions of this second pilot study.

<u>Results of the second pilot study</u>

[1] Since both schemes *are* very much alike, as was shown in chapter 3, using them in a similar way would be a very natural thing to do. In this sense it would be not entirely correct to speak of *emphasising* the similarities. The similarities are obvious, but still have to be shown.

The interview with the students seemed to work as intended, but up to a certain point. The general explanatory scheme could be pointed out to them with the help of the example of sugar dissolving in tea. The transition to explanation of motion could be made, in which students appeared to see the similarities between both explanatory schemes. Also pointing out the explanatory scheme for motion in explanations concerning only personal influences went well. Applying the scheme to other motions, for which also non-personal influences were needed, proved to be very difficult. Students were able to mention a couple of other factors, which may influence a motion apart from personal influences. Some students expressed their intuitions concerning an influence free motion. As expected they were less sure about what a motion without any influences would look like than what it would look like without personal influences. However, in pointing out the connection between the (assumption of an) influence free motion and identified influences I lost them. Students, having understood the explanatory scheme for motion in the case of only personal influences and realising that only personal influences are not enough for a complete explanation of motion, could not extend the explanatory scheme for motions to include all influences by themselves.

<u>Discussion of the second pilot study and implications for the course design</u>

That students could not extend the explanatory scheme for motions to include all influences is in retrospect not surprising. I think two factors account for this: lack of purpose and lack of sufficiently precise interaction theory in combination with an assumption for an influence free motion. The latter was discussed before. It is difficult to apply the explanatory scheme for motion without having a proper interaction theory in combination with an assumption for an influence free motion. At this stage and in this way students cannot be asked to do this by themselves.

It gradually dawned upon me, however, that this difficulty may be a blessing in disguise. ("It's not a bug, it's a feature!") The problem of extending the scheme to include all influences may be used constructively to guide subsequent activities. That is, whereas the process of filling in the explanatory scheme for motion including non-personal influences will remain as difficult as it was for the reasons already indicated, this experienced difficulty need not be disastrous. Rather, overcoming this difficulty will indicate precisely the direction which the students will have to take in the subsequent parts of the course, namely finding a proper assumption for an influence free motion in combination with a proper influence law for the environmental influences involved. As was mentioned before, students did get a sense of the 'unextended' explanatory scheme for motions in the interviews. They can therefore be expected to understand that they need to know more about the elements of the scheme in order to explain (in theory) all motions. They also have to want this of course, which brings us back to the first mentioned factor: the lack of purpose.

In the interviews students easily could have lost sight of (or had not got in the first place) the reason for viewing explanations of motion in this particular *theoretical* way. The point of the extension was to be able (in theory) to give a complete explanation of all motions. The reason that the students did not see this was that it was not made clear in the present design. That the interview was about a theoretical way of looking at explanations (of motions and in general) should have been made more explicit throughout the sequence as well as the reasons for adopting a theoretical perspective. There are several reasons that may be used in a new design to remedy this lack of purpose, for instance:

- The big philosophical picture of mechanicism, in which understanding motions, together with understanding building blocks (subject of another course) can lead (in principle if not in practice) to understanding and thereby predicting or controlling all material events.
- Plain curiosity. People just want to know how things work, sometimes in detail.
- Occasional practical relevance, for instance in predicting whether or not a meteor will collide with earth or in getting a satellite in orbit et cetera, in which also the theoretical perspective can be useful.

To recap: Explicating the explanatory scheme for motion by means of video fragments was seen to be promising (pilot 1), but also difficult (trial 1). The difficulty (apart from difficulties in the execution) was that the explanatory scheme for motion after being explicated from familiar motions, in which personal influences play a part, was applied to motions that were too difficult since they involved non-personal influences for which students lacked a proper assumption for an influence free motion in combination with sufficient interaction theory. A possible way out was to make use of a stepping-stone in the form of the general explanatory scheme. In that way the explanatory scheme for motion is explicated as a special case of the general explanatory scheme and then applied to a situation students *are* familiar with, namely motions involving personal influences. Although this made understanding the explanatory scheme for motion in the case of only personal influences easier, explicating the complete scheme remained difficult. It might appear that we have come full circle to the initial problem, but this is not the case. The difficulty itself has changed from a difficulty in applying the explanatory scheme to motions involving also non-personal influences to a missing perspective on the *theoretical* approach to explaining motions. The first thing is still difficult but serves another purpose: not as an essential part in explicating the scheme, but in providing a direction for subsequent activities and therefore ceases to be a problem. "It’s not a bug, it’s a feature!"

Improving the design by starting with motion directly

I already mentioned that the introductory function of answering the question ‘*why* study mechanics’ did not work well enough, because its relation to motion did not become clear. In revising the design to improve it in this respect the idea of using change as overarching and recognisably important theme was not abandoned at first. To focus more on motion instead of building blocks another presentation of the mechanicism theme was considered, illustrated with another philosopher (Hobbes) and using a more dynamic (i.e. non static in the sense of initial state - change - final state) example.

However, the same function of answering the question ‘why study mechanics’ may more directly be performed in another way, namely with a suitable example of a motion. Such an example should be a motion of which it is clear that it would be important to be able to explain or predict it. This shows that there is at least one motion, and raises at least the suspicion that there may be more, that is important to explain and thereby gives some weight to the subject of explaining motions. Furthermore it should be theoretically challenging to explain it, that is, students should be unable to do it at the moment, but can see ways, however vague, to approach such a problem. In such a way the right theoretically oriented (physical) mindset can be evoked. This way of answering the why-question also enables one to move more quickly to the what-question. In my detailed description of the design in chapter 5 I will argue that the example of an asteroid moving towards earth may perform this function. The mechanicism approach of the first design may still fulfil a function in illustrating the range and scope of mechanics and thereby provide an additional answer to the question about the value of mechanics in main theme 3. It is therefore postponed to that stage of the course.

Outline of the first main theme in the second design

The described revisions led to the second design with a didactical structure that is depicted in Figure 4.

Mechanics	**Motive**	**Explanation**
Broad orientation on motions		that are worth predicting /explaining
	Should result in the notion that this is an important and interesting theme worth knowing more about	
		Starting with explanation in general and explanation of motions in particular in which by reflection an underlying scheme is found and made explicit
	which should lead to the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of this underlying scheme (theoretical orientation)	

Figure 4: Didactical structure of the first main theme in the second design

Note that the third column is now headed ‘explanation’ whereas it was headed ‘reflection on physics’ in the first design. The reason for this change was that the teaching/learning process depicted in the right column is better captured by how explaining works as a driving force for understanding how explaining motion works, which is the teaching/learning process depicted in the left column. The reader may recall that in chapter 3 section 4.2 one of the general uses didactical structures can have in thinking about educational designs was that they force one to think about what the main learning processes related to the main educational goals are, by means of the question ‘what are the column headings in the depiction of the didactical structure?’ Here we see an example of this use.

The function of the first main theme is still the same: It concerns the questions ‘*why* study the topic of explaining motions’ and ‘*how* are motions explained’, for which a theoretical orientation needs to be developed. The question ‘*why* study explaining motions’ is now answered by pointing out that there are motions that are important to predict and explain. This answer should result in the notion that this is an important and interesting theme worth knowing more about. The question ‘*how* motions are explained’ can be answered with the explanatory scheme for motion, which is introduced by using the general explanatory scheme as stepping-stone. In order to appreciate the explanatory scheme for motion students need to be oriented towards its theoretical use for understanding all kinds of motions. Before specific motions can be predicted and explained elements of the explanatory scheme for motion need to be specified in some way. How this is worked out in detail can be found in chapter 5 section 3.

2.2. Extending students’ knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining planetary motion.

I will first describe, in section 2.2.1, how the first design was expected to implement the functions of the second main theme. Then, in section 2.2.2, I will present some results of testing this design that lead to revising this first design. Finally, in section 2.2.3, I will describe the second design in light of these results.

2.2.1. First design

In the second main theme students’ knowledge is extended, for which in the first main theme some willingness should have arisen and which should lead to questions concerning the fruitfulness of the used models, as depicted in Figure 5.

Physics	**Motive**	**Reflection on physics**
	resulting in a willingness to look for deeper understanding	
by means of the study of celestial mechanics in terms of models		
	resulting in a question concerning the fruitfulness of these models	

Figure 5: Didactical structure of the second main theme in the first design

The extension of knowledge consists of the preparation of basic notions of mechanics, like second law, first law, law of gravitation, concept of mass and inertia, by means of a study of Keplerian and Newtonian specifications of the explanatory scheme. For this the motions of heavenly bodies are modelled and criteria for good (enough) models like plausibility and empirical adequacy are (implicitly) used. In chapter 3 section 2.2 I argued for the usefulness of the context of heavenly bodies as well as the choice for both Kepler and Newton. The subsequent question concerning the fruitfulness of these types of models is expected to naturally surface in the process of investigating models by comparing alternative types, i.e. Keplerian and Newtonian models. These will be discussed in section 2.3.

The study of celestial mechanics can be considered too difficult for 16-year-old students, since they cannot determine the motion analytically given some force law (neither can many a physicist), because of the mathematical complexities. However, numerical solutions as acquired by means of computer models can become very useful here. I have tried to give students some feeling for the workings of a computer model that calculates the motion of celestial objects, given some influence law. The method of graphically constructing motions, as used by Newton, served as an inspiration in this matter, see Figure 6.

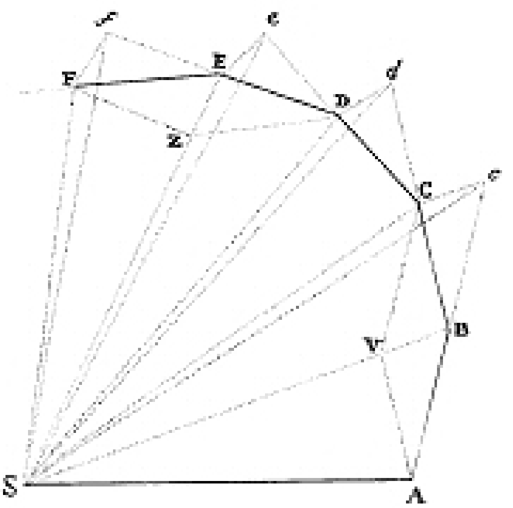


Figure 6: Drawing used by Newton in the Principia in his proof of Kepler's law of equal areas

I merely want to draw attention to how this construction embodies the explanatory scheme for motion. Suppose that in a small period of time an object moves from A to B. In the absence of an influence it would in the next period move straight ahead with the same speed (Newton's assumption for the influence free motion) and arrive at c. Instead, an influence directed towards S causes a deviation BV from that, and the body will therefore end up in C. Without an influence it would in the next period continue in the direction BC with constant speed and end up in d. Instead, an influence directed towards S in C causes a deviation and the body will move to D, et cetera. If smaller periods of time are considered, the polygon ABCD... approaches more and more a curved trajectory and the series of discrete influences becomes a continues influence.

The computer model can finally be introduced as something that performs such a graphical construction very fast, much faster than we could ever do it by hand. Before students could be expected to work with such a computer model two preliminary topics need to have been addressed: (1) how from a given influence in a given situation the motion can be graphically constructed (both in a Newtonian and in a Keplerian way), and (2) how from attributes of the situation the influence in that situation can be determined, i.e. the notion of an influence *law*.

This was the general idea behind the second main theme in the first design. I will now describe the main points of this part of the design, which consisted of five 50-minute lessons (lesson 3 through 7).

The second main theme starts with the point that the explanatory scheme for motion can also be recognised in Kepler and Newton, two important figures who were interested in explaining the motion of heavenly bodies. Next a graphical explanation is given of how influences can be identified (in magnitude and direction) in a given motion or how the motion can be constructed when given the influences. This includes the relation between influence and motion expressed in my translation of Newton's second law in terms that can also be used for Kepler's equivalent second law: deviation (from the influence free motion) = influence/laziness[2]. The term laziness is a translation of 'inertia' and is a measure for how strongly an object reacts to an influence. The larger the laziness, the smaller the reaction (in the form of a deviation from the influence free motion) to some given influence will be. The reason for using a word like 'laziness' instead of 'mass' is the same as for using 'influence' instead of 'force', namely that in this way it is less likely that students will directly associate all kinds of unintended meanings to the word.

The following excerpt from the students' booklet shows how the graphical explanation is given. It is meant to illustrate how such a graphical construction visualises the explanatory scheme and also to give an impression of the complexity of the topic.

1.8 The relation between deviation and influence

A general expression of the relation between motion and influence, which applies to both Kepler and Newton is: A deviation from the influence free motion of an object equals, in magnitude and direction, the influence by both person and environment affecting that object, divided by the laziness of the object. Put in a scheme:

$$\text{Deviation from influence free motion} = \frac{\text{Influence}}{\text{Laziness object}}$$

Since a deviation has got a magnitude and a direction, an influence has those too. The deviation from the influence free motion can be indicated with an arrow, which points from where the object would have arrived without influence to where the object arrived with influence. The length of the arrow indicates the magnitude of the deviation and its direction indicates the direction of the deviation. We can indicate the influence with an arrow as well. This arrow has to point in the same direction, because the influence has

[2] In the Newtonian case the deviation from the influence free motion is a deviation from motion with constant velocity and therefore an acceleration (therefore $a=F_{Newton}/m$). In the Keplerian case the deviation from the influence free motion is deviation from rest and therefore a velocity (therefore $v=F_{Kepler}/m$).

got the same direction as the deviation. The length of the arrow that designates the influence indicates the magnitude of the influence, but this length does not have to equal the length of the arrow indicating the deviation. That depends on the size of the laziness. When the laziness of some object is for instance three (we still have to decide upon a measure for laziness), then the size of the influence will be three times the size of the deviation. We then draw the influence arrow three times as large as the deviation arrow.

We can now try to indicate for a known motion what the influence must have been according to Kepler and Newton. Vice versa we can also indicate from a known influence what the motion would look like, according to Kepler and Newton.

1.8.1 From motion to influence

According to Kepler:

Assume that an object with laziness 2 is at some time in A and that it is given that some time later it is in B (Figure 7).

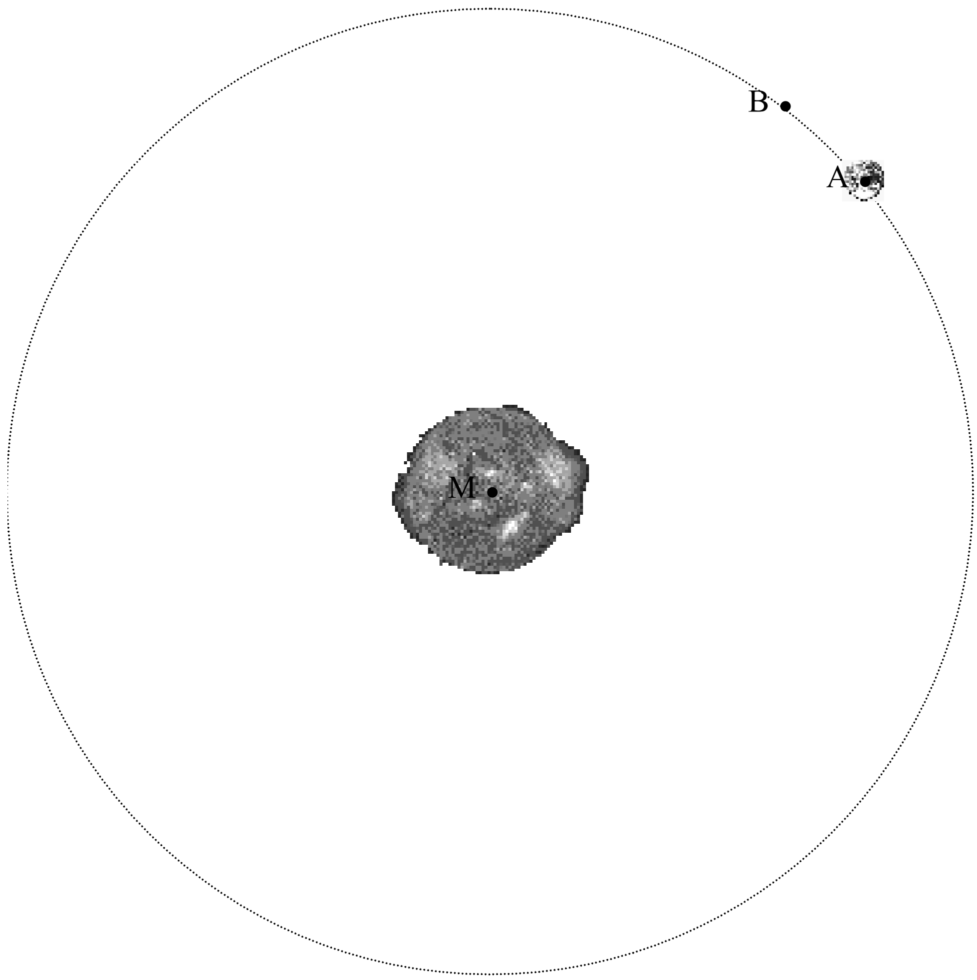


Figure 7: From A to B

Can we now determine what the influence during that time must have been, according to Kepler? We can with the help of the formula ‘deviation = influence / laziness’. We can determine the deviation from the influence free motion in the following way: When no influence had operated, the object would have remained in A according to Kepler, for rest is the influence free motion according to Kepler. However, the object arrives at B. The deviation from the influence free motion can therefore be depicted with the arrow from A to B (see Figure 8).

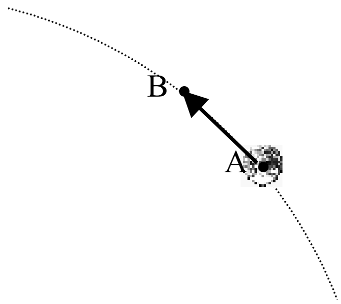


Figure 8: Deviation

We can now determine the influence with the formula 'deviation = influence / laziness'. Since the object has got laziness 2, the influence is two times as large as the deviation, but in the same direction. In Figure 9 this influence is drawn in the form of a thick arrow.

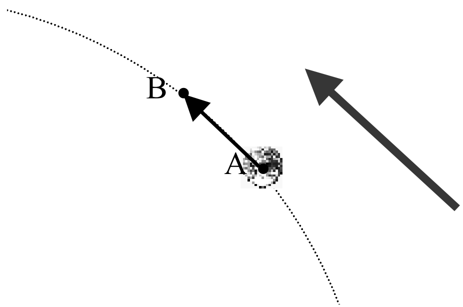


Figure 9: Influence

Similar explanations were given for Newton and for the reversed case where from given influences the motion was constructed. Note that the first design started with determining the influence from the motion.

To develop some confidence in the main point of how the graphical method is an expression of the explanatory scheme for motion and that motion can be determined given an influence and vice versa, students were then meant to practice with such constructions. To illustrate the type of assignments that were offered I present the first one below:

Assignment 8.

An object is moving from A to B during some short time and has got a laziness of 3. See the figure below.

a. Assume that when there was no influence, the object would arrive in B’ after the mentioned short time. Indicate the Newtonian influence with a (red) arrow to the right of the figure.

b. Where would the object have arrived after the same short time and the same influence when its laziness would have been 2 times as large?

c. Where would the object have arrived after the same short time and the same laziness (of 3) when the influence would have been 2 times as large and in the same direction?

Since the details of this graphical method are quite complex and students might therefore easily lose sight of the main point, the explanation of and guidance by the teacher should emphasise that the main point here is that influence can be determined in principle from motion and vice versa and that the way this is done directly expresses the explanatory scheme (in a graphical way). Apart from emphasising the main point when students are working on the various assignments, coached by the teacher, the teacher also expresses this at transitions from one set of activities to the next. For instance from applying the graphical method to the next set of activities about the role of the length of the time interval, described below.

The length of the time interval between successive positions is an important variable. To show that diminishing the time intervals in this constructions leads to more fluent trajectories and better calculations[3], students were presented with a computer simulation showing a quick succession of constructed positions of a thrown object, first with a large time interval and then with a smaller time interval.

The idea of an influence law (force law) as a way of expressing the magnitude of an influence as a function of attributes of the configuration in which the motion takes place is introduced by first recalling the already encountered notions of Kepler and Newton concerning relevant attributes of the configuration like the distance between heavenly bodies and suggesting how this can be expressed in a formula. A couple of questions guide students to the notion that many formulas can be plausible in the sense that they all express the same qualitative regularity like ‘the larger the distance, the smaller the

[3] The precise role the time interval plays is too difficult to address in depth.

influence'. Useful alternatives that later will be put to the test in a computer model are the Keplerian influence laws $I_K = R/r^p$ (in which I_K is the Keplerian influence from the sun dragging the earth, R and r are the attributes of the configuration with R the rotation speed of the sun, r the distance between sun and earth and p = 1, 2 or 3) and the Newtonian influence laws $I_N = H_{sun} \cdot H_{earth}/r^p$ (in which I_N is the Newtonian influence from the sun attracting the earth, H_{sun} and H_{earth} are the heaviness of the sun and the earth respectively and here also p = 1, 2 or 3). 'Heaviness' is a measure for the strength of the attractive influence of the sun on the earth (in this case). These influence laws may seem plausible, because they are in agreement with intuitive notions that the influence should decrease with the distance and increase with the rotation speed in the Keplerian cases (remember that according to Kepler planets were dragged along as a consequence of the sun's rotation) or with heaviness in the Newtonian cases. Students were also asked to come up with some additional factors they think the influence might depend on.

It remains to be seen, however, whether these particular plausible influence laws (and many others may seem equally plausible) are also empirically adequate. An influence law is empirically adequate when the modelled motion of an object moving under the influence described by that law matches the observed motion of that object. Using a computer model that visualises both an 'observed' motion and the modelled motion of a planet moving around the sun, this notion of matching can easily be made clear to students. The computer modelling environment (Modellus) can be introduced as a way of quickly calculating the resulting motion of particular assumptions for an influence law. Students can investigate Keplerian and Newtonian models with Modellus. They solve the 'matching problem ', i.e. they try to find influence laws that result in a match between the motion of the modelled planet and the 'real' observed planet. For this they were presented with a Newtonian and a Keplerian model of earth and mars moving around the sun, see Figure 10 for the computer model interface.

This model shows the sun and four objects moving around it. Two are the modelled earth and modelled mars. The motion of these is controlled by the parameters of the model, that the students can alter. Two follow the 'observed' or real motion of earth and mars and can not be altered. In this model students can alter the influence law by adjusting the power of the distance r in the Newtonian formula $I = H_{sun} \cdot H_{planet}/r^p$ (with p=1, 2 or 3) and in the Keplerian equivalent $I = R_{sun}/r^p$, with R the rotation speed of the sun around its axis, and they can also alter the heaviness and laziness (independently) of the sun and both planets. More details of the precise setup of this and other Modellus models will be presented in chapter 5. I expected this model to show in an intuitive way when a model can be judged empirically adequate, namely when a choice for a particular set of parameters affects a match, that is: the modelled planet stays on top of the observed planet. Students were asked with some hints to describe how they can see that the presented model is a Newtonian (respectively Keplerian) model, to try and affect a match between the model earth and the observed earth for three influence laws (p=1, 2 or 3) and to judge the value of the model by trying to match the second planet as well. For the Newtonian models a match turns out to be only possible for p=2 and when heaviness equals laziness. In that case the match is perfect. A similar investigation of Keplerian models does not result in perfect matches, though there are near perfect cases.

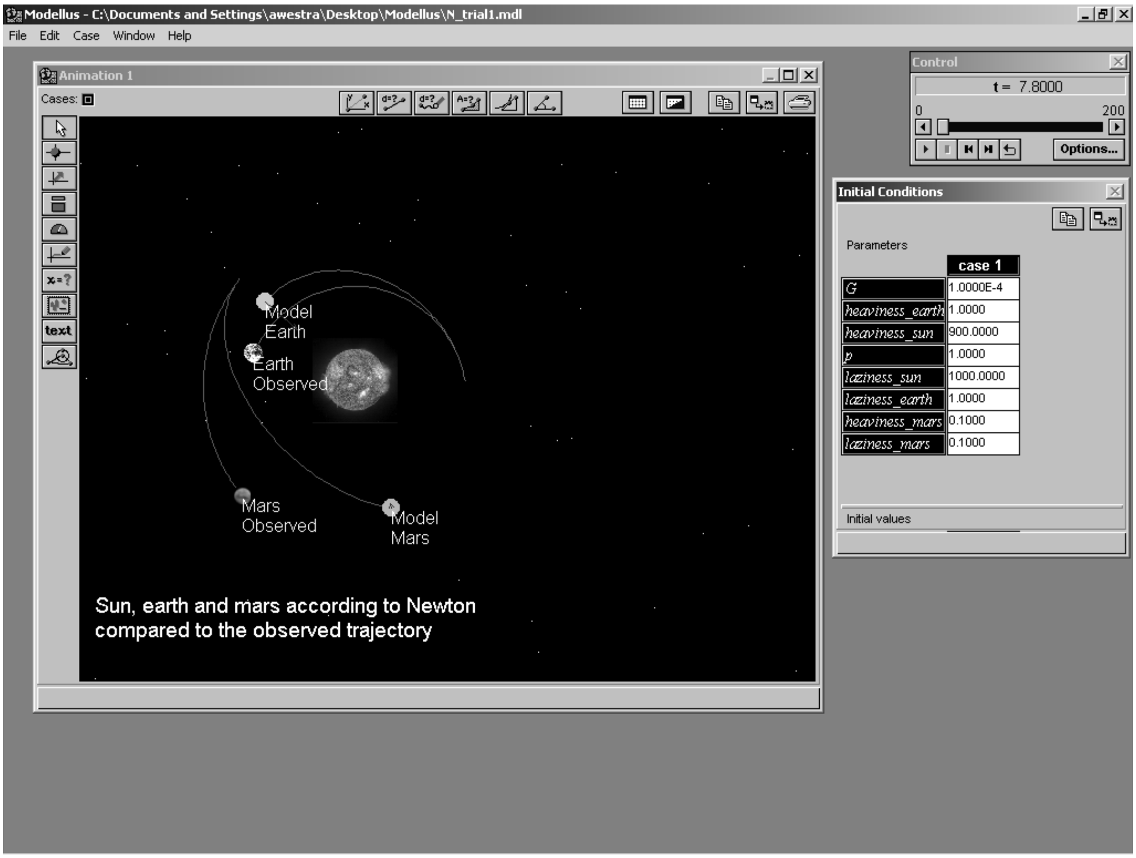


Figure 10: Interface of the computer model of two planets moving around the sun

The teacher's role during the modelling assignments was to keep students on track (and keep the momentum), answering questions, suggesting strategies, applying short corrections et cetera (normal coaching/guiding stuff). When most students were ready he would then evaluate these assignments in a class discussion in which the main point (of how the graphical method is an expression of the explanatory scheme for motion and that motion can be determined given an influence and vice versa) would become clear as much as possible in close relation to student input.

2.2.2. Results leading to revision of the first design

In this section I will describe some results from the first trial and organise those around four subsequent topics addressed in this second main theme: the transition from the first main theme to the topic of heavenly bodies, the method or technique of graphical constructions, the notion of influence law and constructing empirically adequate models by means of computer modelling (the matching problem).

Transition to motion of heavenly bodies

As was said in section 2.1.2 the explanatory scheme was not made explicit effectively. In the transition to the motion of heavenly bodies as explained by Kepler and Newton after the common motions seen in the video fragments in the first main theme, the teacher did not address the intended bridging notion that Kepler and Newton also used the explanatory scheme in their explanations of motion of heavenly bodies[4]. Students could therefore not be expected to see the investigation of the ideas of Kepler and Newton as specifications of the explanatory scheme. This and some other deviations from the plan can be related to the way the teacher was prepared and will be further discussed in section 3.

Graphical construction

Students paid a lot of attention to the explanation of the teacher of the graphical method of constructing influences from a given motion and also to the assignments exercising this method. The assignments were on average completed not too badly, but this took quite some help from the teacher and use of some available sheets with worked out solutions to these problems. The teacher, moreover, focussed on the details of the construction instead of emphasising the main point, that motion can *in principle* be determined given the influence law and vice versa. It was not expected, after all, that students would be able to completely grasp all technicalities of these constructions.

The assignments were to a slight extent evaluated in class, from which became apparent that most students at that time had neither got the main point nor understood the construction technique. To illustrate this the following fragment shows a part of the evaluation in which one student (Els) correctly completes a graphical construction on the blackboard, but the rest of the class is left in the dark.

1. T: You do not get it completely. (4s) Who wants to help? Who can draw Kepler, who can draw Newton? [Els is moving forward]. Fantastic Els.

[Els draws both situations correctly, without any comments.]

2. T: We are talking about the same motion. (3s) Does anyone have a question on this?

[laughter, in the sense of 'yes, of course']

3. T: Yes, Wilco.
4. W: Yes, I do not get at all how she arrived at that, really.
5. T: Can you clarify, Els, how you arrived at that?
6. E: With Kepler [one] must the, because it is 1/2 , do times two. It then becomes two times as big, that arrow. That is how far it goes and then it just goes in that direction, in which the arrow is going. You just put them one behind the other and that is where it ends up.

[The teacher writes the formula deviation=influence/laziness on the blackboard]

7. T: Yes, when the influence is known, and the laziness is 1/2, dividing by 1/2 is the same as multiplying with 2, then the deviation is an arrow that is two times as large as the influence. Hence influence 1 with Kepler leads to a motion from point A, a deviation from point A to point B and influence 2 from B to C.

[The teacher writes points B and C on the blackboard.]

8. T: Is that logical?
9. S: That means that they are equal.
10. T: What is equal, Sebastiaan?

[4] Of course this notion could be expected to be harder to get across, given the ineffectiveness of its introduction in main theme 1, but attention to this point at this stage might have served a purpose in repairing the earlier failure in the sense of that the explanatory scheme may have become somewhat clearer in retrospect.

11. S: Influence 1 and 2.
12. T: That is as such not the point of the question, but that might possibly be equal. It does not matter as such.
13. T: That concludes Kepler. Newton is somewhat more difficult. Sebastiaan can you explain Newton?

That students had difficulties with the construction technique is illustrated by that many students have no clue what Els was doing, indicated by the laughter after (2), which sentiment was expressed by Wilco (4). Someone already familiar with how these constructions work can understand Els' explanation, but of course not the students that have problems understanding this method (6). The addition of the teacher to Els' explanation (7) does not help for the same reason.

Later on in the course students did two assignments that called for an application of the graphical method. They were generally unable to do this, which indicated that the impression that students did not understand this method had been correct.

The main point did also not come across. The teacher hints at the assignment having some point in (12), but does not explain what it is. Students are probably left with the impression that the technique of solving this kind of problems is somehow important. Another indication that the main point had been missed was the reaction to an animation of a quick construction of a succession of positions of a thrown object. For many students only at that stage the notion dawned that constructing subsequent positions actually amounts to constructing a motion. This was an unintentional but fortunate effect of this demonstration, which was originally meant only to illustrate the influence of the size of the time interval. If this insight would have dawned sooner to students, they would not have shown signs that the penny had dropped here.

<u>Discussion of these results concerning the graphical construction</u>

In retrospect the extra light the animation had shed can be understood since all examples and assignments involved only two or three subsequent positions (in which the technique of constructing demanded all of the attention), that were mostly abstract points A and B et cetera (see also the example of an assignment in section 2.2.1). The notion that something is actually moving can be quite easily overlooked.

Working with the graphical construction method was not seen to lead to more insight in the explanatory scheme of which it is a visualisation. One factor that has inhibited such insight is that the graphical construction began with determining influence from motion (cf. section 1.8.1. of the student booklet, presented in section 2.2.1). This, however, is somewhat counter intuitive. One can of course normally argue from result to cause, but this does in general seem to make an argument more difficult when it is not made explicit that the argument uses such a reversal. A fragment that illustrates the difficulty of this counter intuitive approach is the following:

1. T: You also don't get it. What do you not get?
2. Els: Well look, they say, they talk all the time about it is going in this direction, then it is going in that direction. I think that is nice to know, but I do not get why it is going in that direction.

Another inhibiting factor is the introduction of laziness by means of the rule deviation = influence/laziness. The difficulty of getting a clear picture of what is meant by deviation and influence was underestimated. Introducing laziness in terms of its relation to deviation and influence, that were still unclear at that time, led to problems. The following example is quite typical for the confusion surrounding laziness:

1. B: Oh yes, I get that now, but what is laziness?
2. T: What is laziness. Can you imagine something what that could be?
3. B: Yes, that it stops for a moment or something.
4. T: That it stops for a moment. (4s) Someone who is two times as lazy...
5. Emma: When you are lazy, you go slower.

The functioning of the explanatory scheme in constructions is not recognised. The notions of influence free motion, influence, deviation and laziness are still so unclear that they can hardly help in clarifying the construction technique. Or, vice versa, the technique can hardly be expected to illustrate the explanatory scheme. At the most the relation between explanatory scheme and graphical constructions as a visualisation of the scheme might be seen in retrospect.

Notion of interaction law

There are two aspects of the notion of an interaction law that are relevant here. Firstly, knowing what an interaction law is, namely a formula that relates the influence (here on heavenly bodies) to attributes of the configuration[5] (of these heavenly bodies). Secondly, being able to come up with concrete assumptions for influence laws and being able to express assumptions for influence laws, if not one's own then at least Newton's and Kepler's, into mathematical formulas.

Related to the first aspect I cannot say more than that the example discussed in class was confusing and did not show the relation of influence and attributes of the configuration:

1. T: You don't get it completely. You mean that you cannot think of something where it [the influence] might depend on? Or have you not yet thought about it?
2. C: Yes, I have, but …
3. T: You find it very difficult. Nicky, can you think of something?
4. N: Yes, gravity and attraction force.
5. T: The gravity and attraction force.
6. S: That is the same, isn't it?
7. T: Yes, they are both forces, if that's what you mean. That is a possibility: gravity and attraction force. How could it [the influence] depend on these, Nicky?
8. N: …
9. T: In assignment 14 is asked: When the gravity or attraction force is larger, the influence is then larger or smaller, you think, Nicky?
10. N: Well, with the gravity it is larger.

[5] 'Attributes of the configuration' is a monstrous label for things that can also be called 'influence affecting factors'. Both phrases are painful to the ears, but I cannot think of a better way of putting it.

11. T: With the gravity it is larger, then the influence is larger when the gravity is larger. And with attraction force this is different?
12. N: Yes, I think so.
13. T: When the attraction force is larger, the influence will be?
14. N: Smaller.
15. T: Smaller, you think.
16. T: Eh, so in assignment 13 we first try to think of something it [the influence] may depend on. Where does it depend on? In assignment 14 we try to see how it could depend on it and in assignment [15?] we will see what the consequences are for the formula. When the influence is indicated with an 'I' and when gravity is increasing the influence is increasing, how would that formula look like, Nicky?
17. N: I haven't got that one.

According to Nicky the influence depends on gravity and attracting force (4). Maybe because the teacher is not sure about what Nicky means with these terms, he continues his line of questioning by asking how the influence depends on these two 'factors' (7). Here Nicky does seem to attribute different properties to the mentioned factors, gravity increasing the influence when it increases (10) and attraction force decreasing it (12, 14). She was not reading her answer aloud. I had the impression that she was merely talking along with the teacher, inventing things to say on the spot. She could not think of a formula (17).

Related to the second aspect: students were unable to come up with possible attributes by themselves. Furthermore, the distinction between influences and attributes, or influence affecting factors, was found to be difficult, as is illustrated in the following fragment of a couple of students who had just identified pedalling, gravity, speed and wind as influences on a bicycle rider. This fragment came from later in the course:

1. Iwan: Now it says here: on which things does the influence depend?
2. Tara: All, I think.
3. T: Think of an influence law for each influence. Then you should first think of eh (8s) on which things does it depend. How does that influence depends on...
4. Iwan: On all those [meaning the mentioned influences of pedalling, gravity and wind] doesn't it.

[...]

5. T: Try to think what these influences might depend on. And try to arrive at an influence law.
6. Tara: [at the same time] ...(it depends on the) gravity
7. Iwan: It depends on the speed. And other eh 'brakings' ... on the surface, frictions.
8. T: Gravity you mentioned, where could gravity depend on?
9. Iwan: Well....eh...the force of attraction.
10. T: For example.
11. Emma: I though force of attraction and gravity were the same.
12. T: Yes. That is actually kind of the same.
13. Iwan: Yes, but what is it? I don't get ...
14. T: How could a gravity become larger?
15. Iwan: When the object is larger.
16. T: For example, yes, yes.
17. Iwan: Ok, so we can write down that gravity is larger...
18. T: Ok so it could depend on the size of the object, yes.

19. Iwan: 'On which things does the influence depend?' Ok, size of the object.

The question which things the influence depends on (1) is first answered by Tara and Iwan as 'all' (2, 4), that is all the identified influences like pedalling and gravity. The teacher focuses the attention to one influence: gravity (8). Iwan says gravity depends on the force of attraction, but is uncertain (9), which is approved by the teacher (10), leading to a confusion of Emma (11). The teacher then agrees with Emma (12), confusing Iwan (13). This is finally settled by finding a proper influence affecting factor, namely 'size of the object' (15, 17, 18 , 19).

Students were able to find alternative formulas that correctly captured the qualitative notions of Kepler and Newton concerning influence laws. They merely needed the help of some examples of how such a formula might look like. The conceptual difficulty seemed to lie mainly in the value of a formula they invented themselves. Although they were able to do it, students found the translation of assumptions for the relation between influence and influence affecting factors into a formula a strange thing to do. When students were able to formulate some assumptions for the relation between factors affecting influence and influence itself, they were also able to translate this assumption in a mathematical formula. When the formula was missing in their written answers to the relevant questions, the assumption for the mentioned relation was missing as well. Apparently the translation into a mathematical formula as such is not the problem. The strangeness seemed to lay mainly in the fact that one was allowed to 'invent' a formula in this way. This is in contrast with the absolute way in which formulas are commonly treated in science classes, as simply given instead of conjectural.

Discussion

Reflecting on the confusion between factors affecting influence and influence itself, this seems to be a category mistake. The influence that can be related to motion with the rule deviation=influence/laziness is in effect the *total* influence, which is the sum of all particular influences. Each kind of these particular influences depends on specific factors that also determine the kind of influence. So can the total influence I be thought to consist of particular influences like gravity G, friction F, muscle force M, et cetera so that $I=G+F+M+...$. For each of the particular influences some regularity relating influence affecting factors to influence can be identified and sometimes expressed in an influence law, like $G=H_1 \cdot H_2/r^2$ or $F=C \cdot v^2$. What characterises a particular kind of influence as being of that kind is precisely the type of influence affecting factors that are identified[6]. The design may be improved by more clearly distinguishing between factors affecting influence and influence itself.

Another explanation for the confusion between influence and influence affecting factors lies in the fact that the use of constructing interaction laws can only be seen when one also sees a way of testing them, which the students at this stage could not. Without this

[6] For example some influence on an object that is seen to vary according to its distance to a magnet and the kind of material it is made of (for example attraction when iron, no attraction when plastic) may trigger the introduction of a whole new kind of influence, since the identified influence affecting factors (distance and material) do not fit in with the already used categories of G, F and M.

notion it may be difficult to see the point of expressing some unknown influence in *equally unknown* factors like heaviness or rotation speed. After finding that a match can be effected with some particular influence law with specific values for heaviness or rotation speed the use of an influence law (and therefore also the distinction between influence and factor) can be better appreciated.

Computer modelling

Students mainly used trial and error strategies when trying to solve the matching problem. This I observed to be the case with most students. It can be illustrated by one student, Tom, who described his way of working in the next example:

1. Tom: You have to get them both in one trajectory, don't you?
2. I: Yes.
3. Tom: I am just trying to change something and see how it works.
4. I: Ok. What precisely are you changing?
5. Tom: That 'p' and the laziness.
6. I: Ok, yes.
7. Tom: I can perhaps also do heaviness, but I don't know.
8. I: Hm hm

The meaning of the parameters in the models was not immediately clear, but could become clearer with some help. The following two examples illustrate how some guiding questions quite easily led students to correct use of the parameters in both Keplerian and Newtonian models. The first example concerns some (resolved) uncertainty about R in a Keplerian model:

1. Els: Sir, it is going way too fast compared to the observed...
2. I: Yes.
3. Els: ...but how can you change that once again? Because we do not know that.
4. I: Eh, your model is going too fast?
5. Els: Yes.
6. I: Ok, where does it all depend on?
7. Els: Ehm, the influence.
8. I: Ok, so that influence, does it have to become larger or smaller?
9. Eve: Smaller.
10. I: Has to, become smaller. How can you make the influence smaller with Kepler?

[...]

11. Els: When that were three, it would move too fast, but we cannot change that, so we have to change the rotation speed, but I don't know in which direction. Whether it has to get larger or smaller.
12. I: Well, what would you think? Think about the spokes modes.
13. Eve: When it goes too fast it has to get smaller.
14. I: Yes. Yes exactly. Well, you do that.

These students realised that the influence should be made smaller, but were uncertain as to how to do that. The next example illustrates the same phenomenon, only now with the parameter heaviness in a Newtonian model:

1. I: Well ok, what is happening now?

2. S1: The influence is too strong.
3. L: Yes, I was about to say that.
4. I: The influence is too strong. Ok. You would like to decrease it then. Well, how can you do that?
5. L: Eh
6. I: On what does that influence depend?
7. L: The heaviness?
8. I: Yes, but why do you say that so questioningly? The heaviness.
9. L: [giggle] yes, I know ...
10. I: Yes, but of course the heaviness. You can even see it here. The influence depends on the heaviness of the sun, which is not between these, we cannot change that one, but the heaviness of the earth also. You can change that one.

The assignments were expected to fulfil the role that the guiding questions here do: to relate the function of the parameters to motion via their role in the influence law. Without such help students were seen to abandon the assignment in frustration after some time. The modelling assignments by themselves did therefore not serve their purpose of deepening the insight in the functioning of and relations between the variables in these models.

The purpose of the matching problem was instantly clear: finding such values for the parameters that the modelled motion equals the observed motion.

The difference between Keplerian and Newtonian models did not become clearer. Students mentioned the choice for influence free motion as a difference, which of course it is, but I think this was more the result of light drill than on insight in the functioning of the explanatory scheme. At the end of the course some students still could recall the assumptions for influence free motion, but could not explain why these were important.

Another guiding function in the testing of models in the matching assignments could be the use of the criteria of empirical adequacy, plausibility and broad applicability. Information about whether students used these criteria can be found in the relevant sections of the essays students wrote later in the course and that will be described in section 2.3.1. I therefore selected all the fragments from these essays that were related to the testing of models and types of models. I could not find any recognisable use of criteria in 6 of the total of 22 returned essays. The fragments were selected by looking for those instances that students wrote something about the comparison of models in general or (in most cases) Keplerian and Newtonian models in particular.

From all these fragments those that implicitly use the criterion of empirical adequacy are presented below. Two other researchers, one with detailed knowledge of the entire introductory course and one who had only been explained the meaning of the two criteria of empirical adequacy and broad applicability, were asked to indicate in these fragments instances of implicit use of these two criteria. The agreement between the three of us was large. Here follow the fragments containing these criteria:

> Joffrey: We saw in this course that Newton was more precise than Kepler. Most of the time in the Modellus the ideas of Newton were closer to reality than were the ideas of Kepler. The strong point in the model of Kepler was that the properties were easier and

> easier to change and to understand. The weak point in the model of Kepler was that it is not very precise. When you change something in this model, it has much more impact. With Newton the model is incredibly precise. This could almost be made equal to reality.

The phrase ‘easier to understand’ implicitly indicates the criterion of plausibility.

> Sophie: When can we say that we have completely understood a motion, or can completely explain it? I think the answer to this question has to be: when your predictions according to a model agree with your observations. We have ‘tested’ this on the computer. You had to match the observed earth, by adjusting the model of the modelled earth, to the modelled earth.

> Michael: With Modellus (planets) and with an experiment (section 1.13 - measuring an influence), turned out that the model of Newton was better applicable than the model of Kepler. The book stated that the model of Newton was better applicable on situations on earth than the model of Kepler.

‘Better applicable’ in the sense of resulting in a better match, therefore the criterion of empirical adequacy is implicitly used.

> Bertine: Newton was right much more often. The model of Newton fits better than that of Kepler.

‘Fits better’ indicates empirical adequacy. ‘much more often’ indicates broad applicability.

> Emma D.: I consider the model of Newton to be quite useful and I like that I know more about it now, but that of Kepler I consider much less useful, and according to me it isn’t right. In the computer lessons with the program Modellus it also turned out that one could better adapt the model of Newton to make it synchronise the real world (bungee jumper) and let the planets take their right trajectories.

> Rachel: On the computer we could see that both models resemble the reality fairly well, and with a few adjustments we could match the models to the real trajectory of the earth. [...] The most important example in this course had been the model of Newton, which is the one we mainly used with the computer models, probably because it agrees best with reality.

> Mark: I find the model of Kepler (which we used with Modellus) best. It is a model that is not too complicated and it can be easily filled in in such a way that it agrees with reality. With Newton I find that more difficult. [...] it turns out that you have to choose which model is most convenient in each situation.

> Mathilde: I found the model of Newton easier and more logical than Kepler, because I found Kepler more difficult to understand, also because Kepler was more often wrong. Also [on] the computer (with the program Modellus) Newton was more often right than Kepler.

Mathilde also uses implicitly the criterion of plausibility when she indicates that the Kepler model is ‘more difficult to understand’.

> Els: Furthermore I have learned [...] that the model of Newton agreed best. [...] I have learned how to adapt the [computer] model to reality.

> Koen: [...] On these computers we could enter their [meaning Kepler's and Newton's] laws, and subsequently quickly see whether their statements were right.

Koen's use of empirical adequacy in this example is very implicit, as is also the case in the next one:

> Abe: The way [to predict a motion] of Kepler is more difficult or not at all applicable to a motion on earth. The Newtonian way is always well applicable. That was the case in every assignment I did.

'Difficult or not all applicable to a motion on earth' means impossible to find a match, therefore very implicit use of empirical adequacy.

> Tara: In some situations the Keplerian model is better applicable than the Newtonian model, but in other situations that is the other way around. [...] After a couple of weeks participating in this course I knew that the Newtonian model was better applicable on situations on the earth than the Keplerian model. Later we found out that the Newtonian model still contained errors, and that a small piece was missing.

> Tom: After a few weeks we found out that the Keplerian model was less applicable to situations on earth than the Newtonian model. But after that it turned out that also the Newtonian model exhibited some hick-ups, as if something was missing.

> Iwan: You can only say that you understand motion when you have determined in practice that your theoretical predictions are right.

As can be seen from these fragments quite some students (13 from the total of 22 returned essays) implicitly use the criterion of empirical adequacy, albeit sometimes *very* implicitly. Also the criterion of plausibility was on a few occasions encountered. Apparently these criteria can serve in guiding the testing of models.

<u>Discussion</u>

That students use trial and error strategies is not surprising since a more insightful matching procedure requires knowledge of the workings of the parameters in the model. Without knowing what for instance laziness is, changing the value of the parameter laziness in a computer model can at the most lead to some observations of changes in the motion, but will not lead to understanding why the motion changed as it did. In order to make students realise the function or meaning of parameters or adopt a different strategy some guiding questions proved necessary and sufficient. The assignment on its own did not provide sufficient guidance and probably made students adopt a trial and error strategy. The lack of guidance in the assignment was due to its 'density' of questioning. A whole range of questions was condensed into one final question, which was the only one that was actually put to students, namely to investigate which models were empirically adequate. This involved a range of activities like focusing on one planet to start with, noticing its motion, determining how this motion should change, determining how to change it (in what way, with which parameters) and repeating the process for other influence laws. Students would have benefited from more guiding questions in between in the material. Apart from that students were seen to implicitly use the criterion of empirical adequacy in their matching activities, which is therefore as intuitive as was expected and can be retained in the second design.

2.2.3. Second design

The main conclusion from the results presented in section 2.2.2 is that students had insufficient perspective on what they were doing. This was partly caused by the fact that the first main theme had some shortcomings that are still felt here. Furthermore the second main theme contained unnecessarily troublesome elements like the counter intuitive start of the graphical construction section in which force was determined from a given motion, the introduction of laziness with the rule deviation=influence/laziness or the density and difficulty of the computer modelling assignment. However, even when these troublesome elements had been improved, students would probably still have lacked sufficient sight on what they are doing. The graphical construction is and will remain difficult. Students will have to keep clinging to the details with the danger of loosing themselves in those details. Another disadvantage of beginning with the graphical construction is that the actual goal this main theme works towards, explaining or predicting motions by constructing empirically adequate models, remains too far away. How can this be improved?

The first design can be metaphorically described as first establishing the building blocks and then stacking them to make a building. In this metaphor the building stands for predicting the motion of a planet (or any motion for that matter). The building blocks stand for all the elements that are needed for this prediction. In the second design this order of topics is completely reversed, so that it starts with the building and addresses the building blocks from the perspective of their functioning in the building.

The main reason for this reordering was to make students understand the purpose of addressing the subsequent building blocks. All building blocks (or topics) can derive their meaning from the matching problem, which can be introduced right at the beginning of this main theme. In the first design such an early introduction was not considered, or dismissed since, clearly, understanding the matching problem seems to require some knowledge of influence laws, modelling, laziness and the precise relation between influence and motion (second law). How can this be otherwise? I will argue that the matching problem can be understood without first introducing these building blocks and therefore in turn serve as guide in directing the subsequent study of precisely these building blocks. I will here give an outline of how this can be done and refer for a detailed description to chapter 5 section 4.2.

The second design starts, after introducing Kepler and Newton and emphasising their use of the explanatory scheme, with a similar but improved (less dense and difficult) matching problem (see section 2.2.1), which was the end of the first design. The matching problem can be made intuitively clear to students by means of an illustrative computer model that is demonstrated by the teacher. The goal can (again) be expected to be easily recognised: somehow the modelled planet's motion must equal the observed planet's. Clues for what things are needed to affect the modelled motion can be found using the explanatory scheme and can therefore be thought of or at least recognised by the students, I expect. These required elements all get their purpose in light of this matching problem and are the subsequent topics of the second main theme:

- Influence laws. The modelled planet's motion is affected by an influence. The kind of influence (Keplerian or Newtonian), where it comes from and therefore which attributes of the configuration it depends on, is closely related to the assumed influence free motion. The distinction between influence and influence affecting factors should be clearly pointed out. To determine the size and direction of this influence (needed for calculations) an influence law can be introduced, which can be seen as a specification of the element 'regularity' in the explanatory scheme. The functioning of the used influence law can immediately be observed in the computer model.
- The concept of laziness. This concept merits a more careful and gradual introduction given the reported difficulties. The need for this element can also be seen from the perspective of the explanatory scheme, where it functions in the relation between influence and motion (or deviation from the influence free motion). Here the effect of laziness on the motion can be investigated in the same computer model.
- The rule deviation = influence/laziness. After some qualitative feeling for the effects of influence and laziness on the motion (i.e. the deviation from the assumed influence free motion), this can be made more precise with this rule. The need for precision is expected to be clear from the context of the computer model. In order to calculate motion from given (precise) influences and given (precise) laziness, the computer model has to have some precise way of relating influence and laziness to motion. This can be understood even when the way such calculations are performed is not.
- Graphical construction. Finally and optionally the graphical explanation for the precise relation between influence and motion, which can even include the topic of the precise role the step size of the time plays in the models can be investigated using similar (but improved, e.g. starting with constructing motion from given forces instead of vice versa) pencil and paper methods as in the first design. The big difference here is that the purpose of such a precise investigation in what basically is the procedure the computer program follows in determining or calculating the motion is expected to be much clearer for students. This optional graphical construction module is not necessary for understanding the main theme, which is that in order to explain or predict a motion the explanatory scheme for motion needs to be specified and how such specifications look like.

Outline of the second main theme in the second design

The described revisions led to the second design with a didactical structure that is depicted in Figure 11.

Mechanics	**Motive**	**Explanation**
	which should lead to the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of this underlying scheme (theoretical orientation)	
Specification of the underlying scheme into two specific schemes (Keplerian and Newtonian) in the context of developing and testing models of the motion of heavenly bodies.		
	resulting in a question concerning the fruitfulness of the specific schemes and models	

Figure 11: Didactical structure of the second main theme in the second design

The function of the second main theme is still the same: extending students' knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining motion. In the second design this detailing of the explanatory scheme is explicitly made into a guide for understanding the purpose of the subsequent activities, whereas in the first design students could only in retrospect see a similar thread through the activities of this second main theme.

In the process of 'matching' both Keplerian and Newtonian models to the 'observed' motion and seeing that both kinds of models can be made to do the trick one criterion is used all the time: the criterion of empirical adequacy. This criterion does not suffice to base a choice on between Keplerian and Newtonian models, since all used models (including the Keplerian ones) were prefabricated in such a way as to make empirical adequacy possible. The question what can be said about the value of these *types* of models (Keplerian or Newtonian) was expected to slowly grow during the matching process. This question and its answer can fully blossom in the next main theme of the design, which will be discussed in the next section.

2.3. Evaluation of models and types of model in the light of achieving broader applicability.

In the discussion of the first two main themes was seen that students had lost sight of the main thread and did not understand basic concepts like influence and laziness to the expected extent. The accumulated (lack of) results in the first two themes make it rather meaningless to look into the details of the test results of the third theme. The evaluation of earlier activities and continuation of the main thread designed to take place in the third main theme can no longer be expected to yield much results, since this builds on earlier results that should have been achieved before, but were not.

The second design differs from the first. This difference is not primarily based on test results of the third theme from the first design, but on revisions in the first two main themes on which it builds. Since the first themes are different in the second design, the third has to be different as well. The design of the third theme still performs the same function of evaluating models and types of models in the light of achieving broader applicability, but can do so more directly, as will be shown.

I will first describe, in section 2.3.1, how the first design was expected to implement the functions of the third main theme for two reasons. Firstly, it completes the historical picture of the development from first to second design and is therefore illustrative for the used method. Secondly, although the results from the first trial of this main theme, reported in section 2.3.2 were minor, still some noteworthy things may be learned and incorporated in the second design. Section 2.3.3 gives a broad description of the second design.

2.3.1. First design

The second main theme should have resulted in a question concerning the fruitfulness of the investigated models. Since both Keplerian and Newtonian models for the motion of heavenly bodies are both still in the race (although the Newtonian models have a slight lead), the question which one is to be preferred is expected to come up. In the third main theme this question is answered. Models and types of models are evaluated in the light of two criteria, addressed shortly. The didactical structure of the third main theme in the first design is depicted in Figure 12.

The 'reflection on models' part in this didactical structure aimed to make explicit two criteria for determining the usefulness of a model: (1) Whether the interaction theory is plausible. Where does the influence come from? Are the factors and the way an influence depends on them, as described in an influence law, plausible? For instance, an attraction from the sun on a planet that increases with distance is implausible. (2) Whether the influence can be related to 'muscle force'. Is a larger influence according to some to be determined measure in accordance with larger muscle force? In a sense muscle force is a prototypical influence. The Keplerian notion of influence is not in accordance with this criterion, which is a strong argument against Keplerian theory.

In retrospect the second criterion can be considered to be a special case of the first. When some measure for influence failed to be proportional to muscle force it would be considered implausible. At the time of the first trial these criteria were used separately. Note that at that time I did not explicitly use the criterion of broad applicability.

The plan for this reflection consisted of the following elements: The investigation of a simple motion on earth, introduced as a means to say more about the value of the two types of models. Applying Kepler and Newton to e.g. a bicycle rider riding with constant speed who stops pedalling shows some problems for the Keplerian model. Since the only apparent influence that remains after the pedalling stops is friction, which is directed in the opposite direction of the motion, the Keplerian model would predict an instantaneous reversal of direction of the motion, instead of a (gradual) deceleration. Another way of comparing the two types of models is applying them to a motion without friction, e.g. using a glider on an air track. According to Kepler the forward influence in such a case would have to be greater than zero, whereas according to Newton this influence would equal zero. If we would have some means of measuring influence we might be able to check both predictions. After introduction of the spring scale as an intuitive way of measuring influence this experiment is done. This way of measuring influence I expect to be intuitive, because it can be directly related to muscle force: the larger the muscle force is, the larger number a spring scale indicates. Some measure of influence that would *not* adhere to such a regularity would be considered to be strange indeed. The conclusion of this reflection is that the Newtonian models are to be preferred since both situations, the bicycle rider and the frictionless motion, had led to problems for the Keplerian model. The implicit criterion that is used here is the criterion of broad applicability.

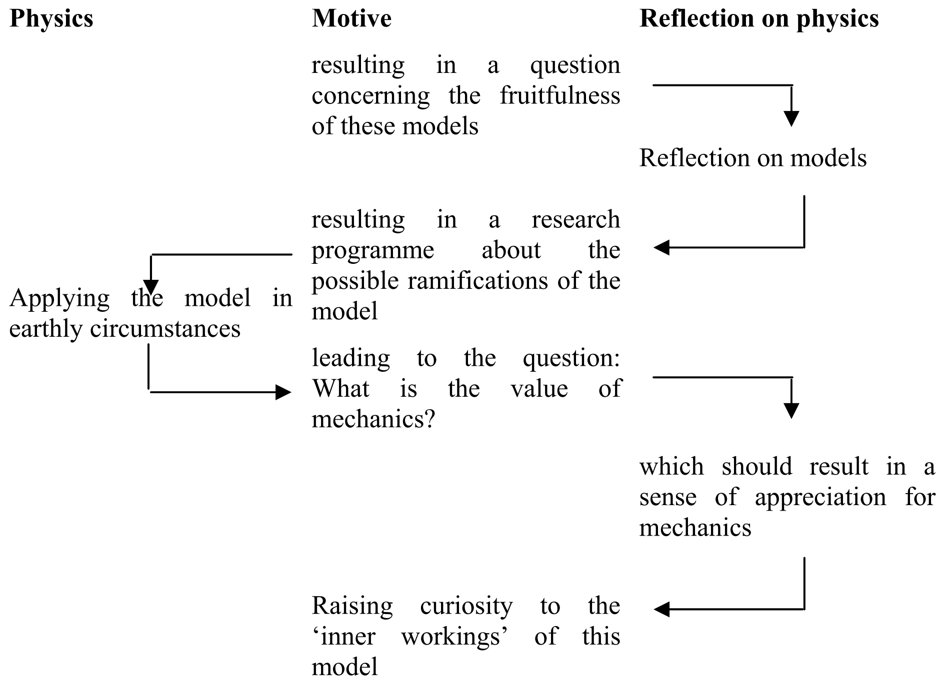


Figure 12: Didactical structure of the third main theme in the first design

The teacher should ensure that the students remain sight on the purpose and meaning of the activities related to this reflection by clearly introducing them as a means for determining the value of Keplerian versus Newtonian models, recalling this perspective from time to time during the details of the investigation of the motions on earth and evaluating them in light of this introduction. In this evaluation the conclusions from these and earlier activities are compiled and made explicit by the following questions in the students booklet. Before the experiences with the first two main themes students were expected to be able to answer those questions as indicated.

- What does the structure of a model for motion look like?

  The expected response was something resembling or describing a figure like the following, which was used in the course.

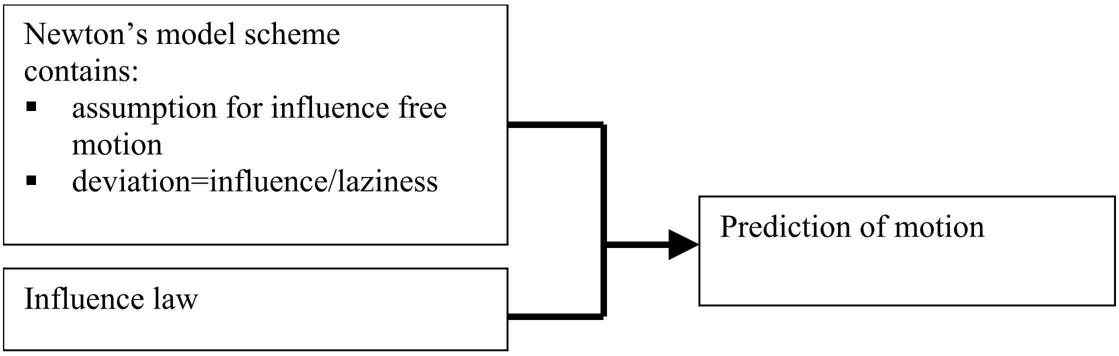


Figure 13: Scheme of the structure of a motion model

- In what ways differ Keplerian models from Newtonian models?

  Here students might give three general differences: their assumption for an influence free motion, the direction of the influence and the particular form of the used influence law (s) and/or say something about their value: Newtonian models are broader applicable, empirically adequate (slightly more so than Keplerian) and allow a plausible (intuitive) measure of influence.

- Why is an influence law needed in a model for motion?

  A precise quantitative description of the influence (at all times) is required in order to calculate or graphically determine the motion.

- How does one arrive at such an influence law? How is a model of motion tested?

  Here students can summarise the process they have been through several times of finding/assuming some relevant factors on which the influence may depend, turn the relationship between influence and these factors in several possible influence laws and check these laws in a model by matching the modelled motion to the observed motion.

- What reasons do you know for rejecting a model for motion?[7]

  The reasons that had been encountered are: a model is not empirically adequate (does not result in a match) or an influence law is implausible (i.e. violates commonsensical notions about the world).

- Which type of models do you prefer: Keplerian or Newtonian? Explain why you think so.

  One argument seen in the second main theme is that a plausible interaction theory can be found in the Newtonian case for heavenly bodies resulting in empirically adequate models. Added to this are the new arguments that in the Newtonian case also a plausible interaction theory can be found for situations on earth, where the plausibility lies in the fact that the interaction theory can be

[7] The reasons for endorsing a model are more difficult to formulate, which may be due to the nature of scientific theorising as described by Popper.

related to muscle force, whereas in the Keplerian case this can not, and that therefore Newtonian models are broader applicable than Keplerian models. The latter argument was expected to be intuitively clear for students and was not addressed explicitly, so that it probably will not be mentioned in response to these questions.

Now the reasons for choosing Newtonian mechanics may be expected to be known, the plan was to further illustrate its power and range by applying it to a more complicated motion. Students can model this motion when they can come up with suitable influence laws. The only influence laws students can be expected to be somewhat familiar with from earlier education are expressions for the force from a spring ($F_s=-C \cdot u$) and gravity ($F_g=m \cdot g$). An example of a (possibly interesting) motion that can be modelled using these two laws and the computer modelling program students are already familiar with is the motion of a bungee jumper. The first step in modelling this motion was to have students realise they would need influence laws and think about how these would look in this case. I expected that presenting them with the situation of a bungee jumper would suffice for some to remember the mentioned influence laws. Others would then probably recognise these laws as appropriate. They would then add the laws to a prefabricated computer model of a bungee jumper, investigate and improve this model, e.g. by adding friction.

Finally the conclusions from these and earlier activities are compiled and made explicit by the following assignment:

Assignment 26:

The conclusion from the preceding activity is that the Newtonian way of doing mechanics is widely applicable. But why would one apply it in the first place? The general motive/goal was to understand change as motion. Did we get any closer to that? Can we at least say that we can tackle motion now? When can we say that we have understood or can completely explain some motion? What is needed to predict a motion? What is the purpose of a model of a motion? What are the weaknesses and strengths of Newtonian models as compared to Keplerian models? What does the structure of any motion model look like?

Write a short essay of about one or two pages in which you describe what you have learned in this course. You could address some (or all) of the above questions. The goal of this assignment is that you look back on all the things you have done and in this way make your own summary and conclusion.

These essays could then be discussed in a way that would provide a bridge to the regular course. The following figure, which is an extension of Figure 13 for the Newtonian case, could serve a purpose to illustrate the point that with the help of the introductory course in principle a broad perspective on dynamics can be retained. Furthermore, kinematics can be shown to serve a technical purpose in explaining/predicting motions, since it plays an important role in calculating motions from force and vice versa.

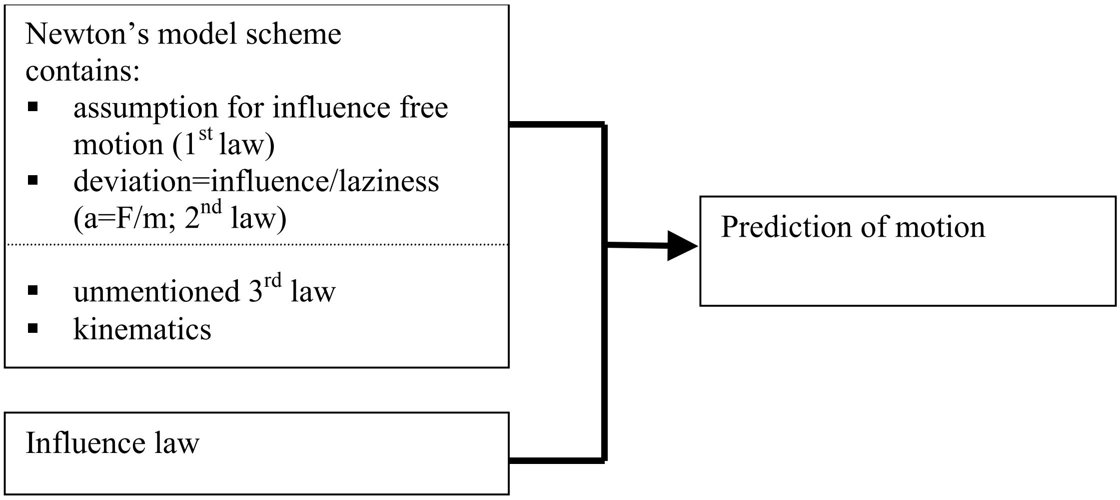


Figure 14: Newtonian model of motion

In this figure some elements of Newton's specification of the explanatory scheme are for the first time labelled in the usual way, i.e. first law and second law. His third law and kinematics are unknown after the introductory course and will be topic of study in the regular course. His scheme together with one or more proper influence laws suffices to predict or explain some particular motion. Kinematics and third law serve a purpose in further understanding the Newtonian scheme. A scheme for which some appreciation should have arisen, as this was one of the goals of the introductory course. The teacher can use this figure in the evaluation of the reflection questions mentioned before. The challenge here lies in using the figure in such a way that students recognise their own answers (as written in the essays) in it.

Apart from the 'relabelling' of laws, also the connection between some other terms used in the introductory course and their more widely used counterparts needs to be addressed. For instance in the regular course the word 'force' will be used for Newtonian influence, mass for 'heaviness' or 'laziness ' et cetera.

This third main theme was expected to take about three 50 minute lessons.

2.3.2. Results leading to revision of the first design

In this section I will describe the main findings from the first trial of the third main theme. Given the fact that the course had already been off-track since the earlier main themes and that also in the third main theme some deviations from the plan occurred (of which some examples will be shown), not very much can be said regarding the results of this main theme. However, notwithstanding these difficulties some findings did surface and are worth mentioning here.

The following two examples give an impression of the kind of deviations in the execution that occurred in this main theme. Firstly, the reflection started with applying Kepler and Newton to a simple motion on earth. No reason for this application was mentioned, unfortunately. Students therefore could not realise that in this way they were supposed to find additional arguments for basing their evaluations of the two types of models on. Secondly, the intended reason for introducing the spring scale was that measuring influence in the second investigated motion, the frictionless one (see section 2.3.1), would provide another example in which the Keplerian model led to problems. This reason was not mentioned. Instead the technical and procedural details of the demonstrated experiment were emphasised, instead of its conclusion.

In this main theme students wrote the essays summarising this course that have already partly been partly presented in section 2.1.2 and 2.2.2. The main interest in this main theme was whether students used the additional criterion of broad applicability when comparing types (Keplerian and Newtonian) of models. In the relevant fragments from these essays[8] I and two other researchers indicated instances of use of this criterion, reaching a large agreement.

There is no use talking about the applicability of an empirically inadequate model. The criterion of empirical adequacy is in that sense more important or more basic than broad applicability. This is reflected in the fragments. The following instances of implicit use of the criterion of broad applicability are in all except one case (Stan) combined with use of the previous criterion.

> Bertine: Newton was right much more often. The model of Newton agrees better than that of Kepler.
>
> Frank: I also understand the differences between the Keplerian model and that of Newton. These two models both perform quite well in predicting the motion of a planet, but only Newton performs well in predicting the motion of the bicycle. [...] I think it would save a lot of time when less time is spent to the motion law [meaning: influence law, ASW] of Kepler. Since that one is not right for all situations it is not really necessary, or at least less important, to discuss. On the other hand, one does learn to test (motion)laws and notice errors.
>
> Lisanne: Because there are multiple theories, we can compare them to each other. That was quite useful, but you do not know which one is correct. We really cannot determine the motion properly. On the other hand I am curious, when it is really researched, what the 'outcome' will be. Perhaps it is possible that the Keplerian as well as the Newtonian way are incorrect. [...] The Newtonian model can also be applied to for example a bicycle, which cannot be done with the Keplerian model. That is one of the strengths of the Newtonian model. I do not know what a weakness of the Newtonian model is.
>
> Stan: Newton was right, for his model also works with a bicycle.
>
> Niek: If I have to compare the model of Newton to that of Kepler and say which one I prefer, I would choose the model of Newton. With Modellus we compared these two models which resulted in that the model of Newton fits better in the Universe. A lesson later we compared these models "on earth" and on an air track. On the air track we found out that a constant motion has in fact a net force of 0. After that we tested both models on a bicycle rider. There too the model of Newton proved best. [...] I myself

[8] This was the same set as used in the discussion of these essays related to main theme 2 in section 2.2.2. There also the way in which these fragments were selected was described.

> consider the model of Newton very well (as far as we have tested), the model of Kepler I am less fond of.

A lot of students did arrive at a correct (albeit implicit) usage of the intended criterion of empirical adequacy and some even of the criterion of broad applicability (and plausibility) even though the shortcomings in the scenario, teacher preparation and execution made this less likely. I find this promising. Apparently these criteria are in fact quite intuitive, as I thought they were, and can therefore be retained in the second trial.

2.3.3. Second design

The second design differs in several respects from the first. These differences were only to a slight extent due to the experiences with the third main theme of the first design. For the most part the differences can be understood as consequences of earlier changes made in the first two main themes. I will first mention the changes and then give an overview of the second design of the third main theme.

Changes

The reflection in this theme can be done more directly. The function of the reflection was to make students realise what still needed to be done, which is finding a way to answer which type of model explains best. For this they have to remember what the goal was (understanding what explaining motion entails) and what has already been achieved (investigating two feasible alternative specifications of the explanatory scheme). In the second design the question which type of model explains best is answered by using a slightly different criterion, namely broad applicability instead of the link to muscle force, because it is more direct. There is no need for introducing measurement and experiment (e.g. with a spring balance). Merely applying Kepler and Newton to situations on earth like the motion of a bicycle rider suffices, since that will already show some difficulties with the Keplerian scheme but not with the Newtonian scheme (see also section 2.3.1). This direct approach will only work if students can value the epistemic virtue of broad applicability, which I expect them to do. This expectation is backed somewhat by the experiences in the first trial, where some students showed quite spontaneous use of this criterion. The notion that a more general theory is better, all other things being equal, than a less general theory is quite intuitive, I think.

The function of the situations on earth to which Keplerian and Newtonian models are applied is different. In the first design they were used to ramify the Newtonian scheme illustrating the power and range of Newtonian models in predicting motions and the process of finding a suitable force law as necessary ingredient for such a prediction. In the second design their function is to demonstrate that applying Keplerian theory leads to problems whereas Newtonian theory does not, thereby showing Newton's broader applicability. In order to fulfil this function, there is no need to model the motion using influence laws and computer modelling tool. The chosen situations on earth can therefore be simpler in the sense that a qualitative description suffices. In the second design the examples of a bicycle rider and hovercraft are used instead of a falling drop and bungee jumper in the first design.

The mechanicism story, adapted from the first design of the first main theme (see section 2.1), is added to the second design of the third theme to give an additional argument for the power and range of (Newtonian) mechanics.

The second design ends with solving the initial asteroid problem introduced at the start of the course in the second version of the design (see section 2.1.3) and a similar bridge to the regular course as was used in the first design. In this way the initial promise (not in so many words, but at least implicitly made) to students that this problem will be solved in the course is fulfilled, which is a nice way of rounding off or making the circle complete. In the second design there is no need to summarise the course in the way of Figure 14, because another figure depicting a summary is used throughout that course, namely Figure 8 from chapter 5. The connection between the terms used in the introductory course and those that will be used in the regular course is depicted in the following table, see Table 3. This table was presented to students in the booklet for easy future reference. It announces to which concepts terms from the introductory course will develop in the regular course.

Introductory course	Regular course
Influence	force
Velocity	velocity
Influence free motion (according to Newton)	rectilinear motion with constant velocity (1^{st} law)
Laziness	inertia
heaviness=laziness=mass	inertial mass=gravitational mass
deviation of influence free motion (according to Newton)	acceleration
deviation=influence/laziness (according to Newton)	$a = F/m$ or $F = m\cdot a$ (2^{nd} law)

Table 3: Terms used in the introductory course and the concepts to which they will develop in the regular course

These changes led to the second design of which I will now give an outline.

Outline of the third main theme in the second design

The didactical structure of the third main theme in the second design is depicted in Figure 15.

Mechanics	**Motive**	**Explanation**
	resulting in a question concerning the fruitfulness of the specific schemes and models	
		Reflection on criteria to determine which schemes and models explain best
	resulting in a plan for further validation of the specified schemes	
Applying the specific Keplerian and Newtonian scheme to other motions		
	leading to a point of closure at which we may ask "which schemes and models explain best?"	
		Evaluation of which schemes and models explain best and which elements of this scheme are still unknown
	resulting in an appreciation of the Newtonian scheme and an outlook on the regular course	

Figure 15: Didactical structure of the third main theme in the second design

As was said before the function is still to evaluate models and types of models in the light of achieving broader applicability. The question concerning the fruitfulness of models and types of models with which the second main theme ends is reflected upon. From this reflection surface the already used criteria of empirical adequacy and plausibility (to select between models) and the now explicitly used criterion of broad applicability to guide a selection between types of models. This results in a plan for further validation of the schemes, namely by applying them to other than planetary motions. This plan is executed by applying both Kepler and Newton to simple motions on earth, e.g. those of a hovercraft and a bicycle rider. This provides additional information about which scheme explains best. Evaluating this information in light of the criterion of broad applicability should result in an appreciation of the Newtonian scheme. The evaluation also makes acceptable the study of some details in the Newtonian specification of the scheme that are still unknown like the kinematics part, which will be the topic of study in the regular mechanics course on which an outlook is provided.

2.4. Embedding in the regular mechanics course.

In this section the fourth main theme is described somewhat differently than the first three. The reason for this is that this part of the design had not been developed and tested to the same extent as the other parts. To properly develop and test a way of making use of the introductory course in the regular course would be an extensive research topic in itself (see also chapter 7). I attempted to develop some guidance in making productive use of the introductory course in the regular course, which is the topic of this section. I also investigated whether this use paid off, which will be described in chapter 6. I will start with describing the design (meaning the product, not the process), which consists of guidelines for the regular course. This will be a description of both the first and second design in one go, without a presentation of results of the first design that led to revisions as was done in the discussion of the first three main points.

Functions of the fourth main theme

The fourth main theme ‘s main function is suggesting suitable moments and ways of addressing specific details in the regular course, like the usual learning difficulties that will be encountered. Here the established vocabulary using terms from the explanatory scheme, which was one of the main goals of the introductory course (see chapter 3 section 2.2), can become useful.

Another function of the fourth main theme is retaining the overall perspective that the introductory course may have provided in the regular course and thereby some sense of meaning and purpose. The picture of mechanics that is sketched in the first design and that students ideally should have adopted shows the process of doing mechanics, i.e. explaining motions, as finding suitable force laws to plug into the Newtonian scheme (which has been seen to fare better according to certain criteria), which results in prediction of motion. In the second design doing mechanics was depicted throughout the course in the manner of Figure 8 from chapter 5, which shows the specification of the explanatory scheme for motion in which of course finding suitable force laws is also important. Although this overall picture of mechanics is in essence what mechanics is all about, it is seldom found in regular courses on mechanics. Regular courses in mechanics traditionally start with kinematics, involving definitions of quantities like displacement, velocity and acceleration and interpreting diagrams depicting these quantities. After that the dynamics part starts, which is mostly concerned with calculating forces, accelerations and velocities in situations with constant resultant force[9]. In the details of such calculations one can easily lose sight of what it is one is doing. The perspective of the introductory course can at such times be recalled, which widens the focus and may give more meaning to these details to students.

Link-manual

For the regular course I did not design teaching/learning activities in great detail (as described in a scenario), but made only some suggestions that were put down in a so-called link-manual. The link-manual is a teachers guide which describes how in the regular course use can be made of the introductory course, i.e. how the introductory and regular course can be ‘linked’, therefore ‘link-manual’. One can expect that the introductory course can be helpful in understanding the mechanics in the regular course, at least that was its intention, but also that such a transfer will not go spontaneously.

[9] Such cases are the only ones that can be calculated without complicated mathematics or computer modelling.

Some effort will have to be made to affect recognition of this link. The connection between introductory and regular course can be emphasised in different ways:

- Related to the content by regularly rephrasing the content as presented in the textbook or other used teaching materials in terms of the introductory course, recall comparable topics or activities from the introductory course or even replace parts of the regular course by material from or in the spirit of the introductory course. Also discussing the inevitable learning difficulties with the vocabulary of the explanatory scheme establishes a link.
- Related to the way of working by using the same kind of teaching formats, attention to student input, or computer modelling environment the students had got used to.
- Related to the way of both formal and informal examining, testing or evaluating, by stressing the same things as were done in the introductory course. For instance laying more emphasis on conceptual questions and real understanding than on plugging and chugging formulas. Students tend to determine what is important and what not by what is on the test (and rightfully so), which means that one should test what one considers important and not what is easy to test. Osborne warned for this phenomenon when he wrote that "when we attempt to make the important measurable, only the measurable becomes important" (Osborne & Collins, 2000).

Apart from these general guidelines the link-manual contains a whole bunch of specific directions for each section or assignment in the used textbook that may be used for establishing and highlighting the link with the introductory course. The regular course following the first introductory course used a textbook by Middelink (1998) and the one following the second course used a textbook called ‘Newton’ (Kortland et al., 1998). I will give some examples of such suggestions related to each textbook, starting with the former. These examples are meant to show the diversity in and nature of the given suggestions.

- In the chapter on kinematics (rectilinear) motion with constant acceleration is introduced solely by describing what it is. My suggestion was to also include the dynamical relevance of such motions: these kinds of motions are the result of a constant force, e.g. gravity near the earth’s surface.
- In the chapter on dynamics Newton’s second law is illustrated or experimentally verified with a practical assignment concerning a frictionless cart driven by a constant force. My suggestion was to skip this assignment since the suggestion if not statement from this assignment that the second law is an empirical law is in complete disagreement with the line of thought from the introductory course. $F=m \cdot a$ is much too much axiomatic to embark on this route (Newburgh, 2001). Instead its functioning as a specification of the precise relationship between force and motion can be recalled.
- When a number of forces are introduced and illustrated, such as gravity, normal force, force from a spring, tension in a rope and three kinds of friction, most are

introduced by implicitly appealing to a rough interaction theory. For instance a spring can push or pull when pressed or extended. Normal force on the other hand is introduced by implicitly appealing to the relation between force and motion. The argument in the textbook follows the following line: *A vase is in rest, standing on a table. Therefore the resulting force has to be zero (first law). We know that gravity is working on the vase. So there has to be another force that compensates gravity. That force we call normal force.* This argument does not use interaction theory, the question 'where does the force come from?' is unanswered. My first suggestion was that some attention should be given to the sources of these forces, i.e. to interaction theory. This would recall the main project of what mechanics is all about: finding suitable force laws. Therefore learning about what kinds of forces can be found may be seen as useful. I also suggested that the two ways of identifying forces by means of answering 'where does it come from?' (interaction theory aspect of mechanics) or 'why has there have to be a force?' (relation force - motion aspect of mechanics) that were used implicitly in the textbook should be made explicit. This might also quite naturally raise the question where normal force (and also tension in a rope for that matter) come(s) from, which is a well-known problematic issue to get across (see chapter 2).

- The chapter on kinematics starts with the following introduction:

  > Motion is everywhere, take for example a speeding rocket, a riding train and an airplane or bird in the sky. Gas molecules, planets and stars move invisibly, but very fast. The growing of a fingernail and the shifting of a glacier are also motions that you cannot see. It is obvious that knowledge of motions teaches us to understand nature better. The study of motions has been the starting point of the modern sciences, for that matter. In this chapter only the motion in a straight line is addressed. This is the easiest motion we know of. (Middelink p.41)

  This expresses the relevance and purpose of mechanics in a nutshell. Motions are omnipresent, understanding motions helps us to understand change in nature (that is almost everything), and even some mentioning of the origin of modern sciences (that is Kepler and Newton among others) is made! It is a pity that the rest of the chapter does not live up to the expectations raised in this introduction, however. The chapters on kinematics and dynamics follow the traditional way of presenting mechanics. My introductory course shows what it would entail to take such an introduction seriously. I wager that all teachers using this textbook simply skip this introduction. My suggestion here was to not skip it.

Some examples of suggestions related to the second textbook are:

- The remark that a question concerning the derivation of the first law from the second is wrong.

- Related to a couple of questions about identifying forces, my suggestion was to also ask the students how they knew that the forces they identified were there.

- Two questions involved non-linear motion. One was about identifying forces on a satellite and another on a soccer ball after being kicked. The first question may trigger some memories of computer model outcomes from the introductory course. The second question can be answered in various ways. One way is as an exercise of elimination. Students simply check for each of the four forces they have come across whether it is present in the situation or not. This way focuses on the interaction theory aspect of mechanics. Another way I expect is to identify three forces, gravity, air friction and some forward force. The arguments for these forces can differ. Identifying gravity and air friction can be based on interaction theory, whereas the identification of a forward force is probably based on the relation force - motion. (For instance a remark like 'the forward force simply has to be there' indicates this kind of reasoning). After a forward force is identified based on the motion of the ball students may come up with some more or less plausible interaction theory like some aftereffect from the kick. After giving this particular expectation of student's responses my suggestions to deal with them were (again) to explicitly use both approaches from interaction theory and relation force - motion, with the related questions to discuss the given answers. For instance the identification of a forward force can be questioned by recalling that Newton did not need any forward motion to explain the motion of planets and in respect to interaction theory that Newtonian forces/influences did not show aftereffects (and did not need to).
- One assignment used a new force law for air friction ($F=C\cdot v^2$). My suggestion was that students could complete a computer model of a bicycle rider in which they have to add this particular force law.

As can be seen from these examples the suggestions varied in length and explicitness. They all tried to use some part of the introductory course in discussing, changing (or omitting) some part of the textbook/regular course and were therefore written in close connection to the used textbooks. What this also shows is the huge difference in the extent and detail of designed activities and their justification between the link-manual and the scenario (see chapter 5). It is clear that the suggestions given in the link-manual do not come close to the worked out, pondered upon and justified prescriptions of a scenario.

One important element still lacking in these link-manuals is more specific advice as to *how* the usual learning difficulties can be addressed. Some instances where they can be expected to occur have been identified and the need for addressing them has been stated, but concrete advice was not part of these link-manuals. The simple reason for this was that at the time of writing these link-manuals I did not know how this nut might be cracked. To get some more grip on this matter several interviews were conducted during the regular course following the second trial in which the usual learning problems were triggered and discussed using the introductory course. These interviews resulted in more detailed information as to how these problems might be successfully addressed. These interviews and their results will be described in chapter 6, section 8. I do not claim to have solved this problem, but I do think some useful insights were obtained that might serve as starting point for a more thorough investigation of this matter.

3. Teacher preparation from first to second design

Where in section 2 the development of the content from the first design and trial to the second design was described, in this section the development of ideas about preparing the teacher will be the topic.

3.1. Goal and problems

The problem posing character of my design calls for a rather different teaching style than most teachers are used to. Specific elements of a desired teaching style for a problem posing approach that are mentioned by both Vollebregt and Kortland include using student input and ensuring that students see the main line of reasoning. I will discuss what is meant here by both elements, thereby summarising what these two authors wrote on the subject, because this will indicate what kind of problems can be expected that the teacher preparation should somehow address.

Using student input is described by Vollebregt as ‘mak[ing] pupils’ own answers part of the general outcomes as much as possible, for instance by using their own expressions in summaries of the outcomes’ (Vollebregt, 1998). This is important to ensure that the questions that certain episodes or activities are designed to trigger become really the questions of the students instead of the designer/teacher. Only then can such a question function as a reason for engaging in the subsequent activity, when this next activity can be expected to contribute to answering that question (on grounds that students can understand). To make student input matter the teacher should not hastily interpret students (put words into their mouths), pose suggestive questions or answer questions herself. Instead, in order to get to know what students really think, some time should be spent discussing their thought for which the teaching format of whole-class discussions is usually appropriate. However, managing whole-class discussions in a way that student input really matters is difficult for most teachers as are other ways of making student input matter.

Ensuring that students see the main line of reasoning calls for explicit attention to the transitions between activities. Although the activities are designed to follow a recognisable thread, it would be too much to ask of students to be able to recognise this thread at all times all by themselves. The teacher should help them with this by pointing out the main line of reasoning. This requires a preview of what will happen in the next set of activities that uses or builds on a reflection of what happened in the last set of activities. This is not a strictly local process, focusing only on the transition of one set of activities to the next. Also the main goal to which all activities should lead can occasionally be recalled to provide a perspective on what it is one is doing. This particular emphasis on transitions between (sets of) activities is unusual for most teachers. In traditional educational designs (standard textbooks) paying attention to such transitions would not be useful or even possible, since many transitions cannot be understood from the point of view of the students. The next activity does not follow 'logically' from the previous one irrespective of how long one would reflect on it and a preview on the next cannot be given in a meaningful or understandable way, simply because it had not been designed that way. (This is not to debunk traditional education. I am merely stating that traditional education is not problem posing.)

So the work of Vollebregt and Kortland warns for the dangers of inadequate attention to student input and inadequate attention to transitions between (sets of) activities. How can one take these dangers into account in the preparation of the teacher? This is a difficult question that still needs to be answered satisfactorily. General guidelines from the literature (e.g. (Joyce & Showers, 1988)) suggest including the elements of demonstration, practice, feedback and coaching of classroom application in teacher training. Another element that is important in teacher preparation to new material and is frequently mentioned in the literature is the teacher having a sense of ownership of the new material.

One can only practice (and give feedback on that practice and coach its application in the classroom) with some material. I did not see a useful and practical way of practicing *before* the first trial. Kortland incorporated a teacher preparation in line with the recommendations of Joyce and Showers *after* the first trial. In this way the first trial provides for the material (e.g. examples of good and not-yet-so-good practice) on which a proper preparation for the second trial can be based. For this approach the same teacher should preferably cooperate in both trials. Within one trial a teacher can of course also be realigned when the execution deviates from the plan. In such a case experiences from earlier lessons serve to adjust the teaching behaviour in subsequent lessons. However, this requires reflection on and quick analysis of these earlier lessons and allows little or no time for practicing the new behaviour or developing a teacher course addressing these specific points. Another problem is that the 'new behaviour' can still be unclear for the teacher, since it is necessarily an extension or trend of earlier behaviour. He might still not fully understand what it is the researcher wants him to change in the coming lesson, based on what was seen (and reflected and analysed) in past lessons.

Apart from the still not fully addressed problem of how to properly prepare the teacher for the first trial, there is also a practical impediment. It is hard to find some room for experimenting within the Dutch educational system. Both the curriculum and the agendas of the teachers are cramped. As a consequence few teachers are prepared to spend 10 lessons and some preparation time on something that is not directly profitable for the curriculum, let alone spend considerable preparation time.

I have taken a less than optimal execution of the first design for granted, because it can still provide sufficient results, in the sense that one can learn useful things about the design itself. This expectation is based on similar research using the same research method. In the next section I will look into the teacher preparation for the first trial. This will illustrate the mentioned expected problems, which did in fact occur (as well as some others), and show a way of dealing with these problems.

3.2. First preparation + some results leading to revision

The first design of the introductory course included both the course content and the way in which it was intended to be practically executed in class and had been written by me. The goal of the teacher preparation was to guarantee as much as possible an execution of the scenario according to plan and to adapt the scenario whenever new arguments by the teacher were convincing. The dangers of inadequate attention to student input and inadequate attention to transitions between activities were thought to be averted to some extent by including descriptions of the role of the teacher in the scenario that emphasised the importance of these particular dangers, which sometimes went as far as written-out suggestions for how to address certain transitions. A sense of ownership was thought to be instilled in the teacher by explaining all considerations in the designing process and using as much as possible his input and suggestions for modifications in the design. This anticipated a rather active interest in the designing process from the teacher. In retrospect this 'instilling ownership by convincing' as well as my anticipation of active interest in what is basically my job seems somewhat naive.

The preparation of the first teacher took place in three phases. The first phase consisted of one meeting of about two hours in which I presented the course as a whole together with its basic ideas to the teacher. In this way the teacher could get an overview on the basis of which he could decide if he wanted to cooperate or not. The second phase consisted of four sessions of approximately two hours each in which each part of the course was presented and discussed in more detail. In the third phase each lesson was extensively discussed one or more days before the lesson took place and shortly evaluated the same day the lesson took place. The communication was pretty much an unidirectional process in which I explained and emphasised what I thought were important points in the scenario. The only indications at that time of what the teacher actually understood, agreed with and remembered were his questions and suggestions during these meetings. This was the best I could do at the time.

Apart from the general difficulty that with a unidirectional way of communication it remains uncertain whether all intentions and meanings of the design are understood, some experiences during the first trial indicated two problems with preparing the first teacher. The first problem was that good introductions and evaluations for activities and proper attention to student input was frequently lacking. Vollebregt and Kortland reported the same problems, as we saw, and these were therefore not unexpected. However, the real importance of these problems (or dangers) they warned for, in a problem posing design had been underestimated by me. Only after experiencing these problems myself up-close in the first trial, I realised that the advice given in the scenario related to the teacher's role and also in the discussion of the scenario during the teacher preparation lacked sufficient clarity and emphasis. There is a difference between being aware of and warning for a problem and *really* realising its crucial importance. Metaphorically put: Although I thought I knew that a candle can burn one's finger, I still had to burn my finger in order to really appreciate this fact.

The second problem, which is related to the first, was that the design asked for a 'content driven' teaching style whereas the teacher was used to a 'procedure driven' style. With this I mean that students should be led by the train of thought that develops during the course instead of procedural guidance like indicating relevant page numbers, section numbers, which assignments should be finished by when et cetera. The problem was not so much the attention to procedure. There is nothing wrong with procedural guidance as long as it does not eclipse the content. The problem was rather the lack of attention to the line of reasoning.

I will first illustrate the problems with some examples and then present a not fully successful way of remedying them during the first trial. A possibly more successful approach will be discussed later, after which the opinion of the teacher on the preparation will be presented.

Illustration of some problems relating to teacher preparation

Example 1: lacking proper introduction and evaluation and not using student input

A motion on earth is investigated as an additional way to say more about the value of Keplerian and Newtonian models, which in the previous activity were seen to lead to comparable results in the case of motions of heavenly bodies. The teacher introduces this activity without using student input.

1. T: The next step. We have seen that with this whole thing model and observation can be matched very well with ‘p’[10] two, with Newton. With Kepler it succeeded reasonably, so it is still not so clear to say ‘the one law we can adopt immediately and the other law is completely wrong’.
2. T: Therefore we will look at some situations like [how] it is on earth according to Newton and according to Kepler.
3. T: We will continue with the next assignment, the assignment 19, 20 and 21 of section 1.12. We are to work on that ourselves and the part we do not finish [in this lesson], we will finish before the next time. If there are some problems with this, I hope to see more often people in the z-lessons[11] than before, for I noticed from the first part of the lesson that some of you have not yet understood how things work.

In (1) the teacher evaluates the preceding activity by drawing a conclusion. Students were meant to arrive at this conclusion, but it remains unclear if they did, because they were not asked what their conclusion was. Even when they did, the conclusion here can not be recognised as verbalising the students’ conclusion. Building on the teacher’s conclusion it may make sense to further investigate the two types of models in situations on earth. Here the teacher simply states that the students will look into situations on earth (2), without mentioning its relation to the evaluation of types of models. I do not expect students to be able to understand why this new direction is taken, since it is not mentioned and quite hard to think of themselves. They cannot at this time recognise the investigation of models on earth *as* an application of the intuitively clear criterion of broad applicability for valuing these types of models. The next assignment is then introduced in a procedural fashion, without relating its content and goal to the previous one (3).

[10] p indicates the power of the distance between sun and planet r, see section 2.2.1.
[11] Lessons used for self-study in which students can opt to see teachers for clarification.

Let us hypothesise for a moment what might have happened, because this can illustrate what I mean by a transition that uses the previous activity to introduce the next. Even without explicitly using the criterion of broad applicability students might be expected to follow the teacher's train of thought *when they can have some part in it*. When they feel committed to their conclusion (not the teacher's) that the two models are still in the race, they may feel more willing to think about a possible further way of investigation and, given some time for discussion, even come up with a suggestion in a direction that can be massaged by the teacher towards investigating other motions (e.g. motions on earth).

Example 2: Attention to process instead of content

The following example is typical for one of these moments in which the teacher puts students to work. As mentioned in chapter 3 section 4.1 footnote 9 I expect that most people involved in education will recognise the phenomenon. The particular topic (here dimensions of the solar system, which was a side issue in the first design and therefore not mentioned before) is of no concern. The point is the way it is introduced.

> T: We will continue with section 1.7 the dimensions of our solar system. It is good that when we are going to explain something on the solar system later on, that we have some notion of the dimensions. For assignments 5, 6 and 7 we will need Binas[12] and drawing compass and a sheet of paper, which I will distribute shortly.

Although something is said about the reason for these assignments, namely that some notion of dimensions will prove useful for a later explanation, this seems not very convincing. For instance the question what this explanation will be about needs to be answered before this reason can make sense. Furthermore the given reason is completely drowned by procedural details about which assignments (5, 6 and 7) are to be done in what way (by ourselves) and with what tools (Binas, drawing compass and sheet of paper). The fact that in this example both some reason for the content and procedural things are addressed makes the ineffectiveness of the content part even more striking, I think. I do not want to downplay the importance of good procedural instructions (although too much can become somewhat patronising), but this shows how it can overshadow attention for course content and reasons to engage in such content.

An attempt to remedy the problems

The scenario was lacking in sufficient indications for the teacher as to how an introduction that builds on students' input could be given. The importance for such indications became more apparent after experiences such as the one in example 1. An idea used in the first trial to pay more attention to these identified important transitions between activities was expressed as a need for so-called 'moralising talks'. I thought that what was lacking were moments in which the teacher told the 'moral of the story', mainly when going from one activity to the next. At those moments a 'moralising talk' from the teacher should explicate the logic of the course, i.e. indicate why the next activity follows the last one. In the preparation for the remaining lessons of the course I

[12] A standard schoolbook mainly containing tables.

indicated these moments and made suggestions for what these ‘moralising talks’ might entail, which the teacher made notes of.

The next example illustrates one of these moralising talks. Here the teacher starts the third lesson by looking back on the second:

1. T: In the second lesson we encountered a difference of opinion concerning the basketball player[13]. We might remember the question: without influence, how will the ball continue? One said the ball will move straight on, another said the ball remains floating, another said the ball will go down and we also heard the ball has no specific direction.
2. T: There was a similarity in the talk about motion. That we called the explanatory scheme. The explanatory scheme had two aspects: How is the influence free motion, the first aspect and the second aspect: which suitable influence explains the deviation from this influence free motion.
3. T: We probably remember the formula 1 racing car and the little ball moving along the tube. Was it or was it not continuing in a circular trajectory? At home we read the texts on Kepler and Newton. Has anyone got questions about that? ...

The teacher starts this introduction in the way we prepared, making use of student input by referring to some notions that had actually surfaced in lesson two (1). Although he was reading from his notes, at this stage the students actually appeared to follow him and recognise the examples he named. He then explicates the explanatory scheme, but (maybe because he is just reading notes) in such a condensed form, that it can be expected to be only comprehensible for those already very familiar with it (2). Here I observed in the classroom that the students appeared to begin to lose interest. The teacher somehow forgets another point that should have been addressed at this stage concerning the similarities between the way the students explained motion and the way Kepler and Newton did, namely that both students and Kepler and Newton differed in their assumption for an influence free motion and both used the same explanatory scheme. This was intended to provide for a bridge to the next topic of (reading texts about) the notions of Kepler and Newton. Instead he continues with addressing these texts directly, without their relation to the preceding lesson (3).

This example shows that preparing the teacher by identifying those moments for, and suggesting the content of, moralising talks works to some extent, namely that at least some attempt is made to introduce the next activity by using actual student input from the preceding one, but that it also leaves much to be desired: in this case the main element was missing, reading from notes is not the best way to involve students in your train of thoughts (for it tends to be too condensed and unappealing) and referring to student input would be even better when some names can be mentioned (although it appeared that some students recognised their answers in the way the teacher put them). The strict adherence to the notes by the teacher also suggests that he found the moralising talks difficult enough to not trust himself to be more free and spontaneous about them. This difficulty was not unexpected given the experiences by Kortland reported earlier. Making the kind of transitions between episodes the design calls for *is*

[13] One of the video fragments.

difficult. The used approach of indicating moments for and suggesting the contents of moralising talks did not suffice in addressing this difficulty.

The teacher's opinion

In an interview after the introductory course I asked the teacher how he considered the preparation. He said that he found the first phase not useful. The sessions in preparation of each lesson he appreciated the most. The concrete students booklets (which were only ready after phase 2) provided him with the most useful information, he said. His opinion of the unidirectional character of the preparation was that he thought this was quite efficient. An alternative in which he would think of a practical execution would take much more time, was his estimate.

Related to the trial as a whole he had two main concerns. The first was the amount of time the course plus preparation had taken him. In addition to the three phase preparation he had spent about an hour preparing each lesson going over notes of our discussions, scenario and student booklet. The second concern was that the way of working in the course had not been in line with recent educational developments (Dutch: tweede fase) in which more emphasis is put on students working independently. He affirmed that he would prepare in the same way if he could repeat the process.

The teacher preferred not to collaborate in a second trial. His reasons were that he would like to wait to see the effect of the course on the regular course. If he had to speedily work his way through the regular course material, not noticeably benefiting in time from the introductory course, this would be unsatisfactory for him and the students. Since I needed an answer from him straight away, he declined. Further reasons he mentioned were that the financial settlement left room for some irritation and that he would like to wait to see at which time in the day he would have to teach the class in the second trial. The latter argument was triggered by the fact that this teacher taught a different subject to the same class late in the afternoon instead of early morning at which the first trial took place. He noticed a huge difference in the ease at which the class could be 'motivated'[14]. He was therefore reluctant to teach an experimental course late in the afternoon. I also thought it best to stop our collaboration.

3.3. Ideas for second preparation: interaction structures

The problems encountered with the teacher preparation in the first trial indicated four points of attention, to recap: attention to student input, the importance of proper introductions and evaluations and related to that the focus on content instead of procedure, getting the ideas and meanings of the scenario across, and instilling a sense of ownership. An unsatisfactory aspect of the preparation of the first teacher underlying some of these problems was that it was mainly unidirectional. To make the teacher more actively involved in the preparation he could be asked to design the practical implementation of the structure of the introductory course. Its content as was summarised in section 2 had already been developed, but how this can be best implemented still leaves a lot of room. For example, when the design argues for students having to think about some question, this can be done in a number of ways.

[14] The word he used was 'motivated', which here means 'getting the students to work', I think.

Students can read the question, the teacher can pose the question, they can write their personal answer down, they can discuss the question in pairs or small groups, the teacher can give the answer himself, to name but a few possibilities. Designing these details of the practical application in collaboration with the teacher who would execute the design could make the teacher not only familiar with, but also actively involved in the already designed product. This would give the teacher a sense of ownership of the final design and would provide me with (written) concrete material to check in what way the teacher had understood the aims and meanings of the course structure and content. Furthermore, since these practical details concern normal teaching stuff I could draw on the experience of an experienced teacher. Filling in these details are a teacher’s cup of tea.

The teacher should be guided in his designing of the practical implementation in such a way that the indicated problems of proper introductions and evaluations of (sets of) activities and using student input are explicitly addressed. To emphasise the importance of these points and to present the teacher with some designing tools that make them explicit I proposed the idea of using interaction structures. I will first describe in rather general terms what is meant by interaction structures and then indicate how they were used in the preparation of the second teacher.

The general idea of interaction structures

Interaction structure is a term coined by Westbroek that can be roughly translated as teaching method or instructional format, but adds to these meanings an emphasis on the way people (teacher and students) communicate. It is inspired by Lemke (1990). Lemke analysed interactions between teacher and students in science classes and came up with recurrent patterns he called ‘dialogue structures’ such as ‘triadic dialogue’, which Lemke describes as a teacher dominated monologue.

The triadic dialogue according to Lemke follows the following sequence of elements, with the three elements printed in bold being characteristic for this structure and the elements in parentheses being optional:

	(teacher preparation)
Triad of moves: 1.	**Teacher Question**
	(teacher call for bids)
	(student bid to answer)
	(teacher nomination)
2.	**Student Answer**
3.	**Teacher Evaluation**
	(teacher elaboration)

His message was that much of the interactions in science classes do not promote students to ‘talk science’ as much as he would like. Student input does not really matter, but is mainly used to further the teacher dominated monologue or as a tool for class management. The basic feature that can be recognised in all his dialogue structures is the recurrent pattern of an introduction, main question, answer and evaluation. In the presented example of triadic dialogue the introduction consists of a teacher preparation.

The main question consists of the teacher question and call for bids. The answer consists of the student bid to answer, teacher nomination and the actual answer. The evaluation finally consists of the teacher evaluation and elaboration.

Westbroek's idea was to work this recurrent feature in several so-called 'interaction structures' as a tool to specifically address the importance of properly introducing and evaluating one or more related activities. The name interaction structure is used to distinguish it from the dialogue structures of Lemke. Apart from their other purpose (in emphasising introduction and evaluation), the difference lies in that interaction structures describe a longer time span. Whereas dialogue structures typically describe interactions ranging from several seconds up to several minutes, interaction structures range from about 30 - 80 minutes, the size of an episode as described in section 1[15].

In the introduction of an interaction structure the main question is introduced in one or more activities in light of the preceding activity and the final goal to which the various activities, episodes, main themes or course should lead. The main question is then posed and answered in several coherent activities. Their coherence lies in the fact that they all contribute to answering one main point of the course content. This part can of course contain many questions and answers, but they all are meant to contribute in answering one central question that expresses the goal of the episode. The evaluation then looks back to the activities related to the introduction, the main question and its answer, also in one or more activities. Here answers are collected, made explicit, evaluated, refined, elaborated and sometimes added to, resulting in a completion of answering the main question in accordance with how it was introduced.

I will now present a short list of interaction structures that will be seen to occur in my design, which will be presented in the next chapter. The basic form of any interaction structure is depicted in Table 4.

Basic form	
Introduction	The teacher bridges the content related outcomes of the prior learning activity with this successive learning activity.
Main Question	Teacher (or textbook) asks for students' opinions or answers concerning the main topic of this set of activities.
Answer	Students produce (written) answers.
Evaluation	Answers are collected, made more explicit, elaborated and evaluated in light of the introduction. The outcome is then linked to the introduction of the next main question / interaction structure.

Table 4: Basic form of interaction structures

Two interaction structures that recur many times in my design, I call 'taking stock' and 'concluding', see Table 5 and Table 6.

[15] Lemke uses the term 'episode' differently. A more substantial discussion of the relation between interaction structure and 'episode' in the way described in section 1 will follow shortly.

Taking stock	
Introduction	The teacher bridges the content related outcomes of the prior learning activity with this successive learning activity.
Main Question	Teacher (or textbook) asks for students' opinions or answers concerning the main topic of this set of activities.
Answer	Students produce (written) answers.
Evaluation	The purpose of the evaluation is to arrive at a conclusion, which is expected to surface quite easily from students' answers (when this is not expected the I.S. 'concluding' is more appropriate).
Introduction	The teacher (or material) gives some perspective on the goal and meaning of the evaluation.
Inventory of answers	The teacher points out one or more students to give their answer.
Evaluation	The teacher evaluates the answers by comparing them to the intended answer. If the answers don't meet the criteria, he/she can elaborate with follow up questions
Clarification/ Elaboration	If an answer is not clear, the students or teacher can ask a student to further clarify her answer (For example: 'what do you mean by… ?').
Addition	If some minor aspect in the answers is still missing the teacher can add it him/herself.
Summary	The teacher summarises the answer and proceeds by linking these outcomes with some short remarks to the preparation of the context of the next question.

Table 5: Description of the interaction structure 'taking stock'

Concluding	
Introduction	The teacher bridges the content related outcomes of the prior learning activity with this successive learning activity.
Main Question	Teacher (or textbook) asks for students' opinions or answers concerning the main topic of this set of activities.
Answer	Students produce (written) answers.
Evaluation	The purpose of the evaluation is to arrive at some conclusion, which is expected to be difficult to surface without help (when this is not expected the I.S. 'taking stock' is perhaps more appropriate).
Introduction	The teacher (or material) gives some perspective on the goal and meaning of the evaluation.
Inventory of answers	The teacher points out one or more students to give their answer.
Evaluation	The teacher evaluates the answers by comparing them to the intended answer. If the answers don't meet the criteria, he/she can elaborate with follow up questions.
Clarification/ Elaboration	If an answer is not clear, the students or teacher can ask a student to further clarify her answer (For example: 'what do you mean by… ?').
Addition	The teacher him/herself can add some aspects in the answers that are still missing. Or, when such an addition is very substantial, at this point new activities concerning such an addition can be introduced.
Summary	The teacher summarises the answer, including his addition, and proceeds by linking these outcomes with some short remarks to the preparation of the context of the next question.

Table 6: Description of the interaction structure 'concluding'

The difference between 'taking stock' and 'concluding' is the emphasis and implementation of the evaluation phase. In taking stock it is expected that the intended answer to the main question of the set of activities fairly easily surfaces from some student answers. Some of these answers therefore only need to be made explicit, requiring only slight clarification, elaboration or addition. The conclusion or answer simply and understandably, but not automatically, follows from these few examples of student responses. The teacher is needed to ensure that the answer to the main question surfaces with enough clarity and emphasis and in close relation to the student input.

In the case of 'concluding' it is expected that more work needs to be done to arrive at the intended conclusions from the answers of the students. In this case these answers still need to be made explicit and evaluated, but also substantially clarified, elaborated and added to by the teacher. Where the evaluation in 'taking stock' might take a short class discussion of two minutes, the evaluation in 'concluding' may involve a class discussion of up to 15 minutes or so, which can even include group discussions of clarifying questions or other activities leading up to the central conclusion.

The difficulty or 'weight' of the evaluation can be considered to lay on a scale ranging from very easy or 'light' to very difficult or 'weighty'. An example of an evaluation on the light end of the scale would involve merely checking whether students had found the correct answer to a problem. Here merely repeating the answer would suffice (carrying the implicit message that this answer is in fact right, and all students should write it down, e.g.). There is no sharp distinction between taking stock and concluding. Within taking stock the input of the teacher can already range from little to some effort. I drew the line where I expected the evaluation to take more than about 5 minutes. (More than 5 minutes indicating 'concluding', less indicating 'taking stock').

The well known teaching format 'thinking - sharing - exchanging'[16] can also be described as an interaction structure, see Table 7.

Thinking - sharing - exchanging	
Introduction	The teacher bridges the content related outcomes of the prior learning activity with this successive learning activity.
Main Question (Thinking)	Teacher (or textbook) asks for student's opinions or answers, specifically addressing every student. All the students in class need to write down their answer.
Answer	Students produce individual written answers
Evaluation (Sharing)	The students are asked to compare their individual answers in groups and produce one 'group answer' to an assignment, which builds on the first, providing a 'deeper insight'.
Introduction	The teacher gives some perspective of the way in which the individual answers require 'deepening', thereby providing for a reason for 'sharing'.
Question	Groups are asked an additional question, which uses/builds on the individual results, but also calls for deeper insight.
Sharing	Students share their individual answers in groups.

[16] The name may be less well known than what it stands for. I surmise that most people involved in education will recognise this format.

Evaluation	The group members elaborate on each individual answer, thereby addressing differences and similarities. And by doing that, the group tries to identify the key features of the problem.
Clarification/ elaboration	If an answer is not clear, group members can ask for clarification. If an answer is superficial, group members can ask for additional information.
Negotiation	Group members negotiate about what the group answer should be. Every group member must agree.
Conclusion	The group writes down a group answer
Evaluation (Exchanging)	The group answers are compared in class producing one 'class answer', which provides for an even deeper insight.
Introduction	The teacher gives some perspective of the way in which the group answers require 'deepening', thereby providing for a reason for 'exchanging'.
Question	All students are asked an additional question, which uses/builds on the group results, but also calls for deeper insight.
Exchanging	The teacher points out one spokesperson for each group and asks each spokesperson to express the group answer.
Evaluation	The teacher evaluates the group answers by comparing them to the intended answer.
Clarification/ elaboration	If a group answer is not clear, the students or teacher can ask a group to further clarify their answer (For example: 'what do you mean by ...?'). If an answer is not complex enough, the students / teacher can ask for further information.
Negotiation	The teacher formulates or let a student formulate the class answer and asks the class to respond.
Addition	The teacher can add some missing elements to the developing class answer.
Summary	The teacher summarises the content related outcomes embodied in the 'one best class answer' and proceeds by linking these outcomes with some short remarks to the preparation of the context of the next question.

Table 7: Description of the interaction structure 'thinking - sharing - exchanging'

This interaction structure is more complex and carries the implicit message that the main question is a difficult one[17]. Let us look in some detail into the relation of interaction structure and episode. Both episode and interaction structure indicate a coherent part of a course. Dividing a course in coherent parts can be done from the perspective of the content and from the perspective of the form in which the content is shaped, i.e. the way the content is addressed. From the perspective of content a course can be organised in a series of subsequent main topics or questions or points or goals. Each topic can be said to have some main goal, which can be stated as answering some main question. The difference here is merely linguistic. The term episode is used here to indicate a part of a course that concerns one particular main question and its answer (and is therefore related to the content perspective). This already establishes a 'grain

[17] Various interaction structures carry various implicit messages about the difficulty of the topic and the kind of answer (opinion, recalled fact, pondered upon conclusion et cetera) that is expected of students. These messages should be in accordance with the goal and function of the set of activities. See for a discussion of this relation (Westbroek, 2005).

size'. An episode is not longer than what is needed to address some question and not shorter than what stating and answering such a question would entail.

From the perspective of the way topics are addressed a course can be organised in a series of interaction structures. The grain size of episodes fits the grain size of interaction structures or in other words: both perspectives on dividing a course in parts suggest the same size for these parts. In this respect the two fit nicely. There is a more fundamental relation, however. Of course the content implicitly suggests one or more appropriate ways of addressing the content, i.e. the content suggests an interaction structure. This also works the other way around: the interaction structure implicitly suggests the difficulty or importance of the content. A more elaborate interaction structure (like 'thinking-sharing-exchanging') already carries the message to students that the topic will be difficult. In this way episode and interaction structure are two sides of the same coin.

Thinking about a suitable interaction structure for some given episode forces one to answer important questions relating to both content and the way to address it. This thought process is somewhat guided by filling in a scheme for an episode such as depicted in Table 7. It makes one think about all interaction aspects that are needed and can be expected. In this way one is likely to consider didactical questions like: Why choose this interaction structure? What answers do I expect? How am I going to respond to these answers? Why respond in that way? How does this serve the educational goal for this activity? (What is the educational goal for this activity?) How can I wrap up the activity in such a way that does justice to what the students have said? I content that a choice based on such a thought process results in more quality in teaching than a choice that simply seems suitable or is 'based on experience' (that is: habit). One could conclude that some aspects, for instance the elaboration, will not be necessary, but this conclusion is then at least the result of some thought.

This concludes my rather general description of the idea of interaction structures. I will now turn to the topic of how these were used in the preparation of the second teacher.

Using interaction structures in preparing the teacher

From the previous part of this section it may have become clear that asking the teacher to design the practical implementation of the already designed content of the introductory course using a set of interaction structures practically forces him to explicitly address the issues of proper introduction and evaluation and use of student input. I intended to present him with a few interaction structures in the form of tables like Table 7. He could be presented tables of 'thinking-sharing-exchanging', 'taking stock', 'concluding' and one or two variations on these structures. I could then ask the teacher to write down a plan for the practical implementation of the designed content presented to him in a proto-scenario and which could be discussed together. The plan was that these discussions of the content follow a similar phase structure as was used in the preparation of the first teacher, except that a more two-way communication could be attempted in the third phase of the preparation of the second teacher. The goal of this phase was to arrive at a finished design of the practical implementation of the already designed content and therefore a complete scenario.

The teacher would choose and fill in interaction structures for all episodes in the third phase. In that way I could read the resulting practical implementation of the already designed course content and get a good impression of what he had understood of the meaning and intentions of the course content. On the basis of this we could then further discuss possible misunderstandings and the choices for the practical implementation that were made, especially whether the way main questions were introduced and evaluated in accordance with the goals and functions of the various episodes. I expected the teacher to be ready and able to do this, since thinking about interaction structures resembles thinking about teaching methods, which teachers do all the time. The main difference now being the explicitness of the thinking and the stronger emphasis on the introduction and evaluation of each episode.

I did not use other experiences from the preparation of the first teacher in the preparation of the second. One might think that for instance fragments (either video or written out audio) indicating the mentioned problems may make the second teacher more sensitive to these problems. In retrospect I think this might have been a good idea. At the time this was considered unnecessary for three reasons. Firstly, the second design was so different from the first that that it would be difficult to find proper fragments that had sufficiently recognisable bearing on the second design. Secondly, the problems in the first teacher preparation were considered at the time to be quite strongly related to his particular teaching style. The second teacher was selected (among other things) for his teaching style that was considered to be more in accordance with the design. It was therefore expected that the problems from the first preparation would not surface to the same extent and would therefore be less urgent. Thirdly, the practical restrictions in time and the choice for prioritising the design for an introductory student course, instead of a teacher course (for his preparation) left too little time for thoroughly using the experiences from the first preparation.

4. Concluding remarks

In this chapter the development from the first design to the second design has been described. It was seen that although the first design seemed quite doable in the sense that a rather convincing justification could be given for it, it still showed several shortcomings when put to the test. Many of these shortcomings were discussed and could be understood in retrospect. This does not mean that the first scenario was prematurely tested, although it might have benefited from more thought. Instead it shows that testing a scenario is the way par excellence to find out in which manner the design can be improved. Both elements, testing and a scenario, are needed in order to learn in what way the design needs revision. This chapter can be seen as an illustration of the method of design experiments at work.

The second main topic of this chapter was the preparation of the teacher. Here a picture was presented of the difficulties involved in such a task, for which a fitting solution has yet to be found (if there is any). A possibly fruitful step in the right direction seems to be the idea of using interaction structures, which has been presented in some detail.

The description of the design as given in this chapter is quite broad, although sometimes some details have been presented for the sake of clarifying the broad description. In the next chapter I will zoom in upon this broad description and will present the scenario on the intermediate level of episodes and the detailed level of activities.

Chapter 5

Scenario

1. Introduction

In this chapter the second design is described on two different levels of detail. In chapter four the second design was described on a quite general level, organised around the four main themes that were identified in chapter 3. In this chapter I will start zooming in on this general description by describing the design on the (intermediate) level of episodes in section 2. In the sections after that I will zoom in even further and give a detailed description of the design on the level of activities within each episode. In section 3 the activities of the episodes within the first main theme are presented, in section 4 the second main theme, and in section 5 the third main theme. As was said in chapter 4, the fourth theme merits a more detailed investigation than was executed in this research project. I will therefore not further discuss it in this chapter.

Why this description on different levels? Answering my research question involves different levels. An answer to the question how the explanatory scheme can become productive in teaching/learning mechanics would have the form ‘by using such and such a design’ in which the more general features of the design (sequence of main themes or episodes) are probably of more interest than the detailed features (episodes or activities). However the process of testing starts on the detailed level where the actual teaching/learning process is followed and compared with the intended teaching/learning process. From this is subsequently gathered to what extent the various activities perform their function. This provides the basis to draw conclusions on the level of episodes and so on, leading to finally answering the research question. This process of ‘adding up’ lower level (that is detailed) findings to result in higher level (broader) findings can only be followed and understood when the different levels of description of the design (and their relation) are clear.

In relation to each episode several analysis questions are formulated on the intermediate level, which require use of more detailed indications to answer. These answers in turn form the basis for broader conclusions on the level of main themes and even introductory course itself. The analysis questions will be presented in section 2 of this chapter and will be answered in chapter 6.

2. Episodes in the second design

In chapter 4 each main theme was depicted in didactical structures, which are pasted together in Figure 1, resulting in a complete didactical structure of the introductory course. The numbers on the left of this figure indicate the four main themes. The functionality of each main theme is performed in several episodes, each with its own function. I will for the first three main themes describe how its main function is expected to be performed by several episodes and then present an overview of these episodes in a table.

	Mechanics	**Motive**	**Explanation**
1	Broad orientation on motions		that are worth predicting / explaining
		Should result in the notion that this is an important and interesting theme worth knowing more about	
			Starting with explanation in general and explanation of motions in particular in which by reflection an underlying scheme is found and made explicit
		which should lead to the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of this underlying scheme (theoretical orientation)	
2	Specification of the underlying scheme into two specific schemes (Keplerian and Newtonian) in the context of developing and testing models of the motion of heavenly bodies.		
		resulting in a question concerning the fruitfulness of the specific schemes and models	
			Reflection on criteria to determine which schemes and models explain best
		resulting in a plan for further validation of the specified schemes	
3	Applying the specific Keplerian and Newtonian scheme to other motions		
		leading to a point of closure at which we may ask "which schemes and models explain best?"	
			Evaluation of which schemes and models explain best and which elements of this scheme are still unknown
		resulting in an appreciation of the Newtonian scheme and an outlook on the regular course	
4	Regular mechanics course		

Figure 1: Didactical structure of the second design of the introductory course

2.1. First main theme

The function of the first main theme is to address the questions '*why* study the topic of explaining motions' and '*how* are motions explained'. This should result firstly in the notion that this is an important and interesting theme worth knowing more about, related to the why-question. Secondly this should result in the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of a causal explanatory scheme, related to the how-question. Both for the notion that this topic is important and interesting and for the notion that it is challenging a theoretical orientation is required.

The first main theme consists of 5 episodes, see Table 1. The first episode is related to the why-question and has the function of introducing situations in which it is clear that explaining or predicting motions can be desirable and is not easy. The first point appeals to a certain importance, the second point to an intellectual challenge. For this the example of an asteroid moving towards earth is used. The subsequent four episodes maintain the theoretical orientation and are related to the how-question, which is answered in terms of the explanatory scheme. As was mentioned before (see chapter 4, section 2.1.3) the explanatory scheme for motion is introduced by using the general explanatory scheme as stepping-stone. The general explanatory scheme is to be triggered, explicated and made use of before the explanatory scheme for motion can be triggered, explicated and made use of. In episode 1.2 the general explanatory scheme is introduced as a way of looking at explanations that is on the one hand familiar, but on the other hand difficult to express. Students should recognise the scheme as underlying their (and others) explanations, but also notice that this structure adds something to these explanations, namely its theoretical use in making clearer *all* explanations. For this they will have to make some active use of the general explanatory scheme. After triggering the scheme with some appropriate example(s), it can be further explicated by involving students actively in some other examples, which is the function of episode 1.3. Episode 1.4 should trigger and explicate the explanatory scheme for motion as a special case of the general explanatory scheme. Episode 1.5 finally should lead to the realisation that the explanatory scheme for motion does indicate what is needed for a concrete explanation, for example the motion of the asteroid, but does not give an explanation itself. It needs to be further specified (e.g. what is assumed for influence free motion) for this purpose. This will provide the direction for the bulk of the course in main theme 2.

In Table 1 for each episode also one or more analysis questions related to the function of the various episodes are shown. Analysis questions are questions that testing the design should provide answers for. These questions are more or less straightforward translations of the episode's functionality in question format. Some relate specifically to the students, some to the teacher and some to both, depending on where the main indications can be expected to be found as to whether the episode's function is fulfilled or not. In episode 1.4, for example, the function of which is that students come to recognise the explanatory scheme for motion (as a special case of the general explanatory scheme), I do not expect students to be able to make this scheme explicit. I do, however, expect them to be able to recognise the scheme's various elements (as special cases of the corresponding elements of the general explanatory case), on the basis of which the teacher should be able to trigger the scheme quite naturally. In chapter 6 attempts are made to answer the analysis questions related to each episode and thereby to answer whether these episodes perform their intended function.

Main theme 1: The why and how of explaining motions.		
Function of main theme: It addresses the questions of *why* the topic of explaining motions is studied and *how* motions are explained. This should result in the notion that this is an important and interesting theme worth knowing more about and the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of a causal explanatory scheme (theoretical orientation).		
Episode	Function	Analysis Questions
1.1 Introductio n to the topic of mechanics	Generally orienting on 'explaining motions'. Introducing situations in which it is clear that - explaining or predicting motions can be desirable - explaining is not an easy job. The first point appeals to a certain importance, the second point to an intellectual challenge and they thereby answer the *why*-question.	1. What indications can be found that explaining or predicting motions can be desirable? 2. What indications can be found that students consider explaining not as a simple matter?
1.2 Triggering the general explanatory scheme	Orienting in an intellectually stimulating way on the *how* of explaining. The general explanatory scheme is introduced as a way of looking at explanations that is on the one hand familiar, but on the other hand difficult to express.	3. Are students intellectually challenged by how explanations work? 4. Can the general explanatory scheme be triggered quite naturally?
1.3 Making use of the general explanatory scheme	Explicating the general explanatory scheme. (At first mainly the elements and to a minor extent their interrelation.)	5. Do the students understand the meaning of the elements of the general explanatory scheme? 6. Is the scheme helpful in clarifying explanations to students?
1.4 Triggering the explanatory scheme for motion	Realising that the explanatory scheme for motion (as a special case of the general explanatory scheme) can be recognised in explanations of motion.	7. Are students able to point out the elements of the explanatory scheme? 8. Can the explanatory scheme for motion be evoked naturally?
1.5 Making use of the explanatory scheme for motion	Realising that for a complete explanation (and therefore prediction) of motion further specification of the elements of the explanatory scheme is necessary.	9. Do students understand that in order to explain the motion of some object, they have to know how it would move without any influences, which influences are operating (and where they come from), and how these influences cause deviations from the influence free motion?

Tabel 1: Episodes in main theme 1 together with their function and analysis questions

2.2. Second main theme

In the second main theme students' knowledge is extended by detailing the explanatory scheme to arrive at empirically adequate models for explaining motion and the question about the fruitfulness of these (types of) models is raised. How these three elements of detailing the scheme, extending knowledge and raising the fruitfulness question are addressed in episodes is presented below and then summarised in Table 2.

Detailing the scheme

The result of the first main theme (if it works) is that students have developed a theoretical orientation towards the topic of explaining motion and know the basic structure of such explanations in terms of the explanatory scheme for motions. Now the still rather unfocused direction the scheme gives is first sharpened to guide the process of knowledge extension, which is the bulk of this main theme (and also the bulk of the introductory course for that matter). For this it should become clearer to students *what* specifications of the explanatory scheme might be and *how* these may lead to predictions of motions, like the one of an asteroid. To address *what* specifications of the explanatory scheme might be two examples are introduced in episode 2.1. Here students come to recognise two qualitative specifications of the explanatory scheme for motion, namely the explanations of Kepler and Newton of the motion of heavenly bodies. The choice for Kepler and Newton was based on that both are clear examples of the explanatory scheme and both had similar theoretical aims and interests. The choice for celestial mechanics was based on that this can illustrate the power and range of mechanics, is relatively simple and avoids practical considerations that might distract from the intended theoretical orientation. See section 2.2 of chapter 3.

How specifications of the explanatory scheme may lead to predictions or explanations of motion can be shown using a computer model. Students can meaningfully use a computer model without knowing all its ins and outs, as was argued in chapter 4 section 2.2.3 in the discussion of the so-called matching problem. This matching problem is introduced to students in episode 2.2. With the matching problem students realise that finding an explanation for the motion of heavenly bodies boils down to matching the modelled motion to the observed motion and that for this first, among other things, a quantitative influence law is needed. Finding a concrete influence law is part of specifying the explanatory scheme, for it concerns the regularity relating the influence to attributes of the configuration. The way to find such a law by means of finding a match seems quite doable for students, I expect, see also my discussion of results from the first trial concerning influence laws in chapter 4 section 2.2.2.

So both episode 2.1 and 2.2 set the stage for the following extension of knowledge. Students realise that they are going to find a complete explanation of the motion of an asteroid (as an example for perhaps all motions) by detailing the explanatory scheme for motion by investigating Keplerian and Newtonian models for the motion of heavenly bodies. Starting with finding proper influence laws.

Knowledge extension

Now basic mechanics concepts like force, mass, first law, second law and a force law (gravitation) and their relations are prepared, all from the perspective of detailing the explanatory scheme. The first topic is finding a proper influence law, which is addressed in episode 2.3. Students are to realise that an influence law describes the influence as a function of attributes of the configuration, that alternative laws are possible, what the role of parameters in these laws is and that the appropriateness of a law can be tested by trying to solve the matching problem. Here the insight in the *what* and *how* of specifying the explanatory scheme for motion is deepened by having students vary some relevant parameters in influence laws in order to solve this matching problem. Furthermore the differences between Keplerian and Newtonian models are to become clearer.

In episode 2.4 the concept of laziness or inertia is addressed as a further element of what specifying the explanatory scheme for motion amounts to. Students should learn that laziness is necessary for specifying the relation between influence and motion, know what it is and does, use it to deepen their insight in the models of Kepler and Newton, and know the rule 'deviation = influence / laziness' as a formula for the relation between influence and motion.

In the optional episode 2.5 the precise relation between influence and motion is further investigated by means of graphical constructions. Here an addition is made to *how* a specification of the explanatory scheme for motion leads to predictions or explanations of motion. Students can find some confidence that the motion of an object can be determined from given influences and type of model (Keplerian or Newtonian), because they can see how this can be done (and is done in the computer model) in minute detail. The quickest and brightest students can even opt for an investigation of the influence of the time step size in computing the resulting motion from the influence.

Raising the question concerning the fruitfulness of the types of model

There is not one specific episode related to the function of raising the question how fruitful these types of model are. This question is expected to pop up occasionally in the process of investigating Keplerian and Newtonian models throughout this second main theme, and to become stronger and stronger along the way. This seems a natural response to continuously investigating alternatives, especially when both alternatives seem feasible. Since within both types of model more or less empirically adequate solutions of the matching problem can be found, the question which type of model is better remains unanswered and is unanswerable solely on the basis of this one criterion. The criterion of empirical adequacy is effective to rule out specific models, but not a *type* of model. Answering this question, for which the additional criterion of broad applicability will be introduced, will take place in the next main theme.

Main theme 2: Extending students' knowledge.		
Function of main theme: Extending students' knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining the motion of heavenly bodies, resulting in a question concerning the fruitfulness of the specific schemes and models.		
Episode	Function	Analysis Questions
2.1 Transition to Kepler and Newton	Making clear to students *what* examples, namely those of Kepler and Newton, of a detailed explanatory scheme might be.	10. Are the given examples (of Kepler and Newton) recognised as specifications of the explanatory scheme?
2.2 Introduction to the matching problem	Giving an idea to students *how* such a detailed explanatory scheme may lead to explanations of motions like the one of an asteroid: an influence law leads to a modelled motion, which needs to match the observed motion.	11. Is it clear for students how a detailed explanatory scheme may lead to predictions of motions? • Did the matching problem come across? • Is the role of an influence law clear?
2.3 Influence laws	Deepening the insight in the *what* and *how* of specifications of the explanatory scheme for motion by having students vary some relevant parameters in the influence laws in order to solve the matching problem. Furthermore slowly starting to raise the question which type of model (Keplerian or Newtonian) is more fruitful.	12. Has students' insight in the *what* and *how* of specifications of the explanatory scheme for motion deepened, or more concretely: • Can students translate assumptions of K and N concerning influences into an influence law? • Do they understand the function of an influence law? • Do they see that alternative laws are possible? • Do they understand the role of parameters in the models? • Do they understand what testing a model entails? • Do they get more feeling for the difference between K and N? 13. Does the question which type of model is fruitful slowly start to pop-up?
2.4 Laziness	Adding the concept 'laziness' as well as the rule 'deviation = influence / laziness' as a further element of what specifying the explanatory scheme for motion amounts to. Furthermore continuing to let the question about the fruitfulness pop-up occasionally.	14. Do students know what laziness is and does? 15. Do they know the rule deviation = influence / laziness? 16. Does the question which type of model is fruitful slowly start to pop-up?
2.5 The precise relation between influence and motion	Adding to *how* a specification of the explanatory scheme for motion may lead to explanations of motion by investigating the precise relation between influence and motions with the help of the method of graphically constructing motions from given influences. Furthermore continuing to let the question about the fruitfulness pop-up occasionally.	17. To what extent do students understand the method of graphically constructing motions from given influences? 18. Does the question which type of model is fruitful come up?

Tabel 2: Episodes in main theme 2 together with their function and analysis questions

2.3. Third main theme

The function of the third main theme is to reflect on criteria to determine which type of model explains best. Subsequent application of these criteria should result in an appreciation of Newtonian models and an outlook on the regular course. See Table 3 for an overview.

Reflection on criteria

The previous main theme resulted in a (slowly growing) question about the fruitfulness of the two types of model. Reflecting on the accomplishments of the first main themes in episode 3.1 leads, apart from summarising the main points concerning mechanics itself, to the conclusion that this question cannot be answered on the basis of the used criteria of empirical adequacy and plausibility. Some students may by now come up with the additional criterion of broad applicability, or otherwise the teacher can introduce it, as part of a possible and intuitively clear way of shedding further light on this question. This additional criterion can guide a strategy for further investigation of the value of the two types of model.

Application

With the new criterion of broad applicability students should see the application of Keplerian and Newtonian models to a situation on earth as an additional way to estimate the value of these types of model and can give a reason to value Newton above Kepler, namely that Newton seems to be wider applicable than Kepler. This application is tried in episode 3.2. The success of Newton is one reason for appreciation of the Newtonian specification of the explanatory scheme, i.e. Newtonian mechanics. This appreciation can be further strengthened by solving the initial asteroid problem with a (Newtonian) model and by yet another argument for the value of mechanics, namely its possible use in understanding all change.

(Further) appreciation

The possibility to explain all kinds of motions with the Newtonian specification of the explanatory scheme is an important element in understanding all change in a mechanicistic sense. (Another element is some knowledge about particle models.) Here, in episode 3.3, a similar account as in the start of the first design is given to provide further appreciation for the power and range of mechanics. With this appreciation the regular course can start in which the Newtonian specification of the explanatory scheme is further applied using new influences and influence laws. A preview of the regular course is given at the end of the introductory course.

Main theme 3: Evaluation of models and *types of model* in the light of achieving broader applicability.		
Function of main theme: Both a reflection on criteria to determine which type of model explains best and subsequent application of these criteria should result in an appreciation of Newtonian models and an outlook on the regular course.		
Episode	Function	Analysis Questions
3.1 Reflection on types of model	Making explicit criteria for valuing models and types of model by a reflection on the first two main themes, resulting in a strategy for further investigation.	19. Do the criteria for valuing models and types of model surface clearly? 20. Does a strategy for further investigation surface naturally?
3.2 Introduction to a choice between types of model for a situation on earth	Valuing types of model (Newtonian and Keplerian) by applying the criteria to a situation on earth.	21. Can students give reasons to value N above K? 22. Do students see the reason for applying K and N to a situation on earth? 23. Does the application of K recognisably (for the students) lead to problems?
3.3 Asteroid problem, mechanicism and transition to the regular course	Further illustrating the power and range of Newtonian motion models, as well as finding a concrete answer to the initial asteroid problem (or similar problem).	24. Do they have some impression of the power and range of Newtonian models? 25. Do they consider the asteroid problem solved?

Tabel 3: Episodes in main theme 3 together with their function and analysis questions

This concludes the description of the design on the intermediate level of episodes. In the following sections a more detailed description will be given.

3. The how and why of explaining motions.

In this section I will further describe the episodes that are part of the first main theme, the how and why of explaining motions, in more detail, i.e. on the level of activities. An episode usually consists of first an introduction, last an evaluation and in between one or more activities like reading text, answering questions, listening to an explanation, working on a computer model et cetera, all in service of the main question or topic of the episode. This part in between introduction and evaluation I call the 'main question and answer phase'. The choice for a specific interaction structure already tells in procedural terms which activities will be part of it. It does not tell the content of these activities, obviously. See also chapter 4, section 3.3.

3.1. Episode 1.1: Introduction to the topic of mechanics

Function of the episode

The function of the first episode is to give a general orientation on 'explaining motion' and to present situations (1) in which it is clear that explaining or predicting motion can be desirable and (2) in which it is clear that explaining is not an easy job. The first point appeals to a certain importance, the second point to an intellectual challenge. These two combined set the agenda for what is coming.

Justification of content and interaction structure (in the light of the function)

A suitable example of a motion should show that predicting the motion can be desirable or important, that it can be done and that it is not straightaway clear how it can be done. It should address the right mindset: a challenging theoretical intellectual puzzle with some suspicion of how it might be solved. A useful situation can be an asteroid moving towards earth. This example is quite recognisable, for it was recently in the news. It might also be known from movies like ‘Armageddon’ or ‘Deep impact’. It is clear that students do not (yet) know the solution, but they do know that there *is* a solution and soon in the course directions will be taken that recognisably might lead to a solution: The introduction to the explanatory scheme in episodes 1.2 - 1.5 ends with the same asteroid problem. By that time it will be clearer what kind of things would be necessary for solving this problem. The attention to the mechanics of heavenly bodies in the section on Kepler and Newton in episode 2.1 is also recognisably relevant for solving this problem.

The main activity for students is to think about motions that demand an explanation and about what is involved in such explanations. Since the precise content of the answers students come up with is irrelevant, a loose inventory of answers will suffice, in which all student input is encouraged, acknowledged, valued and used to make the main point explicit. The teacher probably has to add to this inventory the notion that prediction involves more than merely extending some trend, namely some kind of calculation (suggesting that these things can be predicted with some precision). Accordingly, a suitable interaction structure would be ‘taking stock’, see chapter 4, section 3.3, table 5.

Expected unfolding of the episode

Introduction

The episode (and course) is introduced by an enthusiastic teacher talk in which two things take place. Firstly an introduction to the topic of mechanics as ‘explanation of motion’, without addressing the content of explaining, but emphasising its theoretical importance. Secondly an introduction to the example of an asteroid moving towards earth, as an illustration of both the importance of being able to explain and therefore to predict motion and that explaining motions entails quite a lot.

Main question and answer phase

Students read a number of newspaper headlines and short articles concerning an asteroid possibly colliding with the earth in the year 2019 and answer questions about if they can think of other examples of motions for which it is important to be able to precisely explain or predict them (question 1), what would be needed for such prediction or explanation and what could be meant by (and needed for) ‘calculating’ motion (question 2).

I expect students to be able to come up with some answers to these questions, which will indicate that they know what the topic is about (explaining/predicting motions), that this has some importance and that a lot is needed for this. Possible answers may include bringing a satellite in space, a man on the moon, preventing airplane collisions and estimating where fired projectiles will land, in response to question 1. And vague notions and perhaps mentioning of the use of computers in response to the second question.

Evaluation

The teacher makes a loose inventory of answers to the two questions. In this way the teacher can hear the answers of the students and make sure the intended conclusions surface by highlighting such answers that already contain them or adding to answers that do not. Hopefully in connection to the responses of some students the teacher then addresses the issue that explaining a motion is more than predicting by extending some trend. A trajectory can actually be *calculated*. At this point a discussion can start about what might be needed for such calculation-based explanations or predictions.

I expect that students as a group come up with sufficient elements for a useful discussion, but that the teacher will have to emphasise the main points and has to add the notion of calculating.

When it is not too much forced it can be remarked that what was seen in this episode was that there are quite a number of situations in which it is important to be able to predict motion. In order to be able to do that more knowledge will be needed as to how such predictions or explanations work. We therefore first continue with how explanation in general works and secondly will look into how calculations are used in that.

3.2. Episode 1.2: Triggering the general explanatory scheme

Function of the episode

The function of this episode is to give a general intellectually stimulating orientation on the *how* of explaining. The general explanatory scheme is introduced as a way of looking at explanations that is on the one hand familiar, but on the other hand difficult to express.

Justification of content and interaction structure (in the light of the function)

In order to orient students to the how of explaining by means of the general explanatory scheme they should focus on explanations themselves instead of explained phenomena, which is a first step towards a more theoretical perspective. Appropriate examples of explanations can illustrate all features of the general explanatory scheme: an implicit comparison of situations differing in a relevant factor, yet with the same background, and use of a more or less strict ceteris paribus regularity (cf. chapter 4, section 2.1.3). The examples should be easy so as not to distract from the main point, which is the theoretical goal of finding their structure (illustrating the structure in all causal explanations). That this theoretical goal is the main point should also be expressed clearly. Furthermore, as a bonus the examples should be puzzling in such a way that the explanatory scheme can clarify the puzzle, thereby showing an immediate use of the scheme apart from its theoretical use. The examples that were used are described and justified in the section on the expected unfolding of the episode.

The main activity for students is to try to find out 'what is explained in these examples' and 'how that is explained' In the evaluation their answers to these questions can serve as a basis for the teacher to explicate the general explanatory scheme. The teacher is necessary to point out (elements of) the scheme in the answers of students. They can not be expected to be able to do this by themselves (guided by questions or otherwise). Since the main thing here is to draw a difficult conclusion from the students' input that requires a lot of teacher input an appropriate interaction structure would be 'concluding', see chapter 4, section 3.3, table 6.

Expected unfolding of the episode

Introduction

The teacher tells the students that this episode is about *how* explaining works in general, which is a quite theoretical goal, by looking into some easy examples of explanations.

Main question and answer phase

The general explanatory scheme is gradually triggered as a useful way of looking at some given examples of explanations. For this students are presented with the following questions.

> Question 3.
>
> Kees, Els and Jostein are looking at a cup of tea which contains a lump of sugar. They were asked to write down what happens and how they explain what happens. This is what they wrote down.
>
> Kees: Simply, sugar is soluble. So when you put the lump in the tea it slowly falls apart until it is completely dissolved.
>
> Jostein: The sugar lump dissolves quite fast. The tea is very hot apparently.
>
> Els: The sugar lump dissolves not very fast. You should have stirred.
>
> Kees, Els and Jostein are looking at the same situation and still they come up with different explanations. Does this mean they disagree?
>
> Yes, they disagree on …
>
> No, not necessarily, because …
>
> Question 4. Compare your answers and try to reach agreement on:
>
> - What do Kees, Els and Jostein explain?
> - How do they do that?

These examples of explanations clearly illustrate the general explanatory scheme. The explanation of Kees may seem empty or circular, but in fact he points out a regularity: each time one puts sugar in tea it falls apart and dissolves. We expect sugar to behave in this manner when we want to sweeten our tea. Two more regularities can be found in the explanations of Jostein and Els. Jostein implicitly uses the regularity that the hotter the tea is, the faster sugar dissolves. Els is also saying something about the speed at which sugar dissolves, but implicitly uses the regularity 'when one stirs (faster), sugar dissolves faster'. If we understand their explanations as implicitly containing a comparison, we can understand the difference between Jostein and Els as a difference in the object of comparison. In Jostein's explanation it is a situation in which the tea is colder and the sugar dissolves more slowly. In Els' explanation it is a situation in which someone stirs the tea and the sugar dissolves faster. I expect students to have some sense that Kees, Els and Jostein not necessarily disagree, but that they cannot express this clearly. This is the intended puzzling aspect of thinking about these explanations. The general explanatory scheme can clarify this puzzle by expressing the lack of disagreement as stemming from their different objects of comparison.

The point of question 4 and the subsequent two questions, asking students to mention other things that need to be the same in both situations (question 5) and why these have to be the same (question 6), is to begin to make these ideas explicit to students, by letting them think about how explaining works.

Evaluation

The teacher and question 5 and 6 guide the students in the direction of the explanatory scheme as an answer to the theoretical goal of finding a structure in explanations and an aid to make the (puzzling) distinction and similarity between the explanations of Els, Kees and Jostein clearer. A way to facilitate talking about the general explanatory scheme is by using the following drawing, see Figure 2, which is filled in together.

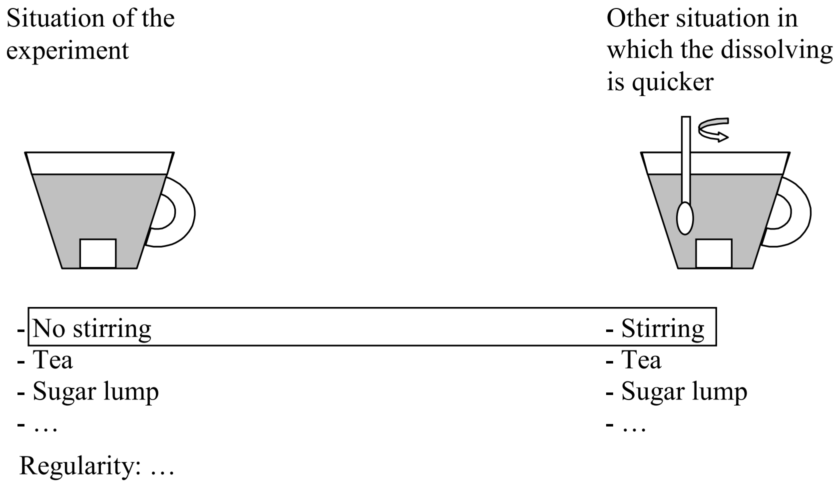


Figure 2: Explanation of Els

Both a remark of the teacher (in connection to what the students have said before) that it seems that Els compares the situation of the experiment mentally to another situation in which the tea is stirred, but is otherwise the same, and questions 5 and 6 make explicit what is involved in an explanation.

I expect that their answers contain sufficient elements that resemble elements of the explanatory scheme, so as to explicate the scheme in a 'natural' way, meaning in a way that recognisably and correctly uses students' input. Some students are able to mention several ceteris paribus conditions like same cup, same amount of tea, same temperature, I think. In their answers some regularity may already be recognised. Wrapping-up, the teacher emphasises that what students have learned seems quite familiar, yet is difficult to put in words. That is why they will first practice a little with it before later applying it to the explanatory scheme for motion.

3.3. Episode 1.3: Making use of the general explanatory scheme

Function

The function of this episode is a further explication of the general explanatory scheme.

Justification of content and interaction structure (in the light of the function)

The previously introduced general explanatory scheme with the related way of depicting it in a figure will require some getting used to before it can serve as a stepping-stone to the explanatory scheme for motion. Students will therefore apply it to other explanations, namely the two that are already available: those of Jostein and Kees. Simply asking to apply the explanatory scheme would be too difficult at this stage. Similar figures as Figure 2 of the other explanations can be used to provide students with some support for applying the explanatory scheme. Especially with the explanation of Kees the structure can appear somewhat farfetched or awkward. Agreed, but it is a way of looking to what he does. This way of looking is in general useful to describe explanations systematically, which was the thing we were looking for. This use and purpose of the scheme should be clearly stated. An additional and immediate use related to these examples is that the difference between the explanation of Jostein and Els, which is expected to be difficult to formulate, can be clearly put in terms of the explanatory scheme as a difference in the object of comparison.

In the evaluation of students' work the teacher can check if they have correctly identified elements of the scheme and can conclude by explicating once more the scheme (again in close relation to the student input), adding the relation between the elements. To make the students actively involved in formulating what the explanatory scheme is, they can then summarise it themselves. This also allows the teacher (and the researcher) to check what has been understood of the explication. These summarisations can be elaborated, corrected or sharpened thereby repeating the scheme once more. Since it is important that all students arrive at a similar notion of the explanatory scheme the function of the evaluation is not merely taking stock of answers, but moulding them towards the desired answer. A suitable interaction structure is therefore 'concluding'.

Expected unfolding of the episode

Introduction

The introduction consists of explicating that the same idea (the general explanatory scheme) will be applied to other explanations[1]. This message is incorporated in the introduction to the first question of this episode (question 7, see below).

[1] The notion that questions concern the application of ideas introduced directly before these questions is considered in many textbooks to be so obvious, that it need not be mentioned. It is certainly obvious for teachers and others who already know the subject, but for many students

Main question and answer phase

Students apply the scheme by filling in similar (but almost blank) figures as Figure 2 but now for the explanation of Jostein (question 7) and Kees (question 8). The students are meant and expected to be able to add something to the drawings, point out the relevant difference between the cases, mention a few factors which have to be the same in both cases and finally formulate a regularity. The students then answer the question why Els and Jostein not necessarily have to disagree even if one says ‘not very fast’ and the other ‘very fast’ (question 9), which is a repetition of question 3. I expect the answers to be sharper by now in the sense that the difference can be explained as a difference in object of comparison, the ‘puzzle’ should have been solved. This question was included to see if students recognised the additional use of the scheme in clarifying the difficult to express notion that Jostein and Els not necessarily disagree. So in answering these questions students show what they can do with the general explanatory scheme. This will give information concerning the extent to which they can make use of the general explanatory scheme.

Evaluation

The teacher takes stock of the answers and points out the structure in them. Incomplete answers he tries to complete by further questioning. In question 10 they themselves try to summarise the general explanatory scheme in a couple of sentences or a story, or by using a picture.

From the summaries of the scheme students made the teacher tries to elicit the main themes of the general explanatory scheme, in which Figure 3, which is an abstraction from the previously used figures, can be used as visual aid for the discussion of the summaries.

Situation without K (with little K)	Situation with K (with a lot K)
1	2
- A	- A
- no B (little B)	- B (a lot B)
- C	- C
- …	- …

Regularity: When there is B, K occurs (the more B, the more K)

Figure 3: Explaining in general

explicating such relations (of application, illustration, contrasting, extending et cetera) can be useful.

The teacher ends this episode by stating that we can now try to use this knowledge of how explanations in general work (as is expressed in the general explanatory scheme) to explanations of motion.

3.4. Episode 1.4: Triggering the explanatory scheme for motion

Function

The function of this episode is that students come to realise that the explanatory scheme for motion (as a special case of the general explanatory scheme) can be recognised in explanations of motion.

Justification of content and interaction structure (in the light of the function)

In order to find how the explanation of motion works use can be made of how explanation in general works. This after all was the reason for studying explanation in general in episode 1.2. To make clear how all explanation of motion can be seen as similarly structured, some easy examples can be used. This purpose of the examples should be clearly stated.

In order to explain a motion two things are necessary: some notion about an influence free motion and some interaction theory, see also chapter 3, section 2. Students can be expected to come up with these two elements for those motions that involve mainly personal influences like pedalling and braking, because such influences are easily identifiable for students, they know from experience their effect (i.e. have a rough interaction theory) and they tend to agree on what would happen without them (i.e. what the related influence free motion would be). Motions that involve only personal influences are therefore easier to recognise the explanatory scheme for motion in than motions involving also non-personal influences like gravity or friction (see chapter 4, section 2.1.3). The explanatory scheme for motion is therefore triggered with examples of motion that involve mainly personal influences.

As was the case with the general explanatory scheme, students are guided in identifying elements of the explanatory scheme (here for motion) by questions and figures like Figure 4, that are quite similar to the earlier used figures depicting examples of general explanations. By talking to each other in group work students are expected to be able to solve each other's difficulties and insecurities with identifying elements of the general explanatory scheme in explanations of motions involving well known influences.

In the evaluation the teacher takes stock of the outcome of the group work, which provides the basis to explicate the explanatory scheme for motion when only personal influences are concerned. When students realise that there are also non-personal influences, the scheme is extended to include all influences. This extended scheme is then called the explanatory scheme for motion and it can be announced that some of its uses will be investigated in the next episode. Although the conclusion of the evaluation is further extended, which might suggest a weighty interaction structure, this extension is expected to be fairly straightforward, so that this does not merit a heavier interaction structure than 'concluding'.

Expected unfolding of the episode

Introduction

The teacher and text make the transition to the explanation of motions by pointing out that since explaining motions is a particular case of explaining in general the general explanatory scheme may give ideas of how to look for the structure in explaining motions. This is tried out on an example of a bicycle rider riding with constant speed.

Main question and answer phase

A number of questions guide students in filling in elements of an explanation of easy examples of motion. Questions 11, 12 and 13 concern an example in which two different motions are compared: a bicycle rider keeping its speed (or even increasing its speed) and one gradually moving slower (see Figure 4). Question 14 and 15 concern a similar example using a similar figure in which a braking bicycle rider is compared to one gradually decelerating.

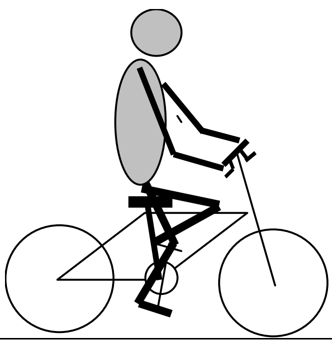
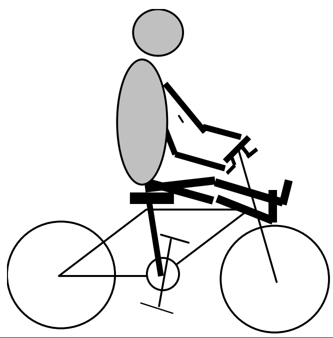
Keeping speed or increasing speed	Gradually moving slower
	
- … - … - …	- … - … - …
Regularity: …	

Figure 4: Comparison bicycle riders

Students should be able to fill in the elements of the explanatory scheme correctly. The explanatory scheme including all kinds of influences will be addressed after question 15. The questions on the two examples are expected to guide students quite easily in pointing out the elements of the scheme. This expectation is backed by earlier experiences in the second pilot study (cf. chapter 4, section 2.1.3).

Evaluation

The teacher takes stock of the answers and points out that each time the same structure can be seen: A comparison of two different situations, the identification of a relevant factor related to this difference and in what way (magnitude and direction) this factor contributes to the difference, which can be expressed in a regularity. This regularity only holds all other things being equal. It may be useful to use Figure 3 in this and the following explication.

The conclusion from these examples is that in both comparisons explaining the motion consisted of:

1. determining the motion in a situation in which there is no personal influence
2. determining the operating personal influences (and how they depend regularly on other factors)
3. determining in which direction and to what extent these influences cause deviations from 1.

This formulation of the explanatory scheme for motion is then extended to include all influences by first asking, in question 16, whether there exist, apart from personal influences, other factors which may influence a motion.

Students might come up with viable intuitions for influences, but they might be unsure. If no answers are given the teacher can show some motions like a falling object, a rivet gliding over the table because of a magnet under the table or an object propelled by a rubber band. These I expect to trigger influences like gravity, magnetic attraction or elasticity.

To be more specific in what can be considered an influence the following distinction is made: An influence (like pedalling, braking, pushing, attracting, dragging, colliding) is something an influencer (earth, ground, air, sun, person) does to an influenced thing (the moving object). Heaviness/mass for example is no influence, but a larger heaviness of the sun (influencer) relates to more attraction (influence) on a planet or asteroid (influenced thing). In this way influence is distinguished from what is called here ‘factors’ or ‘attributes of the configuration’, that is things influences depend on. I expect students to mix examples of both factors and influences, as was seen in the first trial (see chapter 4, section 2.2.2), that now can be used by the teacher to make the distinction clearer.

The extended formulation of the explanatory scheme for motion can now be formulated as follows:

Explaining motions consists of:

1. determining the motion in a situation in which there are no influences at all
2. determining all operating influences (and how they depend regularly on other factors)
3. determining in which direction and to what extent these influences together cause deviations from 1.

This is the explanatory scheme for motions.

To explicate these elements in their interrelation the teacher is necessary to guarantee sufficient emphasis and focus on this important point. The teacher concludes that we arrived at an explanatory scheme for motion and announces that in the next episode its uses will be explored.

3.5. Episode 1.5: Making use of the explanatory scheme for motion

Function

The function of this episode is that students realise that for a complete explanation (and therefore prediction) of motion further specification of the elements of the explanatory scheme is necessary.

Justification of content and interaction structure (in the light of the function)

Returning to the initial asteroid problem gives one use of the explanatory scheme, namely providing a direction in which a solution may be found. When students realise that in order to find a solution all elements of the explanatory scheme of motion need to be further specified, this will give them some hold on the further directions the course will take. Applying the explanatory scheme for motion to the example of the asteroid will be quite difficult, because students lack sufficient interaction theory and clear notions about an influence free motion. Their answers will therefore be rather speculative, which at this stage is perfectly alright since the point is to show *that* the elements of the scheme need to be specified, not *how* they need to be specified.

Since for bringing out the main point no specific answer is necessary and therefore students' answers do not need to be moulded towards such an answer, merely taking stock of the answers in the evaluation would suffice. The conclusion that the elements of the explanatory scheme need to be further specified can surface quite naturally from students' answers, I expect. Explicating this conclusion and giving it the proper emphasis still requires teacher input, of course. A suitable interaction structure is therefore 'taking stock'.

Expected unfolding of the episode

Introduction

The teacher introduces this episode by pointing out that one use of the explanatory scheme for motion may lie in solving the initial asteroid problem (and implicitly therefore also in explaining and predicting any motion).

Main question and answer phase

Students identify those elements that are needed to solve the asteroid problem by answering the question, with the help of Figure 5, what things one would have to know to be able to give an explanation, given the explanatory scheme for motion (question 17). By now, after all the practice with filling in these type of figures, students are expected to be able to fill in this figure. (They will of course not know what some elements look like, and may invent things on the spot.) The element 'regularity' in the general explanatory scheme is here divided in two: 'Regularities' indicating the interaction theory aspect of mechanics and preparing for influence laws and 'relation influence – motion' preparing for my phrasing of Newton's second law, the rule deviation = influence/laziness.

Evaluation

Discussing the given answers the teacher emphasises *that* the elements of the explanatory scheme are needed for an explanation and that we do not yet know *what* these elements look like precisely. The explanatory scheme for motion, therefore, is useful, not in the sense that it delivers a ready solution to the asteroid problem, but in the sense that it provides for a handle on the problem by pointing out the elements student still need to learn more about. This amounts to a further specification of the scheme: which influences are operating and on what do they depend? What is the influence free motion? How do influences cause deviations from the influence free motion? Answering those questions will be the topic of the rest of the introductory course (and in a sense the topic of mechanics itself).

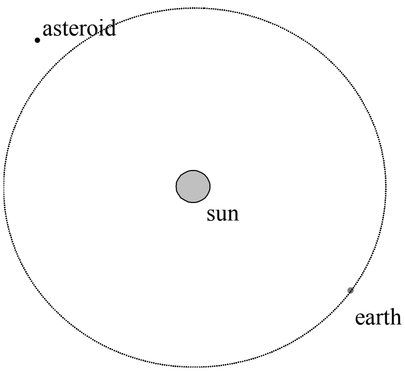
Motion of the asteroid: …	**Influence free motion** of the asteroid:…
	asteroid
Working is: - … - …	No influence is working on the asteroid.
Regularities: …. ….	
Relation influence – motion: …	

Figure 5: Asteroid towards earth

4. Extending students' knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining planetary motion.

The second main theme, extending students' knowledge, consists of a lot of episodes and consequently took a lot of lesson time (8 out of 13 lessons). It can be considered to be the bulk of the introductory course. In my description I will restrict myself to describing in detail only those elements that have direct bearing on the main point, which is that what happens here is a further specification of the explanatory scheme for motion.

4.1. Episode 2.1: Transition to Kepler and Newton

Function

Making clear to students *what* examples, namely those of Kepler and Newton, of a detailed explanatory scheme might be.

Justification of content and interaction structure (in the light of the function)

The main reason to start with the investigation of Keplerian and Newtonian models for the motion of heavenly bodies is that both had developed particular specifications of the explanatory scheme for motions. Furthermore, mechanics of heavenly bodies is clearly relevant for the asteroid problem[2]. In the previous episode students had realised that in order to find a general theory for explaining motion (and thereby solve the asteroid problem as well as other relevant examples) the explanatory scheme for motion needed to be further specified. It seems straightforward to explore some early specifications of the scheme as a first step in this process. For this it is important that students recognise Kepler's and Newton's theories as specifications of the explanatory scheme, which is the function of this episode.

The main activity is recognising the explanatory scheme for motion in texts on Keplerian and Newtonian mechanics. This purpose of the texts should be clear from the introduction to this activity. In the evaluation the teacher has to make sure that students did in fact recognise the explanatory scheme for motion in the texts they have read by taking stock of, clarifying and elaborating their interpretations of the texts and making the conclusion surface clearly. The conclusion is that Kepler and Newton explained the same phenomenon in the same structural manner, but differently in respect to the specifications of the elements of the scheme. The teacher can end by stating that some of the elements of the scheme can be made more precise, which will be the topic of the next episodes. Since identifying the *elements* of the scheme is fairly easy an interaction structure like 'taking stock' would seem suitable if these were the only things students were to recognise. However, the connection of these elements, which is also part of recognising the scheme, is more difficult to point out. For this guiding questions and help of the teacher are required and the interaction structure 'concluding' seems therefore more appropriate.

Expected unfolding of the episode

Introduction

Students should be oriented towards the texts on Kepler and Newton as particular specifications of the explanatory scheme. For this, simply reading a small paragraph with this message was thought to suffice.

[2] See chapter 3, section 2.2 for a more elaborate presentation of this and other reasons for the choice for Kepler and Newton and the choice for the context of celestial mechanics.

Main activity

Students then read two texts on Kepler and Newton in which their use of the explanatory scheme for motion should be easily recognisable. Their reading is guided by the following question:

> Question 18: Do you recognise the explanatory scheme in these texts? How did Kepler specify its elements? And how Newton? Study these texts so that you can give an oral presentation.

The text on Kepler as it was presented in the students' booklet is given below.

Kepler

Figure 6: Kepler, Johannes (Weil, Württemberg, December 27 1571 – Regensburg November 15 1630), German astronomer, mainly known for the laws named after him concerning the motion of planets around a sun.

Kepler thought that when no influences are working on an object, that object would remain at rest. The planets however move in circular orbits. This deviation from what he considered to be the influence free motion he had to explain by identifying a suitable influence.

That influence Kepler sought in the sun. He had noticed that the sun is not at rest, but is turning about her axis and that the planets in our solar system all turn around the sun in the same direction. See Figure 7.

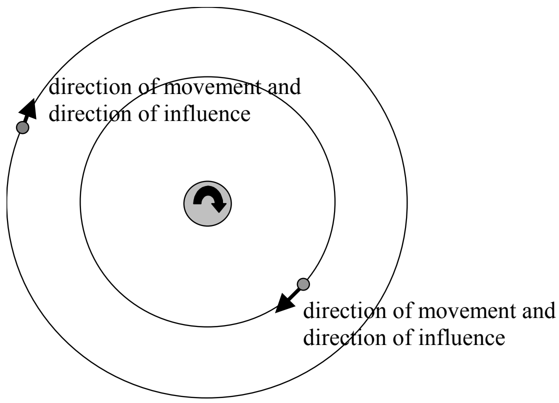


Figure 7: Direction of turning of sun about her axis and planets around the sun.

Kepler thought this could not be a coincidence. Apparently the turning of the sun about her axis causes the planets to turn around the sun. You can think of this as a wheel with spokes. Imaginary spokes protrude from the sun towards different planets. When the sun turns, these spokes turn and therefore also the planets on these spokes. The influence of the sun on the planets is a kind of dragging in the direction in which the planets move.

Furthermore Kepler thought that the influence depends on the rotation speed of the sun. If planets circled around another sun, which turned about her axis quicker, these planets would move faster. So Kepler assumed:

The larger the rotation speed of the sun, the larger the influence.

Kepler knew that planets that were more distant from the sun took longer to complete one turning around the sun then those that were nearer to the sun. He therefore assumed that the influence is smaller as the distance to the sun is larger. So Kepler assumed:

> The larger the distance between sun and planet, the smaller the influence.

Finally Kepler assumed:

> The larger the influence on an object, the larger the deviation from the influence free motion.

A similar text on Newton was used, which is not printed here. I expect students to easily identify the elements of the explanatory scheme of motion in these texts. More difficult will be to explain the relation between these elements, for which help of the teacher is required.

Evaluation

The teacher discusses several presentations of students and tries to elicit answers to the following questions:

1. What were the facts that Kepler and Newton tried to explain?
2. Do you recognise the general way of explaining? How was it applied by Kepler? How by Newton?

3. Why did Newton come up with assumptions for the influence law, which differed from those of Kepler, in particular with respect to the direction of the influence?

These points/questions emphasise that Kepler and Newton explained the same phenomenon in the same structural manner, but differently in respect to the specifications of the elements of the scheme. The third point addresses specifically the connection between assumed influence free motion and identified influences. I expect the first two points to surface easily. The third point will require more help.

As a product of this discussion the diagram of Figure 8 is filled in (question 19).

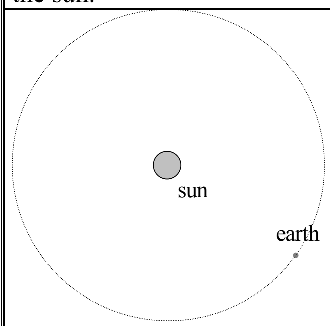
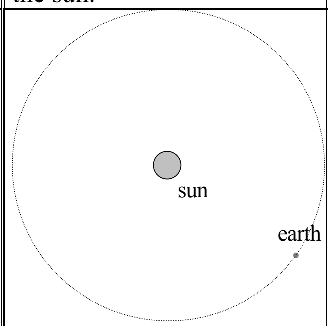
Kepler		**Newton**	
Motion to be explained: Earth making turns around the sun.	Influence free motion: … *rest*	Motion to be explained: Earth making turns around the sun.	Influence free motion: *straight, with constant speed*
	*some drawing indicating rest*		*some drawing indicating straight motion, with constant speed*
Working is: - *drag from sun (in direction of motion)*	Working is no influence	Working is: - *attraction from sun (in direction of sun)*	Working is no influence
Regularities: - *The larger the rotation speed of the sun, the larger the influence.* - *The larger the distance between sun and planet, the smaller the influence.*		Regularities: - *The larger the heavinesses (heaviness of planet, heaviness of sun, or both), the larger the influence.* - *The larger the distance between sun and planet, the smaller the influence.*	
Relation influence - motion: *The larger the influence on an object, the larger the deviation from the influence free motion.*		Relation influence - motion: …. *The larger the influence on an object, the larger the deviation from the influence free motion.*	

Figure 8:'Status diagram' from the students' booklet indicating the state of affairs, in which they recurrently add their findings

This gives an overview of what is already known and which elements are still lacking or need to be made more precise. This diagram plays an important role in the course. It serves as a summary of the findings, which are added whenever some new conclusion has been reached. It also shows which elements are still unknown and therefore guides or points forward to what needs to be done, i.e. which elements of the explanatory scheme for motions needs to be further specified. The trajectory of the earth around the sun is depicted as resembling a circle, which is in agreement with its real orbit. All planets in our solar system follow elliptical trajectories with such small eccentricities that they cannot easily be distinguished from circles. The elements students are expected to add to this figure at this stage are indicated in italics (the rest was already part of this diagram). This diagram will also recur in this chapter at those moments when students are expected to add something to it, for it might help the reader to keep track of the main line of thought as well as it is expected to do for students.

The teacher states that some of the elements of the scheme, as added to Figure 8, ought to be made more precise and that this will be the topic of the following couple of episodes.

4.2. Episode 2.2: Introduction to the matching problem

Episode 2.2 will be described in more detail than the others to show what is precisely meant with the matching problem. This is important because this problem is used extensively for guiding the further filling in/specifying of the elements of the explanatory scheme for motion. It was my claim that this introduction does not presuppose any of the elements it introduces (see chapter 4, section 2.2.3). In this way going from 'building to building blocks' (which was the turnaround of traditional education and the first trial's approach of 'first building blocks, then building') seems possible, which will be shown by providing the details, especially those concerning the used computer program, of the episode. In the next section episode 2.3 will be described more succinctly.

Function

Giving an idea to students *how* a detailed explanatory scheme, like those seen from Kepler and Newton, may lead to explanations of motions like the one of an asteroid: an influence law leads to a modelled motion, which needs to match the observed motion.

Justification of content and interaction structure (in the light of the function)

How specifications of the explanatory scheme may lead to predictions or explanations of motion can be shown using a computer model. Students can meaningfully use a computer model without knowing all its ins and outs, as was argued in chapter 4 section 2.2.3 in the discussion of the matching problem. The specification of the explanatory scheme for motion can therefore start with a single element of that scheme. The element 'regularity' (see Figure 8), which is to be detailed in an influence law, is suitable to start with. It can be related to and derive its meaning from the problem of finding a 'match' between observed and modelled motion. The basic test to estimate the value of such a match uses the criterion of empirical adequacy, which simply states that the model's prediction should 'match' the real (observed) motion as well as possible. By displaying both the real or observed motion and the motion which is the result of the used model simultaneously, it can be made clear how to arrive at an empirically adequate model.

This whole episode is an introduction and can be seen as setting the stage for the subsequent episodes. Within this 'setting the stage' (for the next episodes) also an introduction, main question and answer phase and evaluation can be distinguished, which forms the interaction structure of this episode. The main question of this episode, *how* a motion model may lead to predictions of motions, can be addressed in a demonstration of the described computer model by the teacher. This is introduced by indicating one element in the 'status diagram' that is lacking in precision, namely the regularity. The demonstration is evaluated by concluding how effecting a match results in a (plausible) quantitative influence law, which is a conclusion that I expect to surface pretty straightforward from the observations that a match *can* be effected, that it can be effected by using a proper influence law, and that within that influence law the parameter has to have a suitable value. Students are expected to have noticed these things, but the teacher will be needed to give them the proper emphasis and to take the next (small but important) step that in this way, by matching, a proper influence law (which is a specification of the element 'regularity') can be found. For this, the interaction structure of 'taking stock' seems suitable.

Expected unfolding of the episode

Introduction

The teacher introduces this episode by saying that both Kepler and Newton had ideas about what kind of influence was working on the planets and that these were expressed in regularities like 'the larger the distance between sun and planet, the smaller the influence'. In order to really predict motions, for instance with the help of a computer model, these regularities have to be made quantitative. One way of doing that is by expressing these regularities in a formula.

Main question and answer phase

The teacher asks the students how such a formula may look like. I expect that they will find answering this very difficult, but whatever is put forward can be incorporated in the demonstration later on. The teacher can guide by repeating the regularities seen before and suggesting symbols for influence, rotation speed of the sun (in the case of Kepler) and distance. The teacher makes an inventory of suggestions, adds some of his own when needed and makes sure that a formula is agreed upon that is in accordance with the regularities. Remarks that more than one formula does the trick are confirmed with the promise that this point will be picked up later.

The teacher then opens in Modellus an unfinished Keplerian model of the sun and earth and types the agreed upon formula in its model window, see Figure 9. In this figure the Modellus interface that students are presented with is shown. The model itself, consisting of some lines of code shown partly here in the 'model window' can remain hidden. What students see is a model output in the form of moving dots in the 'animation window' and a model input in the form of one or more adjustable parameters in the 'initial conditions window'. In this first model there are two dots representing earths. One earth follows the 'real' or 'observed' motion and cannot be changed. The other earth shows the motion the computer model calculates based on the used influence law and value for the parameters. The third object represents the sun. In this Keplerian case only one parameter is used: rotation speed of the sun, indicated by R.

The teacher explains that the computer has now been made ready to calculate the motion of the earth. The program still needs a starting value for the rotation speed of the sun. He demonstrates what happens for a value of 0 for the rotation speed and describes what can be seen on the screen. The influence working on the modelled planet is indicated by an arrow. Its length is a measure for the magnitude of the influence and it points in the direction in which the influence is working, which in the Keplerian case is the direction in which it moves. The influence can be made 0 by adjusting a parameter in the influence law. In this case the parameter is the rotation speed of the sun R. When the sun stops rotating, its dragging effect on the surrounding planets would according to Kepler's spokes explanation also stop. The planet would then exhibit Kepler's assumed influence free motion, which is rest. Both a model planet standing still and an arrow with length 0 can be observed in the animation window in the case that R is made 0. The observed relation between parameter and influence can of course also be seen in the influence law I = R/r, with I the Keplerian influence. For this the 'model window' has to be made visible, as is the case in Figure 9.

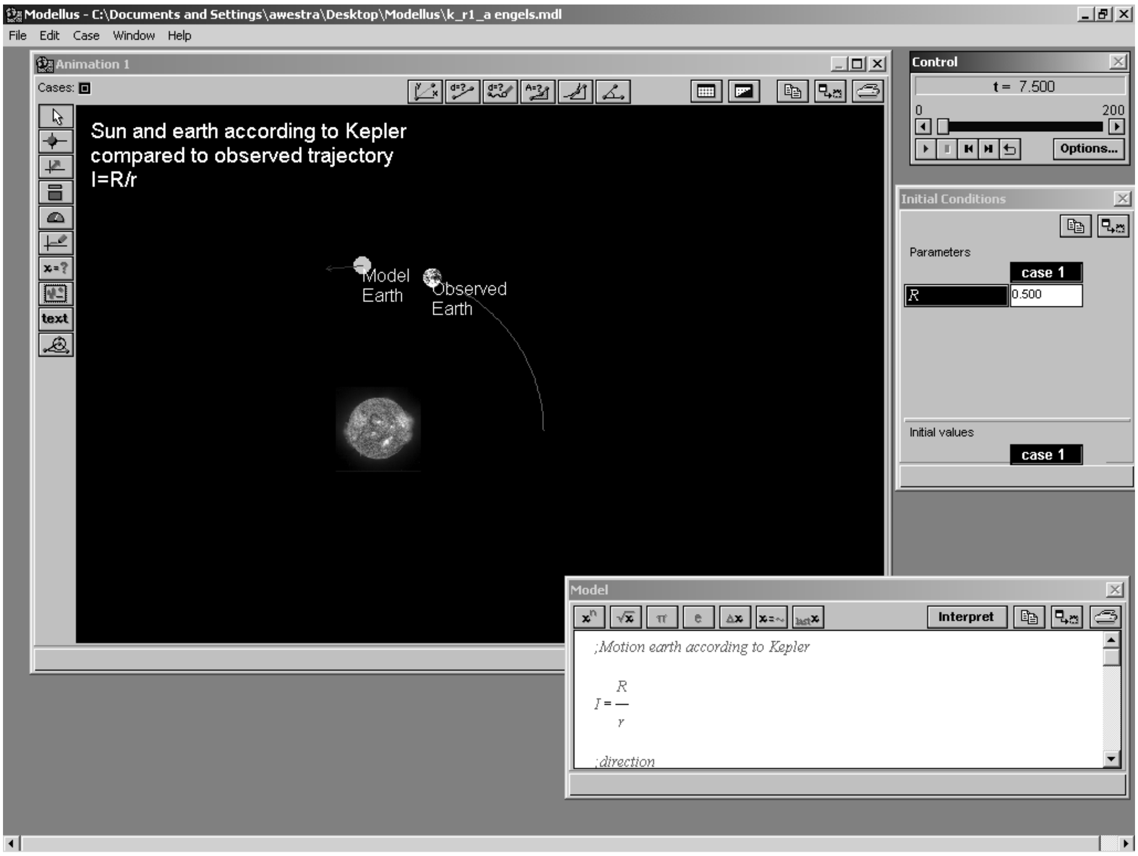


Figure 9: Modellus model of the motion of the earth around the sun demonstrating the matching problem.

So with this computer model and these simple actions already Kepler's assumption for an influence free motion, his notion of influence including his spokes explanation and a Keplerian influence law have been illustrated.

The teacher then invites suggestions for effecting a 'match' from the students, which consist of various changes in the value of R, I expect.

Evaluation

In conclusion the teacher says (in connection to what the students have observed) that a model can be made correct by matching the 'model planet' with the 'observed planet'. This can be done in two ways: the value of the parameter R can be altered or another influence law can be used. Later on the students will work themselves with such models, but first they will look into the possibility of other influence laws.

4.3. Episode 2.3: Influence laws

Function

Deepening the insight in the *what* and *how* of specifications of the explanatory scheme for motion by having students vary some relevant parameters in the influence laws in order to solve the matching problem. Furthermore slowly starting to raise the question which type of model (Keplerian or Newtonian) is more fruitful.

Justification of content, interaction structure and computer model (in the light of the function)

The first element of the explanatory scheme for motion that is further investigated or 'deepened' is that of influence law, as was already announced in the previous episode. The notion that an influence law is something that gives the magnitude of the influence as a function of relevant factors in the environment can be addressed by having students come up with several formulas relating rotation speed of the sun R and distance between sun and planet r to Keplerian influence, and heaviness of the sun H_{sun} and the distance r to Newtonian influence. This repeats what Kepler and Newton considered to be relevant factors and illustrates that alternative influence laws are possible that all quantify the same qualitative regularity. Seeing several alternatives raises the question which influence law is good (enough). By now this question can be answered by recalling the earlier demonstration of the matching problem and solving it for these alternatives. The modelling assignment in which this happens can start easily by matching only one planet and varying only one parameter. In this way the attention can be focussed on influence, adding laziness later. The effect of the parameters, R in the Keplerian models and H_{sun} in the Newtonian, can be made easily visible, as will be described in this section in the discussion of the computer model.

Having students investigate motion models using the computer calls for an active teaching format with lots of student interaction. The introduction to this episode has already been given in episode 2.2, but before testing some laws with computer models, students should know what such laws (must) look like, which requires more than being told by the teacher (in the explanation in episode 2.2). Therefore a further preparation ought to take place in which students think of several alternative Keplerian and Newtonian influence laws themselves. In the evaluation the teacher makes sure that the main points surface clearly from the modelling results the students put in, which mainly involves taking stock of students' answers. The interaction structure is therefore 'taking stock'.

I will now describe in some detail some considerations concerning the used computer models for it will make clearer what is actually done in this second main theme.

The construction of computer models was guided by the desire to make Keplerian models viable alternatives to Newtonian models. An early victory for Newtonian models would stop the driving force the matching problem provides for further investigation and therefore the learning of the subsequent topics of laziness, the rule 'deviation = influence / laziness', the criterion of broad applicability, et cetera. An important consideration in this respect was to have a plausible Keplerian influence law. This restricted the Keplerian influence law to one with only a tangential component and no radial component. A Keplerian influence law that would include a radial component would look much more complicated mathematically and I could not think of a plausible account for students to insightfully relate a radial component to Kepler's spokes explanation. As a consequence all Keplerian models will predict circular motions and there will be no difference in the quality of the matching results of the used influence laws $I=R/r$, $I=R/r^2$ or $I=R/r^3$. Only the value for R for which the best match occurs differs. The reason to investigate three Keplerian models is that also three Newtonian models, that do differ in matching result, will be investigated. An explanation of why the three Keplerian models have the same quality and that therefore one Keplerian model would suffice, would be more difficult and time consuming than simply testing all three. By retaining the 'symmetry' in the number of investigated models, such an explanation can be avoided.

In order to retain Kepler as a viable alternative the so-called observed motion of the heavenly bodies, which follows a Newtonian motion model with a correct influence law, should follow an elliptical trajectory with a slight eccentricity that resembles a circular trajectory. The used Keplerian models can therefore still result in a match, albeit a less than perfect one.

Another alternative would have been to let the models match a 'real' *circular* motion. This was considered undesirable for it would not show the superiority (in the sense of perfect empirical adequacy) of Newton's law of gravitation, because the difference between this law, $I = H_{sun} \cdot H_{planet} / r^2$ with I the Newtonian influence, H the heaviness and r the distance between sun and planet, and the same formula with any other power of r would merely be some constant factor when r is constant, which would be the case when the trajectory is circular.

Computer models will prove equally useful in further addressing another element of the 'status diagram' (Figure 8), namely the topic of laziness (episode 2.4). I will continue my discussion of the used computer models in the section that concerns this episode and turn now to the expected unfolding of episode 2.3.

Expected unfolding of the episode

Introduction

Students read a short introductory paragraph and try to think of several formulas expressing Kepler's notions about factors the influence depends on (question 20) and the same for Newton (question 21). They can also express their own notions about additional factors this influence may depend on (question 22). In discussing their answers the teacher poses the question how one can choose between the given alternatives, which should trigger a recollection of the earlier demonstrated matching problem.

I expect students to be able to write down several formulas that are in agreement with the earlier read notions like 'the larger the rotation speed of the sun, the larger the influence' et cetera. I do not expect much of an answer to question 22. I included that question to allow the occasional student that has an opinion on the matter to express it.

Main question and answer phase

Students test three Keplerian and three Newtonian influence laws (question 23). This amount allows some variation in matching result in the Newtonian cases, e.g. one model will almost match, one not at all and one perfectly, whereas testing six models would not take too much time. After this testing of several influence laws the students are asked to describe how one can see if some model is Keplerian or Newtonian (question 24) and to add the best influence laws to their 'status diagram', see Figure 10 (question 25).

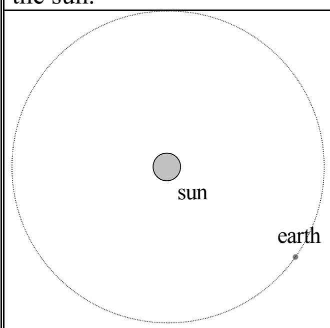
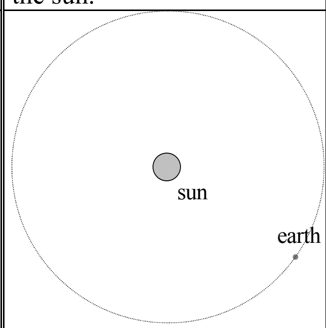
Kepler		**Newton**	
Motion to be explained: Earth making turns around the sun.	Influence free motion: … *rest*	Motion to be explained: Earth making turns around the sun.	Influence free motion: *straight, with constant speed*
	*some drawing indicating rest*		*some drawing indicating straight motion, with constant speed*
Working is: - *drag from sun (in direction of motion)*	Working is no influence	Working is: - *attraction from sun (in direction of sun)*	Working is no influence
Regularities: *I = R/r, with R the rotation speed of the sun*		Regularities: $I = H_{sun} \cdot H_{earth} / r^2$, *with H the heaviness.*	
Relation influence - motion: *The larger the influence on an object, the larger the deviation from the influence free motion.*		Relation influence - motion: …. *The larger the influence on an object, the larger the deviation from the influence free motion.*	

Figure 10: Expected 'status diagram' from the students' booklet indicating the state of affairs, after episode 2.3.

After playing with the models for a while effecting a match should be fairly easy. Differences between Keplerian and Newtonian models I expect students to come up with are the kind of influence law (containing parameters associated to either Kepler or Newton), the direction of the influence, and the observed motion after the 'test' of making the influence zero by making the relevant parameter (R or H_{sun}) zero.

Evaluation

The teacher takes stock of several answers and makes sure the main points surface clearly: a quantification of the regularity is necessary in order to predict motion, an influence law is testable by matching, and some feeling for the effects of R and H.

4.4. Episode 2.4: Laziness

Function

Adding the concept 'laziness' as well as the rule 'deviation = influence / laziness' as further elements of what specifying the explanatory scheme for motion amounts to. Furthermore continuing to let the question about the fruitfulness pop-up occasionally.

Justification of content, interaction structure and computer models (in the light of the function)

By now students have further specified one element in their 'status diagram' and are about to further specify the element of 'relation between influence - motion', see Figure 10.

For this specification two points need to be addressed: Firstly, how the concept of laziness is important for the relation between influence and motion. Secondly, how laziness can be determined according to Kepler and Newton. A third point in this episode relates to the question about the fruitfulness of the two types of model and concerns an argument in favour of Newtonian models. I will now address these three points.

The importance of laziness

The concept of laziness can be introduced as a relevant concept for the relation influence - motion by recalling that different objects can react differently to the same influence, in the sense of deviating to a larger or smaller extent from the influence free motion. Apparently something else besides influence, something which is connected to the object itself, also has some bearing on this relation. Some easy examples can illustrate this phenomenon. 'Laziness' is then introduced as an attribute of an object that determines how strongly that object reacts to some influence. The larger the laziness of an object, the smaller its reaction to some influence. Students can first get a qualitative feeling for the concept, which can later be made semi-quantitative in the rule 'deviation=influence/laziness', and deepen their insight in Keplerian and Newtonian models and the role influence plays in them, by trying to match models that explicitly include laziness. In the models used in the previous episodes laziness was hidden from view. Take for example the following Newtonian model that includes the laziness of the earth as a parameter, see Figure 11. It uses an influence law students are already familiar with from episode 2.3. In this example the law $I = H_{sun} \cdot H_{earth} / r^3$ is used, but students are free to choose one model from the same set of models that were used in episode 2.3. Most students will chose the model with the best influence law, I expect.

In this model laziness and heaviness of the earth can be varied separately. Increasing the heaviness increases the influence, which is in this case the attraction towards the sun, indicated by an arrow. This causes the model planet to deviate more strongly from its influence free motion, i.e. curve more inwards. Increasing the laziness makes the model earth react less strongly to the influence, it therefore deviates less from its influence free motion, i.e. curves less inwards. When the laziness is made very large, the influence has practically no effect on the motion of the model earth and it will then follow its influence free motion. Changing both heaviness and laziness of the earth at the same time in the same way, e.g. doubling both of them, does not change the motion. The effect of the larger influence is in such a case balanced by the lesser reaction to that influence. (What can be observed is that the arrow indicating the influence doubles in length.) When students perform simple actions like these with Newtonian and Keplerian models, I expect them to develop more feeling for the effects of the parameters laziness and heaviness in these models.

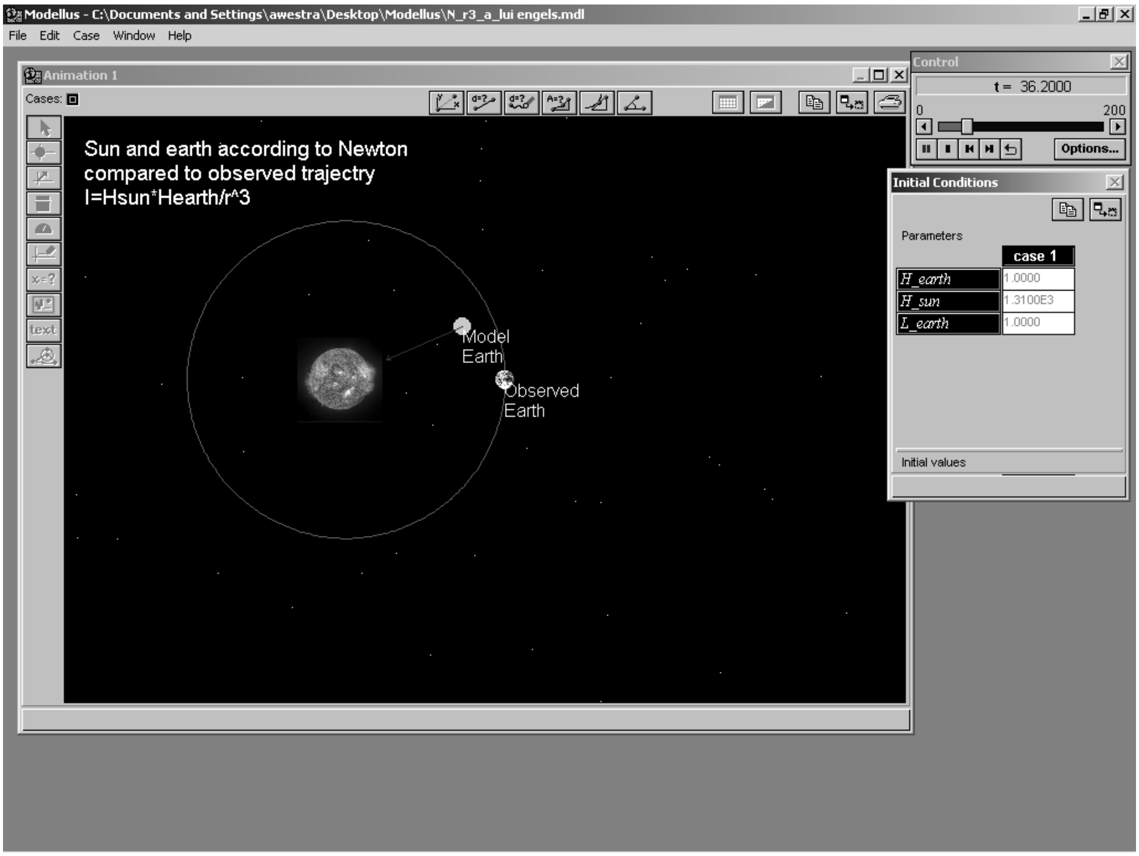


Figure 11: Newtonian motion model of the motion of the earth around the sun including laziness as a parameter.

Determining the laziness of heavenly bodies

Up till now I expect student to find the investigation with the computer models quite easy. The next part in which this investigation is extended to see how laziness can be determined using the matching procedure I am more uncertain about what students can understand. The following is ambitious, maybe too ambitious.

One important aspect of the concept of laziness is how it can be determined in general or how the laziness of heavenly bodies can be determined in particular. A first intuition here that can be ascribed to both Kepler and Newton is that the laziness of an object is proportional to the amount of matter (or mass) that object consists of. A larger planet containing a larger amount of matter would then have a larger laziness. If this were the case an estimate of the laziness of planets can be made when their size can be observed, assuming that the planets have equal densities. More precisely, the ratio of lazinesses of planets can in this way be determined. One could then simply define the laziness of one planet in some unit of laziness and calculate the others from that.

There is also another method for determining ratios of lazinesses of planets. This method uses the matching method tried before, which works out differently according to Newtonian or Keplerian models and will be discussed separately for both cases.

A Keplerian model of two planets, e.g. Venus and earth, moving around the sun with the laziness of Venus L_{venus}, the laziness of the earth L_{earth} and the rotation speed of the sun R as parameters can be matched, resulting in a ratio L_{venus}/L_{earth}. Although there are (infinitely) many solutions (R, L_{earth}, L_{venus}) that effect a match, the ratio L_{earth}/L_{venus} is constant for all matching values for (R, L_{earth}, L_{venus}) and can therefore be determined in this way.

A similar Newtonian model with L_{earth}, L_{venus}, H_{earth} and H_{venus} as parameters can also be matched in an infinite number of ways, even if we make (as Newton did) the assumption that heaviness equals laziness. But it does not give one solution for the ratio L_{venus}/L_{earth}. As long as laziness equals heaviness and is much smaller than the heaviness or laziness of the sun, a match can be achieved for the right value of the heaviness of the sun. That is, the matching problem only yields a value for the heaviness of the sun, but not for the planets. This is because of the interesting phenomenon that the mass of a planet does not influence its motion as long as it is much smaller than the mass of the sun it moves around. A greater mass implies a greater heaviness and therefore a greater influence working on the planet, but this is compensated by an equally greater laziness, causing the planet to react less to that greater influence. Both effects balance[3]. In the Newtonian case this second way of determining laziness should therefore be approached differently. Another model is needed, for instance one of the sun, earth and moon. By matching the earth the heaviness of the sun can be determined and by matching the moon the heaviness of the earth can be determined. I expect this notion to be too difficult for students to think of themselves, but some (probably not all) might be able to follow it when carefully presented. The students *are* supposed to notice that a match occurs whenever laziness and heaviness are equal and to be able to determine the ratio $L_{earth}/L_{sun} = H_{earth}/H_{sun}$ in this way, since this only requires already developed matching skills. Students have practiced matching a number of times, have seen the balancing effects of heaviness and laziness, so I expect some students to pull this off. I am uncertain about what they understand of the reason for this complex procedure, though. That may be too ambitious.

[3] The same phenomenon is found in the classic (thought)experiment of Aristotle, later criticised by Galileo in which two stones of different size are dropped. Galileo's point was to show how they have to reach the ground at practically the same time.

Evaluating Keplerian and Newtonian models: a weak argument in favour of Newton

Given my uncertainty about how much can be achieved in students' understanding of determining laziness by means of the matching procedure, the topic of evaluating Keplerian and Newtonian models in this respect is even more doubtful, since it further builds on the previous topic. Both ways of determining the (ratio of) laziness of planets can be compared, which results in a weak argument in favour of Newton. The ratio L_{venus}/L_{earth} as determined from matching modelled planets with a Keplerian model differs from the ratio m_{venus}/m_{earth} as determined by comparing quantities of matter. Keplerian laziness is apparently not the same as mass. A similar comparison of L_{earth}/L_{sun} to m_{earth}/m_{sun} in the Newtonian case does yield practically the same numbers, suggesting that Newtonian laziness can in fact be considered equal to mass, whereas Keplerian laziness can not.

With respect to the interaction structure, the main points that should be emphasised at the end are that the concept 'laziness' is necessary for specifying the relation between influence and motion from the explanatory scheme for motion (including the rule 'deviation = influence/laziness' as a quantitative specification of this relation), what laziness is and does, and a weak argument for preferring Newton to Kepler.

The main activities here are getting the feel for laziness with some simple models and determining the laziness with the help of more complex models. The first is such an elaborate preparation for or introduction to the second, that the first can be seen to consist itself of a division in the three elements of introduction, main question and answer phase and evaluation. The introduction of the introduction part can be given with a text in which the concept laziness is explained in qualitative terms. In the evaluation of the main question and answer phase of the introduction the teacher makes sure that all students have arrived at a proper feel for laziness, which should only involve taking stock of their answers that are expected to require few and little adjustments.

In the main activity of determining the laziness of heavenly bodies students investigate the more complex models. Although students are expected to be able to find matches, since they have practiced this a lot in simpler models, help from the teacher is needed to emphasise the main line of why this more complex matching takes place. In the evaluation simply taking stock of the matching results should suffice for making the outcomes explicit, like Kepler's assumption that laziness equals mass was wrong. The meaning of such outcomes, such as that they provide an argument in favour of Newtonian models, can be expected to be more difficult and therefore requires more teacher input in the evaluation. The interaction structure here is one with an extensive introduction that itself consists of the elements introduction, question and answer, and evaluation, and a fairly 'heavy' (in the sense of requiring quite some teacher input) evaluation of the episode as a whole. The evaluation part resembles the evaluation part of 'concluding'. I did not name this particular interaction structure, because it occurs only once.

Expected unfolding of the episode

Introduction

The introductory part is about getting a feel for laziness and consists itself of an introduction, main question and answer phase and evaluation. This sets the stage for the main part, described subsequently.

Introduction (of the introduction)

Students read about laziness in the context of further specifying the relation influence – motion. I expect the text to be clear and easy enough so as not to require specific teacher attention. By now students should recognise the guiding function of the status diagram and be able to continue their work in this second main theme largely by themselves. Introducing the main question and answer phase and, if possible, guiding the evaluation in the text of the student booklet has the advantage of allowing students to work at their own pace.

Main question and answer phase (of the introduction)

A simple Keplerian model similar to the one depicted in Figure 9, but including laziness as a parameter, is investigated guided by questions asking to vary the laziness of the earth and look for what happens with the influence on and the motion of the earth (question 26, 27), match the motion of the earth by finding suitable sets of parameters R and L and explain why several sets are possible (question 28). The same is done for a Newtonian model (question 29, 30 and 31). I expect students in this way to easily observe the effect of laziness on the motion and notice the balancing effect of influence and laziness.

Evaluation (of the introduction)

After discussing their answers the teacher recapitulates that Kepler and Newton both attributed various lazinesses to various objects and that the laziness of an object indicates how strongly the object reacts to an influence. He then introduces the next part by stating that Kepler and Newton tried to establish the laziness of different planets and that the topic of the next part, here described under main question and answer phase (see below), is to investigate how they did this.

Main question and answer phase

Having developed a better feeling for the effects of the parameters laziness and heaviness in the models, students read about determining laziness according to Kepler. They then use the matching method described before in the 'justification' section and apply this method using a Keplerian model of two planets moving around the sun. This is guided by a matching assignment that asks for several solutions (R, L_{earth}, L_{venus}), which prepares for the next question that asks to calculate the ratio L_{earth}/L_{venus} for the found sets. This is by now pretty straightforward application of the acquired matching procedure and should result in the conclusion that this ratio is constant.

A similar application then takes place of a Newtonian model of earth and Venus, which should lead to the conclusion that in this way the ratio L_{earth}/L_{venus} or H_{earth}/H_{venus} cannot be determined.

Students then read a text explaining Newton's assumption that both laziness and heaviness are proportional to amount of matter or mass. Here also the 'balancing' of the effects of influence (or indirectly heaviness) and laziness that students had seen earlier but may not have been able to explain is clarified. Furthermore the idea to use a model of sun, earth and moon is introduced as a means to determine the laziness of heavenly bodies.

They then apply these ways of determining laziness with the Newtonian model of sun, earth and moon, guided by some preparatory questions asking to calculate the ratio L_{earth}/L_{sun} and whether with this model the laziness of the moon can be determined. These prepare for the question of which planets the laziness can be determined in this way, which is meant to lead to the conclusion that in this way only the laziness of heavenly bodies can be determined if they have another object circling around it.

The conclusions for the respective value of Newtonian and Keplerian models are guided by the question whether Kepler's assumption that laziness equals mass was right, whether Newton's assumption that heaviness equals laziness equals mass was right, and the task to add these new findings to the 'status diagram'. Here I expect students to add the notions that Newton's assumption was right, whereas Kepler's was not seen to be right under the heading 'relation influence – motion'. (Kepler's assumption could still be right, because not all Keplerian models were tested. It is thinkable that with some special influence law a match can be found so that laziness does equal mass.)

Kepler | **Newton**

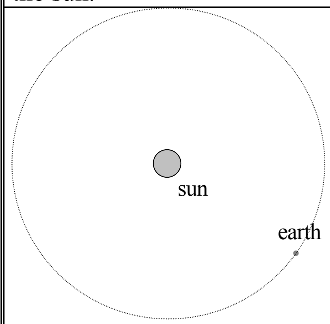
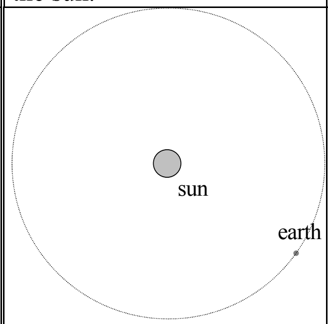
Motion to be explained: Earth making turns around the sun.	Influence free motion: … *rest*	Motion to be explained: Earth making turns around the sun.	Influence free motion: *straight, with constant speed*
	*some drawing indicating rest*		*some drawing indicating straight motion, with constant speed*
Working is: - *drag from sun (in direction of motion)*	Working is no influence	Working is: - *attraction from sun (in direction of sun)*	Working is no influence
Regularities: $I = R/r$, *with R the rotation speed of the sun*		Regularities: $I = H_{sun} \cdot H_{earth} / r^2$, *with H the heaviness*	
Relation influence - motion: *deviation=influence / laziness* *laziness does not equal 'amount of matter' or 'mass' (which is strange).*		Relation influence - motion: *deviation=influence / laziness* *laziness equals heaviness equals 'amount of matter' or 'mass' (which seems quite right).*	

Figure 12: Expected 'status diagram' from the students' booklet indicating the state of affairs, after episode 2.4.

Evaluation

The answers are then discussed. The teacher emphasises the main point, which is the role laziness plays in relating influence to motion. This relation is finally quantified in a text students read in which the rule 'deviation = influence/laziness' is introduced. Students are asked to add this information to their 'status diagram'. Also the teacher checks if the expectedly difficult point of determining laziness with the matching method for Newtonian models is understood. I expect in the discussion the question 'which type of model is best?' to slowly surface. At this point this question cannot be answered although one weak argument in favour of Newtonian models can now be understood. The teacher acknowledges this question if it arises, but postpones the answer. Their 'status diagrams' are supposed to look now like the one depicted in Figure 12.

4.5. Episode 2.5: The precise relation between influence and motion.

Function

Adding to *how* a specification of the explanatory scheme for motion may lead to explanations of motion by investigating the precise relation between influence and motions with the help of the method of graphically constructing motions from given influences. Furthermore continuing to let the question about the fruitfulness pop-up occasionally.

Justification of content and interaction structure (in the light of the function)

Students have seen by now that the computer models they investigated somehow 'transformed' influence given by an influence law into motion. Apparently this can be done, but clearly what they know about it at this stage (as summarised in the status diagram, depicted in Figure 12) is not yet sufficient to understand how it is done in detail. What needs to be further specified, in particular, is the element 'relation influence - motion'. Students are therefore presented with a step by step graphical account of how successive deviations from the influence free motion can be calculated and constructed given some influence(law). This construction of successive positions *is* then the motion of the object on which the influence was working. In chapter 4 section 2.2.1 an example of such an explanation from the first trial was given. Some improvements have been made, notably a more gradual introduction of this method, starting with concepts of influence and laziness in isolation before using them in connection in graphical constructions as was seen in chapter 4 section 2.2.3. It is obvious that such a technical and detailed way of explaining how a motion can be constructed from a given influence law remains quite difficult. However, I expect that after an explanation by the teacher using the blackboard (which nicely shows and explicates the subsequent steps in such a construction), reading a similar explanation again in the booklet, practicing with some questions and discussing those in the group the students will have developed some confidence in that the motion can be determined in this way. Not all will be able to perform all the details of such a procedure correctly, but they do not have to. Confidence that motion can *in principle* be determined when the influence(law) is known and thereby removing the mystery suffices.

The main activity is coming to understand (to some extent) how motion can be constructed. Since this is a difficult and technical topic using many ways of approaching it seems appropriate. Therefore listening to an explanation, reading a similar explanation, practicing with a computer model, practicing with paper and pencil construction assignments, lots of interaction during this work and discussion afterwards all help in coming to grips with this matter. The point here is not to effect a deepening of understanding with each activity, but simply to approach the subject in different ways. The main activity is introduced by indicating that students will be further detailing the element 'relation influence – motion' in the status diagram. In the evaluation the students' findings are taken stock of and the main point is emphasised that motion can *in principle* be constructed when the influence law is known (although many students may still be unable to do that themselves *in practice*). This conclusion as such I expect to be not to difficult to draw in close connection to the student input, so that the interaction structure 'taking stock' should suffice.

Expected unfolding of the episode

Introduction

The relation with the main thread can be addressed using the status diagram, Figure 12. Students have seen in their investigation of computer models that the computer in some way manages to calculate the motion given some influence law and also that laziness had something to do with that according to the rule deviation=influence/laziness. In this episode we further investigate how this is done precisely.

Main question and answer.

The teacher then explains and demonstrates an example of either the Newtonian or Keplerian graphical way of constructing subsequent positions (explaining both will take too long, the other can be read about in the students' booklet) using the blackboard since this shows each step/addition to the figure in the construction clearly.

Students then read a similar explanation as they have just heard for both Kepler and Newton. The following is an excerpt from the students' booklet in which a Newtonian graphical construction is explained:

> See Figure 13. Suppose that an object with laziness 2 is moving through A with a speed straight up. According to Newton the influence free motion is moving with constant speed in the direction the object is already going. The object will therefore if there are no influences after some time be in B'. During this time there *is* an influence in the direction of the sun. We will pretend for the moment that this influence consists of a short tap in point A that can be calculated with a Newtonian influence law like $I=H_{sun}\cdot H_{earth}/r^2$. When H_{sun} is 100 and H_{earth} is 0,1 and the distance AM is 10, then the influence in A would be 1. To find where the object is after this time we have to transform the red influence arrow in a deviation arrow with the rule deviation=influence/laziness. The deviation arrow is in this case twice as short as the influence arrow. We then attach the deviation arrow to point A. The object moves during this time therefore to point B. This is the 'sum' of the influence free motion and the deviation. Without influence the object would then move from B to C'. This can be understood by considering that during the first time interval the object moved from A to B and according to Newton without influences an object would remain its

direction and speed. This means that without influences the object would move in a next time interval the same distance AB in the direction of AB, therefore to C' (note that C' is positioned on the line through A and B). During this time interval there *was* an influence. We again pretend that this influence consists of a tap in point B that again can be calculated with the influence law. The heavinesses remain unchanged, but the distance BM is slightly different, for example 9,9 which results in an influence in B of 1,02 in the direction of the sun. This influence is indicated by the red arrow 2. In order to determine where the object is after the second time interval we again have to translate the influence arrow in a deviation arrow by means of the rule deviation=influence/laziness. The deviation arrow is twice as short as the influence arrow. Then we attach the deviation arrow to point B. The object moved in this time interval therefore to C. Et cetera.

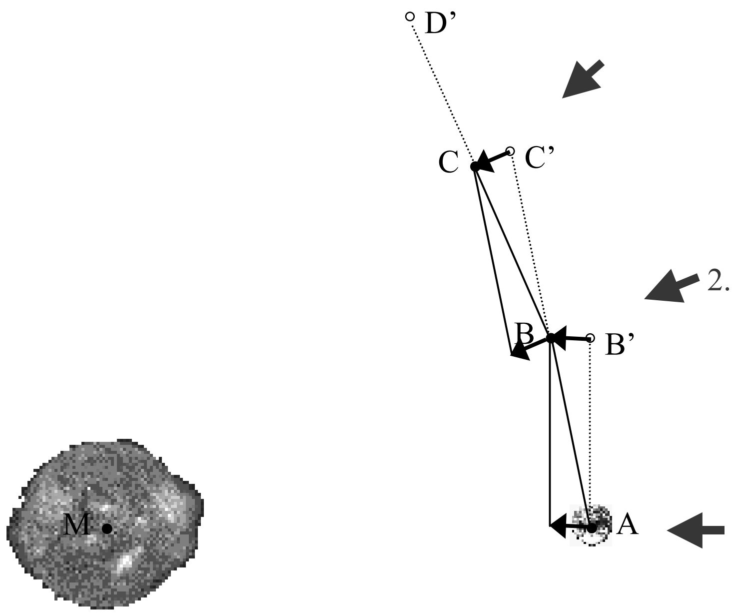


Figure 13: Two subsequent influences

This explanation is then illustrated with a computer model depicting a quick succession of constructions of positions of a planet, which is investigated in small groups. Students can then try to come to grips with this difficult constructing business by applying the (paper and pen) technique in one Newtonian (question 89) and one Keplerian (question 88) linear case. Help by the teacher during this work should emphasise the main point, that it is possible in principle to construct the motion from a given influence law, not the specific details.

Evaluation

The questions are discussed in which again the main point is emphasised. The quick and bright students can continue with investigating the effect of the time step size by changing this parameter in yet another computer model and observing its effects (question 90). These are that a smaller step size results in a more precise and more fluent trajectory.

5. Evaluation of models and *types of model* in the light of achieving broader applicability.

The third main theme, evaluation of models and types of model in the light of achieving broader applicability, contains three episodes that will be subsequently addressed.

5.1. Episode 3.1: Reflection on types of model

Function

Making explicit criteria for valuing models and types of model by a reflection on the first two main themes, resulting in a strategy for further investigation.

Justification of content and interaction structure (in the light of the function)

The reason for a reflection at this stage has been argued for before, see section 2.3 in this chapter. The function of the reflection is to make students realise what still needs to be done, which is finding a way to answer which type of model explains best. For this they have to remember what the goal is, namely understanding what explaining motion entails, and what has already been achieved, namely investigating two feasible alternative specifications of the explanatory scheme (see chapter 4, section 2.3.3). Such a reflection can be guided by questions that simply ask students to write down the previous main points of the course. Each question addresses one main point, thereby already indicating what the main points were and as such structuring the students' responses, making it easier to evaluate these points.

The context for the main activity of reflecting in stages on the first two main themes is prepared by simply announcing that this episode is about looking back on the main points. This is an important and for students difficult episode. The difficulty lies in expressing the main points that involve the structure or main thread instead of the particular details. Because of this difficulty a real weighty interaction structure like thinking-sharing-exchanging in which a lot of interaction can take place, helping each other in clearly expressing one's thoughts, seems in order. The evaluation of the individual students' answers (which are the result of the thinking phase) takes place in two steps: First they compare their answers in small groups. In this way already some gaps and uncertainties are remedied. Second the results of the groups are exchanged in class. The teacher checks whether the answers are complete and clear and can address possible remaining difficulties. Furthermore he explicitly adds the criterion of broad applicability as a help to find a strategy for further investigation.

Expected unfolding of the episode

Introduction

The teacher introduces this reflection by remarking that in order to decide how to continue it would be useful to look back for a moment.

Main question and answer phase

The reflection is guided by the following questions that are first answered individually (thinking), than shared in small groups (sharing) and then evaluated in class (exchanging):

44. What was the main question? With what did it all start?
45. a. What was the explanatory scheme for motion? b. What was its purpose? What was it good for?
46. We looked at two kinds of model: Keplerian and Newtonian. Those were examples of specifications of the explanatory scheme for motion. We also looked at different examples of Keplerian models. And also of Newtonian models. a. In what did these Keplerian models differ? In what did the Newtonian models differ? b. In what did these two *kinds* of model differ?
47. a. Why did we investigate all these (Keplerian and Newtonian) models? b. How did we do that? c. What have we learned from it? Do these models work?
48. The Newtonian model with the influence law $I=H_{earth}\cdot H_{sun}/r^3$ did not provide a match between modelled and observed earth. a. What conclusion can you draw from this lack of matching? b. What does this say about the Newtonian specification of the explanatory scheme in general, that is to say the Newtonian kind of model?
49. Have these two alternative kinds of model the same value? How might we answer such a question? What would we need for such an answer? On what grounds can one choose for a particular model? And on what grounds can one choose for a particular *type* of model? These questions can help you for the assignment: Write half a page in which you argue for your choice of *type* of model.

In answering these questions students make a summary of the preceding part. All main points are captured in these questions. After all the modelling work of the previous couple of lessons students can be expected to, if not appreciate, then at least not be hostile towards looking back on what has been achieved so far.

Evaluation

In the sharing phase of the evaluation the students share in small groups their answers to questions 44 – 49. Here they are expected to complete missing elements in their answers and try to reach agreement within their groups on what proper answers should be.

In the exchanging phase the findings of the groups are exchanged in the class. Possible wrong or incomplete group answers can now be corrected or completed. The conclusion that both kinds of model can be argued for at this stage also provides the basis for the continuation in the next episode. (If the choice would have been settled already, there would be no point in continuing.) The teacher should ensure that the mentioned conclusion surfaces in as close a connection to the students input as possible, which is, needless to say, quite a challenge. He also introduces (or if possible even points out in some group response) the additional criterion of broad applicability that will allow for a feasible test of the types of model by applying them to other motions, e.g. motions on earth. In that way the still open question of which kind of model is to be preferred can perhaps be answered as will be tried in the next episode.

5.2. Episode 3.2: Introduction to a choice between types of model for a situation on earth.

Function

Valuing types of model (Newtonian and Keplerian) by applying the criteria to a situation on earth.

Justification of content and interaction structure (in the light of the function)

The choice for situations on earth to apply Kepler and Newton to was guided by the following consideration: The application must lead to obvious difficulties in the case of Kepler and not so in the case of Newton and the motion must be simple, therefore some well known or easily accessible motion with only one or two dominant influences. The number of examples should be more than one to prevent the notion that the one example is some special case, but not too many to avoid repetition.

The two examples that were used were of a bicycle rider first riding with constant speed and then slowly decelerating after she stops pedalling and of a hovercraft gliding with constant speed (after a little push) and then accelerating after the propeller is turned on.

Comparing the size of the influences working in the first part of the example of the bicycle rider (where the object moves with constant speed) should lead to the observation that according to Kepler, solely focussing on the motion itself, there has to be a net forward influence. Therefore the forward influence has to be larger than the opposing influence. According to Newton no net forward influence is needed and therefore forward and opposing influences balance. Both a plausible forward and an opposing influence can be identified, namely pedalling and friction. Without measuring these influences both the explanations of Kepler as well as Newton might properly account for this motion. This picture changes in the second part of the motion. Here the bicycle rider decelerates. This motion still requires a Keplerian net influence in the direction of motion, whereas it requires a Newtonian net influence in the opposing direction. (Both predictions can be shown by graphical constructions similar to those exercised in episode 2.5). The only plausible influence that can be identified from an interaction theory perspective is opposing friction, which is in accordance with the Newtonian explanation, but in sharp contrast with the Keplerian explanation. The Keplerian model even predicts instantaneous reversal of the direction of motion the moment the pedalling stops when only an opposing influence is identified, which is clearly in sharp contrast with experience. This example can therefore plainly show a shortcoming in a Keplerian model.

A similar account can be given for the other example of the hovercraft: Comparing the size of the influences working in the first part of the example of the hovercraft (where the object moves with constant speed) should lead to the observation that, solely focussing on the motion itself, according to Kepler there has to be a net forward influence. Therefore the forward influence has to be larger than the opposing influence. According to Newton no net forward influence is required and therefore forward and opposing influence balance. The only ‘plausible’ forward influence that can be identified is the push with which the hovercraft started. A plausible opposing influence is friction. Here for some students the Keplerian model might already show some shortcoming, given the for them implausible ‘aftereffect’ of the push, but I expect that most students will not see anything wrong in attributing this aftereffect to the push.

In the second part of the motion the hovercraft accelerates. This motion requires an increasing Keplerian net influence in the direction of motion, whereas it requires a constant Newtonian net influence. The only plausible influence that can be identified from an interaction theory perspective is the influence from the propeller, which is not continually increasing. This is therefore in accordance with the Newtonian explanation, but in contrast with the Keplerian explanation. This example can therefore clearly show a shortcoming in a Keplerian model.

It can be remarked that the Keplerian model might be improved so that it can also account for these kinds of motions. One can for instance allow for Keplerian influences to exhibit an aftereffect. However, the Newtonian model did not require any adaptation and scores therefore better on the criterion of broad applicability.

The conclusion that Kepler leads to problems, whereas Newton does not in the evaluation should surface without too much difficulty, so that the teacher’s role there is mainly taking stock of the group answers, so a suitable interaction structure here would be ‘taking stock’.

Expected unfolding of the episode

Introduction

In the introduction the main thread is emphasised, that by applying Kepler and Newton to situations on earth we try to find out more about the value of these two types of model.

Main question and answer phase

Students then work in a group on one example guided by the following questions (there are two groups in all, the bicycle group and the hovercraft group):

> 50. Consider the case in which you cycle with constant speed. In this case there is a forward influence because of your pedalling and an opposing influence by the air, the surface et cetera. What must be the case according to a Keplerian model? Clarify your answer.
>
> - The forward influence is smaller than the opposing influence
> - The forward influence is equal to the opposing influence
> - The forward influence is larger than the opposing influence
>
> 51 is a similar question concerning Newton.
>
> 52. Consider the situation in which you stop pedalling. A fair assumption would seem to be that the forward influence is gone and only the opposing influence remains. What kind of motion does a Keplerian model predict? In which direction? Accelerating, decelerating or constant? Clarify your answer.
>
> 53 is a similar question concerning Newton.
>
> 54. If according to you one or both types of model predict a wrong motion, could that model be adjusted in some way so that it predicts the right motion?

The hovercraft group answers similar questions 60 – 64 (60 corresponding to 50 et cetera) that were of course slightly adapted to fit the other example. These questions are expected to trigger the considerations mentioned in the justification part of this section.

Evaluation

The groups' findings are then exchanged so that everyone has seen two examples. Students then answer the following three questions (e.g. in pairs) and thereby express the goal of this episode:

65. Why are Keplerian and Newtonian models applied to motions on earth?

66. What is your conclusion concerning the applicability of Newton and Kepler on a situation on earth?

67. You now have applied Keplerian and Newtonian models to an situation on earth and before that to the motion of heavenly bodies. What can you now say about the value of these two kinds of models in general?

I expect that these questions guide students to the conclusion that applying Kepler to these examples of motion leads to a problem in the sense of that it predicts a motion that is known not to occur. Newton does not give such a problem and is therefore broader applicable.

The teacher can sharpen the answers keeping the criteria plausibility, empirical adequacy and broad applicability in mind. He can then end by stating that since we now value Newtonian models more than Keplerian, we can try to solve the initial asteroid problem using a Newtonian model (with the best influence law we encountered).

5.3. Episode 3.3: Asteroid problem, mechanicism and transition to the regular course

Function

Further illustrating the power and range of Newtonian motion models, as well as finding a concrete answer to the initial asteroid problem (or similar problem).

Justification of content and interaction structure (in the light of the function)

By now students should have sufficient elements to solve the asteroid problem with a computer model of an asteroid moving towards earth. Since they cannot be expected to build such a model from scratch they are presented with a prefabricated model of the earth moving around the sun and an asteroid moving in the direction of the earth. This model allows the students a lot of freedom in changing parameters like the starting positions and velocities of the earth and asteroid, which is a new element for students in this computer model. Whether the two shall meet depends entirely on these starting conditions. The masses of asteroid, earth and sun can also be changed. This does not effect the motion as long as the mass of the asteroid and earth remain much smaller than the mass of the sun[4]. Another new element in this model is that students are meant to actively explore the model code itself, depicted in the model window (see Figure 14 in

[4] Both sun and earth, or sun and asteroid, rotate around their mutual centre of mass, which in this case is practically on the same spot as the centre of mass of the sun.

which only part of the code is displayed), to convince them that this model is in fact a proper Newtonian model for such a motion.

Part of this investigation is recognising all the elements of a Newtonian[5] model they have encountered so far and have 'collected' in their summarisation figure, like influence laws, the assumption that laziness = heaviness = mass et cetera. Although students are unfamiliar with the model code as it is used in Modellus, I expect them to recognise for instance three influence laws in the section of the code depicted in the model window in Figure 14. In the same manner the other elements can be recognised. In this way students can realise that with this particular specification of the elements of the explanatory scheme the motion of an asteroid can be calculated correctly, thereby solving the asteroid problem and showing that such a model, together with the proper starting values is all that it takes for calculating such a motion, which shows its power.

The mechanicism part is introduced as yet another reason why mechanics is important, namely the notion that understanding mechanics is a crucial ingredient for understanding all events. To begin to appreciate what this notion means students can be led by some questions through an example of a microscopic explanation of a macroscopic phenomenon, namely the dissolution of sugar in tea. This example shows how the macroscopic phenomenon of dissolution can be understood in terms of moving and interacting but otherwise unchanging particles. After such an example students are expected to have a first glimpse of the possibility of extending this notion to other and perhaps all events. In that case understanding mechanics would be an important ingredient for understanding all events, which would increase the range of mechanics even further.

The transition to the regular course can then be made by recalling the result of the introductory course by returning to the reflection in episode 3.1. The highlights of this reflection can be brought back to mind by the following three questions: 'What is the use of this introductory course?', 'What can we do with this introductory course?' and 'What are we going to do in the regular course?' The teacher can also give a preview of how this will be used in the regular course. Since with the Newtonian specification of the explanatory scheme in principle all motions can be explained, we will continue in the regular course with this specification and study new influences, influence laws and how they can be applied.

This episode can be introduced by stating that three topics still remain, namely solving the initial asteroid problem this introductory course started with, an additional argument for why mechanics is important that returns to the earlier seen dissolution of sugar in tea example and an outlook on how the subject of mechanics will be continued. In the evaluation the teacher first checks whether the students really consider the asteroid problem solved, for which taking stock of their answers should suffice. Secondly, he concludes that a microscopic explanation of a macroscopic phenomenon can be given, which is further extended to conjecture the possibility that all phenomena might be explained in this way, which makes mechanics an important tool. This conclusion takes more work than only taking stock of answers, I expect. Thirdly the three reflection

[5] By now the reason for choosing Newtonian models should have become clear.

questions can be answered in a class discussion where the teacher ensures that the main points surface clearly and adds the preview to the regular course himself. Since the evaluation of the three elements in this episode involves quite some teacher input the interaction structure ‘concluding’ seems appropriate.

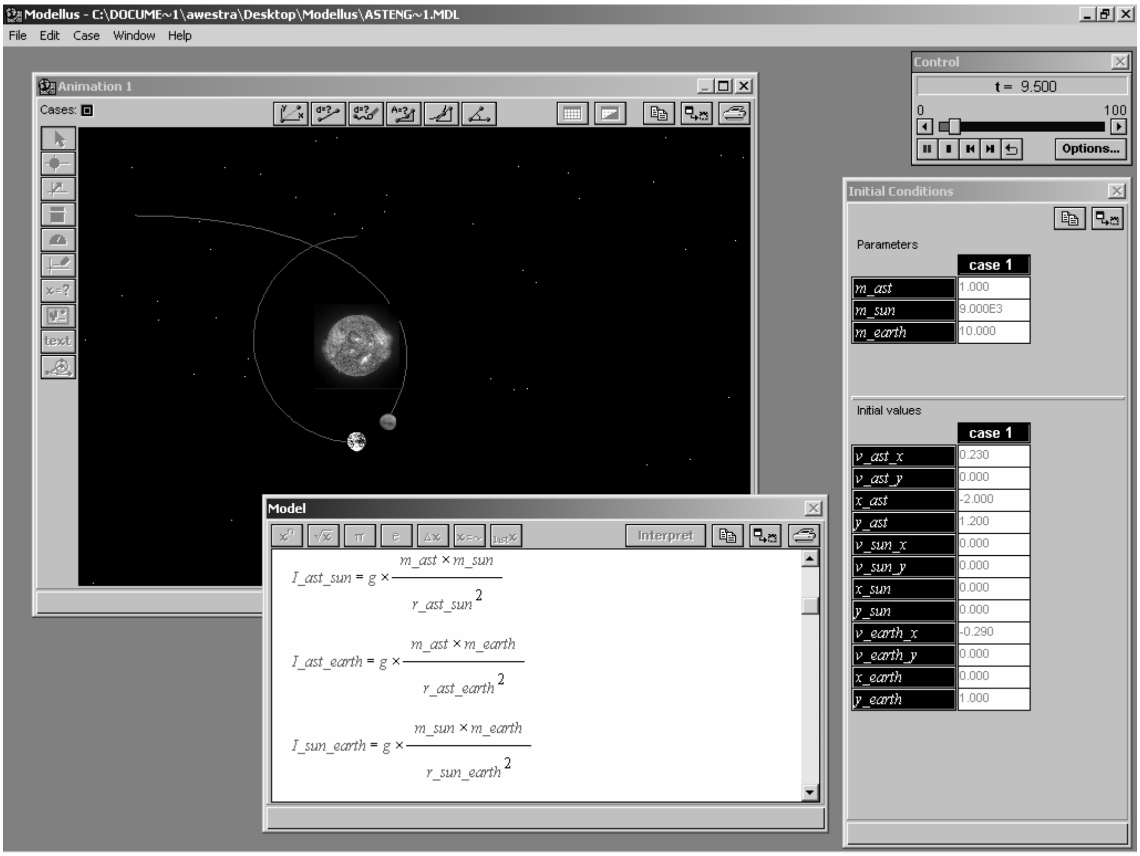


Figure 14: Newtonian motion model of the motion of an asteroid moving towards earth.

Expected unfolding of the episode

Introduction

This episode is introduced by recalling the initial asteroid problem and the (implicit) promise that this problem would be solved in this introductory course. This can now be tackled using a Newtonian model with the best influence law we encountered. Furthermore an additional argument for why mechanics is important will be encountered that returns to the earlier seen example of the dissolution of sugar in tea.

Main question and answer phase

A lot of questions guide students through the computer model code, which they see for the first time, although some of it has been demonstrated in episode 2.2. Take the following excerpt from the students’ booklet:

> The Modellus model aster.mdl contains a Newtonian model of sun, earth and asteroid. We will first see if we can retrieve in this computer model all elements that are needed for an explanation of motion.

> 68. **Influences**. The only working influence according to Newton is gravitation. In the model window you can find three influence laws. Look them up. In which form are they here?
>
> 69. Why three?
>
> 70. Are you satisfied with this choice of influence laws? When you consider other laws to be better, you can use these. Change them in the model window and write down your other choice with your reasons.
>
> For the **relation influence – motion** Newton adopted the rule deviation = influence/laziness.
>
> 71. Find the rule deviation = influence/laziness in the model window. In what form do you find it here?
>
> 72. The **assumption laziness = mass** and **heaviness = mass**. Where do you find this in the model window?
>
> 73. Are there elements missing in this computer model that are required for a Newtonian explanation for motion? If so, which?
>
> Initial values that you can change are the masses, initial positions and initial velocities of earth, asteroid and sun. For example the initial velocity of the earth can be changed by adjusting the value for v_earth_x (velocity (v) of the earth (earth) in the x-direction (x)) and v_earth_y (velocity (v) of the earth (earth) in the y-direction (y)).
>
> 77. Try to find several initial values for the positions and velocities of earth and asteroid that result in a collision after some time. Write down the values you have found.

Question 68 – 73 guide the students in finding the elements of their status diagram (here printed in bold). The reason that three influence laws can be found is that there is one for each interaction between sun and earth, sun and asteroid, and earth and asteroid. Question 73 is meant to provoke the answer that the influence free motion is not explicitly found in the model window. This does not mean that it is not there at all as can be tested by making the influence zero and observing the resulting motion. Question 77 is meant to make students realise that the collision of earth with an asteroid depends entirely on the initial conditions. When these are known the motion can be predicted.

The following paragraph in the student booklet wraps this investigation up:

> We have looked into what explaining motion as a special case of explaining in general entails. We are now able to exactly explain and predict some important motions. There are however more reasons why mechanics could be important.

After which the topic of mechanicism follows.

Students read a text in which mechanicism is introduced as the belief that science can explain all events in terms of moving and interacting particles. To come to grips with what this entails students look into the example of sugar dissolving in tea. They answer questions about what they imagine these particles to be like (question 82), what will happen with the particles during dissolution (question 83), why this would explain the observed phenomenon that solid sugar 'disappears' (question 84), why dissolution would go quicker when the tea is stirred (question 85) and why the dissolution would go quicker when the temperature is higher (question 86).

I expect the students to come up with perhaps ingenious answers to questions 82 – 85. The last question is probably too difficult. It is meant to show that a plausible answer is possible, although it may have to be brought in by the teacher. Students then read a text in which this notion is extended to be perhaps applicable to all phenomena, using also the famous quotation of Laplace:

> "We ought then to consider the present state of the universe as the effect of its previous state and as the cause of that which is to follow. An intelligence that, at a given instant, could comprehend all the forces by which nature is animated and the respective situation of the beings that make it up, if moreover it were vast enough to submit these data to analysis, would encompass in the same formula the movements of the greatest bodies of the universe and those of the lightest atoms. For such an intelligence nothing would be uncertain, and the future, like the past, would be open to its eyes.
>
> The human mind affords, in the perfection that it has been able to give to astronomy, a feeble likeness of this intelligence. Its discoveries in mechanics and in geometry, joined to the discovery of universal gravitation, have enabled it to comprehend in the same analytical expressions the past and future states of the system of the world. In applying the same method to some other objects of its knowledge, it has succeeded in relating observed phenomena to general laws, and in anticipating those that given circumstances ought to bring to light. All these efforts in the search for truth tend to lead the mind continually towards the intelligence we have just mentioned, although it will always remain infinitely distant from this intelligence. This tendency, peculiar to the human race, is what makes it superior to the animals; and their progress in this respect distinguishes nations and ages, and constitutes their real glory".
>
> (Laplace, 1995)

Evaluation

The teacher takes stock of the students' answers concerning the asteroid problem and checks whether they consider the asteroid problem solved. He then takes stock of some answers concerning the mechanicism part and concludes that at least in this example a macroscopic phenomenon can be explained using the notion of moving and interacting constituting particles. The teacher then addresses the following questions quite briefly:

- What is the use of this introductory course?

In answering this question the following points should surface: We now know what explaining motion entails. We know what is needed for that, namely a concrete specification of the elements of the explanatory scheme. The Newtonian specification can be preferred for several reasons.

- What can we do with this introductory course?

In answering this question the following points should surface: We can in principle, although not in practice, explain all motions, for example the motion of the asteroid moving towards earth the course started with.

- What are we going to do in the regular course?

In answering this question the following points should surface: In the regular course more influences and influence laws will be encountered. We will mainly look into situations in which the net influence is constant, because in those situations the motion can be calculated using pen and paper, which will prove to be difficult enough. Furthermore the concepts to which several terms used in the introductory course will develop (like the term 'influence' developing to the concept 'force') are introduced, see Table 3 in section 2.3.3. in chapter 4.

6. Concluding remarks

This concludes the detailed description of the episodes within the first three main themes. The main thread of the introductory course as described on a quite general level in chapter 4 had been detailed into episodes with related analysis questions in section 2. An important point I hope has been made clearly there is how the subsequent episodes within each main theme contribute in fulfilling the function of the main theme (and finally the introductory course). The episodes have been detailed even further in sections 3, 4 and 5 where again I hope has become clear how the activities within each episode contribute to fulfilling the episode's function. Here also each episode was connected to a suitable interaction structure, where the decisive argument for choosing one interaction structure over another was seen to lay mainly in the difficulties in the evaluation part, and therefore the required teacher input, that were expected.

In chapter 6 the intended teaching/learning process described here will be compared to the actual teaching/learning process that took place and the related analyses questions from section 2 will be answered.

Chapter 6

Results

1. Introduction

In this chapter the analysis questions are answered. For this the executed teaching/learning process is compared to the intended teaching/learning process as written down in the scenario (chapter 5). For each episode I will describe what happened in the introduction, main question and answer phase, and evaluation, insofar this is relevant for answering the analysis questions as stated in chapter 5, table 1, 2 and 3. I will then answer these questions and finally draw some conclusions regarding the episode and discuss possible improvements in the design of the episode. After all episodes within the first main theme (section 4) have been treated in this way I will draw some conclusions regarding this main theme. The same process is then repeated for the second and third main themes in sections 5 and 6 respectively.

The choices for interaction structures will be discussed in a separate section, section 7, instead of including it in the discussion of each episode, because that would involve too much repetition.

Section 8 contains an account of main theme 4, embedding in the regular mechanics course, for which advice in the form of a link-manual had been given. Here some results of and experiences with the link-manual are reported. Additional information concerning possible use of the introductory course in the regular course was obtained from interviews during the regular course in which mechanics problems were discussed using elements of the introductory course. The design and results of these interviews will be presented here.

Before showing the results of the introductory course, I will present the results of the preparation of the teacher in section 3 and start in section 2 with a more concrete description of the methodology including the kind of data that were collected, how they were analysed and how they will be presented.

The evaluation of classroom practice in this chapter includes sometimes rather critical comments on the design itself but also on the execution of the design by the teacher. These comments resulted from a cool analysis of the classroom practice from behind a desk in the quiet environment of a university building long after the heated confusion and hustle and bustle of a normal secondary school[1] in which the lessons took place. The teacher had to execute the scenario, manage his class and all intrusions from colleagues and other students and decide in the spur of the moment how to react to what happened in line of the scenario and all other considerations. The fact that the scenario was and is still in development and therefore lacked in clarity did not help. The critical comments in this chapter should therefore not be seen as criticism of the teacher personally but of the teaching/learning process as laid down in the scenario and as criticism of the way the teacher was prepared.

[1] People who happen to visit both kind of places know that the differences can be striking.

2. Methodology

In addition to what I said about the used method in chapter 3, section 3, I will present here more concretely what data were collected, how they were analysed and how they will be presented in this chapter.

Data sources and collection

The whole class sections of each lesson were video taped. The teacher and researcher carried an audio recorder at all times, recording all teacher - student or researcher - student interactions. Furthermore student - student interactions during group work (or work in pairs) were recorded on audio. Since the class consisted of only seven students (five girls and two boys), this amounted to not more than five or six (1 teacher + 1 researcher + 3 or 4 pairs) audio tapes per lesson. After each lesson students' written materials were photocopied. Each lesson was shortly discussed with the teacher before and after the lesson of which no recordings were made. Finally, I made notes of my observations in each lesson. In all, this is a plethora of data. After the introductory course students filled in a questionnaire about how they had experienced the course. I also conducted two different kinds of interviews afterwards. The first concerned students recognition of the main thread of the course and consisted mainly of questions like 'why did we do this particular section?' and 'why did we do this after that?' The second kind of interview aimed to find indications of recognition and application of elements of the introductory course in the regular course.

Data analysis

The scenario was an important tool in the analysis, for it contained the means to compare the observed teaching/learning process to the expected one, which was written down in the scenario, and the analysis questions and therefore guided the determination of what data was relevant and what not. For each episode several analysis questions were formulated, see chapter 5. I tried to answer these questions using the available data, which were organised in so-called 'lesson reports' to facilitate this. In these lesson reports possibly relevant discussions between teacher and students or between students among themselves were transcribed. Also students' written answers were summarised. Furthermore they contained my observations and preliminary comments on possible interpretations, relevant examples and first rough conclusions. Lesson reports can be seen as somewhere in between raw data and the results presented in this chapter for which they provided the basis. Lesson reports resulted in an average of 24 pages for each lesson with a total of 13 lessons including one lesson spent on a test, which is reduced in this chapter to about 45 pages. More on the presentation and selection of data follows in the last part of this section.

Answering analysis questions using the mentioned lesson reports amounted to first selecting the relevant episode in the lesson reports (and sometimes also data from one of the two interviews after the course), then comparing these data to expected responses and comparing different sources, for instance students' discussion of, written answer to and teacher help given in, some particular assignment. Using different data sources adds weight to one's interpretation, for obvious reasons.

My answers to the analysis questions were read by a second researcher who had access to the lesson reports and who went through the process of selecting and interpreting relevant data from the lesson reports in order to arrive at answers to a subset of analysis questions. In discussing these interpretations and answers we usually reached agreement.

A big problem in this process was when the execution of the episode deviated strongly from the design. In those cases it was much harder to arrive at sound conclusions about the scenario, since the intended design was not fully put to the test and only very tentative answers to analysis questions could be given.

Data presentation

Not all data on which I based my conclusions can be meaningfully reported here, for obvious reasons. I will present those findings that I deem sufficient for an interested reader to be able to follow and possibly (dis)agree with my conclusions, or at least allow raising in this reader the right kind of (critical) questions.

In my description of the results of the first couple of episodes I will use an abundance of examples to give the reader some impression of the sort and amount of data on which my conclusions are based. In later episodes I will restrict myself more to the findings themselves, only illustrated by one or two typical or merely illustrative examples[2] from the original data sources. My choice of examples was also checked by another researcher who had access to the lesson reports and was intimately acquainted with the design. Only those examples we reached agreement on were used in this presentation of the results.

3. Teacher preparation

How I intended to prepare the teacher was described in chapter 4, section 3.3. In this section I will describe some deviations from that plan insofar they have a bearing on the *results* of the preparation, which is the main topic of this section.

The teacher preparation went according to plan to the extent that the teacher was prepared in three phases, of which the third and most important phase consisted of about eight sessions of approximately two hours each. (The first phase consisted of one meeting of about two hours in which I presented the course as a whole together with its basic ideas to the teacher. The second phase consisted of four sessions of approximately two hours each in which each part of the course was presented and discussed in more

[2] With a *typical* example I mean an example that is representative for the majority of instances which the example illustrates. Another example could have easily been selected, since it would show the same point. An *illustrative* example is an example that clearly shows a particular point I try to make and does not carry the burden of being *typical*. 'Illustrative example' is of course a strange way of putting things, since all examples mean to illustrate something. However, it is used here to distinguish it from 'typical example'.

detail.) In this phase the scenario as well as its practical implementation were discussed in detail. I intended to use interaction structures in the teacher preparation as a tool for designing the practical implementation part of the scenario for a number of reasons, amongst which making the preparation more two-directional, but unfortunately the teacher rejected the idea. I could not convince him of its use for improving the quality of the designed education. He did see the use for me as a researcher, but not for him as a teacher. That was not enough to engage in what he considered to be a gruelling job. His rejection is quite understandable. It *was* a difficult and time consuming job for which he did not see the purpose. At the time I was unable to make him appreciate the dangers of the experienced problems from the first trial (which were similar to those reported by Kortland (2001)). A for the teacher recognisable purpose would have consisted of some experienced shortcoming in his teaching for which the method of filling in interaction structures could be seen to provide a remedy. Firstly there was no experienced shortcoming in his teaching. He was by all normal standards of teaching a very good teacher of the usual courses he taught. The newly designed introductory course in mechanics he had not taught yet, so he could not have experienced any shortcomings there either. Secondly it is not self evident that the method of using interaction structures in the proposed way would remedy a possible teaching problem in the new introductory course. It can be argued that it does, but these arguments probably are only convincing for those that have experienced the problems, like I did in the first trial.

Although the teacher did not accept my proposal to write down a design for the practical implementation of the course content in terms of interaction structures, he did write a description of the implementation, which consisted of a very briefly stated lesson plan. In order to complete the scenario in which the practical implementation was still lacking, I used his description as a basis for filling in the interaction structures myself and adding those to the scenario. In the third phase we discussed the in this way completed scenario in detail. Given the extensive additions and changes I have made in the teacher's lesson plan that were necessary for filling in the interaction structures, my original goal of instilling some sense of ownership in the teacher is probably not met. The teacher's lesson plan gave very little feedback as to what had been understood about the meaning and intentions of the design. However, although substantial written feedback was lacking, the discussions of the scenario in the second and third phase of the teacher preparation were naturally more two-directional for the simple reason that the second teacher found the ideas behind the scenario and the scenario itself quite interesting and was therefore more actively involved in their discussion. From these discussions I got the impression that this teacher understood the main points as well as the details. However, such an impression is rather unsure. Written feedback in the form of a design for the practical implementation would have been a much more solid indication of what has been understood by the teacher.

The goal of arriving at a complete scenario including the practical implementation was met. We could therefore start testing a scenario that was pondered upon and justified in much detail, but with a teacher of whom it was not certain if he shared the meaning and intentions of the design and who did not own the design to the extent that was possible or desirable.

In the subsequent sections I will describe what results the various episodes brought.

4. The how and why of explaining motion

The following sections, section 4.1 through 4.5, concern the results related to the first main theme, the how and why of explaining motion. Each section starts with a description of what happened, followed by the answers to the analysis questions and ends with a conclusion on the level of episode and possibly some suggestions for improvement of the design. The analysis questions can be found in chapter 5, section 2 and will be numbered here accordingly from 1 through 25.

After the last episode of this main theme some conclusions on the level of main theme will be drawn. This structure is then repeated for the second and third main theme.

The reader may find it helpful to consult the episode descriptions in the scenario and the related analysis questions from chapter 5 when reading the following sections.

4.1. Episode 1.1: Introduction to the topic of mechanics

What happened?

One aim of the introduction was to enthuse the students. This the teacher seemed to have made happen, though perhaps more by his way of presenting than by what he said. At any rate, the students listened attentively. Concerning the content of the introduction let us look at the relevant fragment. (In the rest of the introduction the students are reminded to bring certain materials with them and a space shuttle accident is further discussed, leading to a discussion of dinosaurs, which is irrelevant for the function of this introduction).

1. T: We are going to talk about motion. What is motion? How does it work? How is it put together? Well, we know how motion is put together, don't we? Why something moves. Do you know that?
2. Car: Well, to go on.
3. T: Yes, but how can something go on? Or, and we proceed by following two people of very long ago when this all, when they thought, yes, not knew exactly how things were put together, with motion. And what you then have to do, of course, is think of some kind of theory. You have to think of, I think it 'll work in this way, and that you develop somewhat. Well, if you do one theory, you always think: this is it, of course. That's why we do two, of two different people who had different ideas and which we will, yes, 'think through'. Think through in the sense of think in the same way as they had done. From the same starting points. And we changed it a little and adapted it a little,
4. T: for it does not really concern these two people, that is also rather funny to know, but they are Newton and Kepler, which is not really the main point. The main point is what have they come up with? And how can you come up with these things? So you have to think of some theory and then check if it works in practice and we will do that using motions in the solar system. Why solar system? Well, that is what they started with too. It is of course very strange that the sun turns around the earth, or the other way around. And that it, yes how does it work? How can it be that that happens? And why does it happen in that way and not differently? They

came up with all kinds of thoughts on these things and that is what we are going to do too. [...]

5. T: […] Something moved in space recently, that went slightly wrong. What was that? Did something go wrong in space recently?
6. Lln: Space shuttle.
7. T: Yes. […]
8. T: How can that be? What could have gone wrong?
9. Chr: Wrong side, wrong entrance into the atmosphere.
10. T: Yes, how can that [go] wrong?
11. Chr: When it eh, when it, like, plunges into the atmosphere in a wrong curve...
12. Ll: It burns.
13. Chr: …then it burns.
14. T: Yes, yes, so that can…
15. Chr: It stays longer in the atmosphere and then, it ‘ll remain longer hot.
16. T: Yes, yes, that could be. What could be as well? (2s) I thought, it can have encountered something along the way. […]

[…]

17. T: […] All right, where we are going to think about for a moment is all those things that fly in space. All those fragments. Why would it be important to know how they fly?

When compared to the scenario several remarks can be made concerning the content of this introduction. According to the scenario the teacher should firstly introduce the topic of mechanics as ‘explanation of motion’, without addressing the content of explaining, but emphasising its theoretical importance. Secondly he should introduce the example of an asteroid moving towards earth, as an illustration of both the importance of being able to explain and therefore to predict motion and that explaining motions entails quite a lot.

This does not quite happen in (1). On the basis of the teacher’s questions moreover, a student seems to consider the topic rather unproblematic (2). The teacher’s follow-up question in (3) ‘Yes, but how can something go on’ cannot yet be a real question for students. The long account in (3) is rather confusing. What can students understand from ‘the things we have altered and adapted a bit’, or of the reason given for studying two theories, for example? The teacher then does give some outlook on what is going to happen in the course (4), namely thinking of some kind of theory and then checking if it works in practice using the motions in the solar system. According to the scenario, the example of an asteroid moving towards earth should be addressed. This does not quite happen from (5) onwards. The teacher chose another example, which is perfectly alright as long as it is equally, or even more, clear in making the intended point that explaining or predicting motion can be desirable and is not an easy job. However, this was not the case. The question the teacher poses is why it would be important to know the motion of rock fragments (17). The example of the space shuttle (5, 6) was at the time current, but did not emphasise prediction or explanation of motion.

In the ‘main question and answer phase’ students were expected to come up with some answers that would indicate that they knew what the topic was about (explaining/predicting motions), that this had some importance and that a lot is needed for this. Students responded to the questions roughly as expected. Written answers that were given in response to what other motions are important to be able to predict or explain (question 1) were for instance typhoons, earthquakes, day and night, collapsing of demolished buildings and the tides. These things, which can be described as 'major contrasts to rest', apparently came up when students thought about 'motion'.

What the topic was about was not immediately clear, since there was some confusion about the meaning of 'motion'. Take for example the following two fragments:

1. Jol: What kind of motions do they mean?
2. Chr: Well, if they indeed reach the earth.
3. Jol: Hm. (50s)

4. Chr: What does this mean: can you think of other motions?
5. T: Yes.
6. Chr: Is it not simply assertions?
7. T: No motions. Motions. Things that move. Look, those asteroids move and sometimes they encounter the earth and sometimes not. Yes? Well, that is an example. So it is important to know whether it will encounter the earth...

Jolien expressed uncertainty about the kind of motions the question refers to (1) and is not convinced by Christiaan's response (2). Christiaan himself was equally uncertain, for some moments later he asked the teacher what is meant by motions (4) and even suggested that something else could be meant, namely 'assertion' (6) (in Dutch the words for motion 'beweging' and assertion 'bewering' are quite similar). The teacher's response that what is meant by motions is 'things that move' seemed to satisfy these students.

The spectrum of responses to the question what would be needed for such a prediction or explanation of motion and what could be meant by (and needed for) 'calculating' motion (question 2) included (the number of students that wrote a particular item down is written in parentheses behind the item): Measuring equipment (2), investigation of earlier asteroids that had hit the earth (3), simulations (2), the response of Merlijn (see below) or the response of Mick (see below). What is calculated is the trajectory (7) and the speed (4), for which is needed things as (initial) speed (2), changes in direction (1), the size of the asteroid (1), data from motion of other asteroids (5), data, rules or formulas (3), the manner in which the asteroid moves (1), influence of other asteroids (1), air pressure (1).

From the questions to the teacher and me that were posed in the lesson follows that students were not content with and certain about the given answers. From these answers can become clear that what is predicted is the trajectory of the asteroid and its speed and that it somehow includes calculations for which several useful intuitions surfaced, including the kind of data and required rules or formulas.

The purpose of the evaluation of these answers was to make sure that the intended conclusions, that precisely predicting or explaining motion is both important and difficult, surface by highlighting such answers that already contained them or adding to answers that did not. This was not done by the teacher, although sufficient student input was available. Take for example the response of Merlijn to question 2:

1. T: Yes. How does the predicting or explaining work?
2. Mer: Well, I've got the explaining with mathematics or physics. Then you calculate it. And by investigating.
3. T: Yes.
4. Mer: And prediction: the speed, starting point, magnitude of the thing, where it goes to and the larger the object is, the more difficult it will change its speed direction or something like that.
5. T: Yes, so you say like, a real motion of [this] thing eh. That is the speed, there it is. And with mathematics, physics you simply mean calculating with formulas, put things in and get things out.

As expected, Merlijn's answer is pretty vague, but does indicate that explaining involves quite a lot including mathematics, physics, investigation (2) and knowledge of specific conditions like speed and starting point (4) in which already a first regularity relating some condition (in this case the size of the moving object) to its change in direction or speed is found (4). At this stage it would be premature to address this last remark. Instead of emphasising the conclusion that explaining involves quite a lot and adding to this that it is therefore quite difficult and challenging, the teacher repeats her answer and adds to this his reading of what she meant by 'mathematics and physics' (5).

The point that predicting motions can be important would have needed more drawing out by the teacher, take for example Mick's response to the first question:

1. T: Right, do explain. Question 1 if you please.
2. Mic: [Reads aloud] Rotation of the earth, the answer is, people would like to know when it will be day and night. And eh, for example the seasons. On one side the sun is standing more to the north of the earth.
3. T: Yes.
4. Mic: Asteroid move towards earth. They like to know whether the earth is hit. Because people like to be prepared. And not be made afraid unnecessarily.
5. T: Yes. (many?) examples. And you?

The examples Mick mentions are at face value not very useful for illustrating the main points. Predicting day and night or seasons (2) is not particularly hard to do and it is not clear why it would be important. However, follow up questions might have led to the main points, for instance 'what is being predicted?', 'is this really predicting?', 'which motions are we talking about?' and 'why do you consider these important?'. (Mick does indicate why prediction of asteroids would be important, namely people like to be prepared (4)). With questions like these the point that predicting motion could be important may surface.

According to the scenario the teacher also should initiate a discussion (related to question 2) about what might be needed for *calculation*-based explanations or predictions. This did not happen, although the written answers to question 2 showed promising leads, like the mentioned data, formula or rules.

So some opportunities for explicating or drawing out the intended conclusions were lost. Unfortunately the raised uncertainty about how explaining works has not been made explicit as such by the teacher, thereby giving a sense of direction, e.g. by saying that these kind of questions will be the topic of study in this course.

Answering the analysis questions

1. It has to be pretty vague at this stage what is meant by explaining motions and also why that may be important, since both the introduction and evaluation did not focus on this point to the extent that was intended and possible. Students did get some impression in the introduction and did mention (implicit) reasons for the importance of what they thought to be the topic. In all they did seem willing enough to continue.

2. Explaining is not considered to be a simple matter, since students are aware that it involves numerous things. However, its difficulty and that it involves calculations has not yet been sufficiently emphasised and it is uncertain whether this is recognised.

Suggestions for improvement

There are no indications that the design needs to be changed, except for a reformulation of question 1. Question 1 did not focus on motions. A better formulation of this question would therefore be:

> Question 1: Of which other things would it be important to know how they continue their motion?

4.2. Episode 1.2: Triggering the general explanatory scheme

What happened?

It was intended that in the introduction a transition should be made from *why* one would study explaining motions to *how* this explaining might work. The teacher did not do this.

According to the scenario, in the main question and answer phase the general explanatory scheme is gradually triggered as a useful way of looking at some given examples of explanations. The examples concerned three explanations, attributed to Kees, Els and Jostein, of the dissolution of sugar in tea, which were expected to clearly illustrate the general explanatory scheme. The related questions of what these three people (dis)agree on (question 3) and what they explain and how (question 4) were discussed in groups of 3 or 4 students. The common written answer to question 3 was that Kees, Els and Jostein agreed on the fact that sugar dissolves and disagreed on the speed in which it dissolves. This was unexpected. I expected that students would have had some notion that Jostein and Els not necessarily disagreed, but that they would have found it difficult to express this notion. In response to question 4 students wrote that Kees, Els and Jostein explained in different ways that sugar dissolves. As an answer to how they do that the statements of Kees, Els or Jostein were repeated. Apparently this was found to be difficult to express, as was expected.

Whether the general explanatory scheme can be triggered quite naturally depends on whether question 3 and 4 triggered statements in which the teacher could recognise elements of the explanatory scheme. For this the written answers did not suffice and I had to look into the recorded discussions to see which statements were triggered by question 3 and 4. The relevant audio fragments were found by selecting the sections where students discussed question 3 and 4 and searching for keywords indicating talk about causality like ‘because’, ‘hence’, ‘why’, ‘so’, ‘for’. I found three relevant fragments in the two groups. For each group I will first display the fragments and then discuss them.

Group 1, first fragment

1. Nic: So, it is right that those, those Kees and Jostein say, no, no, Kees and…
2. Ros: Els
3. Nic: …Els, yes, say that it therefore, that it slowly dissolves. And how that is reached. And Jostein says that it dissolves quickly and he also says what the cause of that is.
4. Ros: But what do they *explain*?
5. Mic: But does Els say that it quickly dissolves? Or doesn’t quickly dissolve, but of why.
6. Ros: ‘It dissolves quite fast.’
7. Mic: No, Els. You should have stirred. But then she does not explain why it does not dissolve quickly.
8. Ros: Yes, she does, because they do not stir, it does not dissolve quickly, according to her.

Group 1, second fragment

9. Ros: Kees just says sugar is dissolvable. (2s) That is his explanation.
10. Nic/Ais?: Ok.
11. Ros: Isn’t it?
12. Mic: Well also. Just say it slowly falls apart, it is dissolvable.
13. Ros: But that is no explanation. That is just something he sees. You have to say why he says that it falls apart, in my opinion.
14. Nic: Yes, ok.
15. Mic: Just say it slowly falls apart. It is dissolvable.
16. Nic: Jostein says that the tea is very hot, but that doesn’t make sense either.
17. Mic: No, but he explains it in that way.
18. Ros: Yes, he does, but it is the warmer that thing …
19. Nic: Yes, that is so, ok.
20. Ros: … the tea is.
21. Mic: Jostein: the tea is hot.
22. Ros: And there hav…
23. Nic: Els.
24. Ais?: Sugar.
25. Ros: Shouldn’t there be, shouldn’t we add ‘and how quickly it goes’
26. Nic: Yes.
27. Mic: Yes?
28. Nic: And Els is eh. If you want sugar to dissolve you have to stir.
29. Ros: Els.
30. Nic: No, if you no.
31. Ros: Can you sooner, or you haven’t stirred. (4s)

32. Nic: What, you haven't what?
33. Ros: You haven't stirred. There was no stirring. That's why it goes more slowly.

Discussion of these fragments: In their descriptions of how explaining works basic elements of the explanatory scheme can be recognised. Nic formulates this as 'and how that is reached' (3) and 'what the cause of that is' (3). This points in the direction of a causal factor or a regularity (which is almost the same thing, see chapter 3 section 2.1). When Mic objects that Els does not answer the question why it doesn't dissolve fast (5, 7), Ros counters by mentioning a causal factor: 'Yes, she does, because they do not stir, it does not dissolve quickly, according to her' (8). When Nic seems to protest that Jostein also doesn't give an explanation (16), Ros counters again by giving a causal factor: 'Yes, he does, but it is the warmer that thing, the tea is…' (18, 20). In both cases Mic and Nic seem to accept Ros's argumentation. They do not continue objecting and they actively add a causal factor: Mic mentions in relation to Jostein the factor 'hot' (21) and Nic in relation to Els the regularity 'If you want sugar to dissolve you have to stir' (28). An element of the explanatory scheme that I only implicitly recognise is the element of comparison of two situations. It was not said, for instance, 'if the tea would have been colder, it would not have dissolved as fast' or 'if one had stirred, it would have dissolved faster'. Ros is getting close when she uses a comparative degree in her half finished regularity: 'Yes, he does, but it is the warmer that thing, the tea is…' (18, 20). And when she corrects Nic's regularity: 'You haven't stirred. There was no stirring. That's why it goes more slowly' (33)

Group 2

1. Mer: How do they explain it? By looking, isn't it. Different ways.
2. Jol: The one says you have to stir.
3. Mer: The one says: it slowly falls apart.
4. Car: Yes, the other says that it is very hot.
5. Chr: They just think (…), they think about the properties of tea and sugar. And then they think of yes the one thinks that really hot sugar falls apart and the other (says) because you stir. Does fall apart.
6. Mer: Oh yes.
7. Car?: Yes.
8. Jol?: (…)
9. Mer: I don't know too. I think about the properties of tea and sugar.
10. Car?: Because tea is hot.
11. Mer: Yes
12. Car?: And sugar dissolves.

Discussion of this fragment: Also in the discussion of this group elements of the explanatory scheme can be recognised. Jolien and Carlijn start by mentioning 'stirring' (2) and 'very hot' (4), that Christiaan tries to characterise more generally as 'properties' (5). At least Christiaan and Carlijn seem to be using these as causal factors: 'because you stir' (5) and 'because tea is hot' (10) respectively. The fact that they only talk about Jostein and Els suggests that the students in group 2 implicitly question whether Kees explains anything at all. I do not recognise explicit mentioning of a regularity, neither the comparison of two situations as elements of the explanatory scheme. (They are implicitly contained in the idea of causal factors).

So question 4 did seem to do the trick in triggering talk in which elements of the explanatory scheme can be recognised (the missing explanatory scheme element of a comparison is taken care of in later questions, so that need not trouble us here). No elements were found in connection with question 3, which suggests that it may be revised or skipped altogether.

These fragments also illustrate some other features of the group discussions of these assignments, namely that students participated enthusiastically in their group discussions, that the assignments seemed to be understood, given the type of answers that were given (all related to the questions) and that the discussions were about what was asked, and that the focus of the attention lay on explaining instead of the explained phenomenon.

According to the scenario, in the evaluation phase the general explanatory scheme is made explicit in connection to what the students had put forward in the discussed examples of explanations, which is facilitated by using a figure depicting the explanation of Els (see chapter 5, figure 2). The teacher did not use this figure. Sufficient elements in students' answers could have been pointed out, but were not. Among these elements the notion of comparison of two situations did become clear, but it was introduced in the context of an experiment instead of emphasising that the *explanations* that were given can be understood in that light. The element 'regularity' was not clear at first but was later clarified after some questions from students.

There is an indication that a proper evaluation would have led to more understanding. I answered a question from Rosa concerning the filling in of the mentioned figure (when she encountered it in the students booklet), which made the explanatory scheme explicit in the intended way. This seemed to solve Rosa's problem, which indicates that the intended evaluation can in fact be understood.

Answering the analysis questions

3. Since the answers to questions 3 and 4 and especially the related discussions showed considerable participation and interest (for the right theoretical reasons) and the focus lay on explanations instead of explained phenomena students can be said to be intellectually challenged by how explanations work, although it is hard to say whether the goal of finding a structure in explanations has become clear.

4. The general explanatory scheme can be triggered quite naturally in this way. There are plenty of elements of the scheme that can be recognised and pointed out in students' responses to the questions. (To what extent students would recognise the scheme as underlying their own explanations and consider looking at their explanations in this particular way as quite obvious or even familiar when it would have been made explicit is difficult to say at this stage.)

Suggestions for improvement

Question 3 might be incorporated in question 4. Question 3 leads up to question 4, but the same function of 'leading up to' can be more efficiently taken care of by reformulating question 4 as (after the explanations of Kees, Els and Jostein)

Question 4. Compare your answers and try to reach agreement on:

- *Do Kees, Els and Jostein explain the same thing? What do they actually explain?*
- *How do they do that?*

4.3. Episode 1.3: Making use of the general explanatory scheme

What happened?

The introduction was read by the students, as was intended. According to the scenario, in the main question and answer phase students were to apply the explanatory scheme to the explanation of Jostein (question 7) and Kees (question 8). They were expected to be able to add something to the drawings, point out the relevant difference between the cases, mention a few factors which have to be the same in both cases and finally formulate a regularity. They were then expected to answer more sharply the question why Els and Jostein not necessarily have to disagree (question 9), which is a repetition of question 3.

The students were able to answer questions 7 and 8 in the expected way. Most came up with the regularities 'when you stir, it goes faster' related to the explanation of Els and 'when the tea is hotter, the sugar dissolves faster' related to the explanation of Jostein. Mentioned factors that need to remain the same were temperature (in the case of Els), amount of tea, size of the cup, same sugar and same tea. In response to question 9 the students stuck to their opinion that Jostein and Els agreed on the fact that sugar dissolves in tea and disagreed on the speed in which sugar dissolves. Some suspicion that Jostein and Els might have agreed on the speed of dissolution was not found. Students' ability to answer these questions correctly at least indicates that they have some understanding of the used figures and elements of the explanatory scheme.

In the evaluation the teacher was meant to take stock of the answers and to point out the structure in them. Incomplete answers he should try to complete by further questioning. Students should then try to summarise the general explanatory scheme themselves in a couple of sentences or a story, or by using a picture (question 10). From these summaries of the scheme the teacher then should try to elicit the main elements of the general explanatory scheme using figure 3 from chapter 5. The teacher should end this episode by announcing an application of this general scheme to motion.

Question 7 - 9 were not exchanged. Question 10 was done as homework instead of the planned summary of exchanging the outcome of question 7 – 9. This question became much harder in this way, because students had to come up with a summarisation on their own. The original function of question 10, to indicate what they have understood of the general explanatory scheme, can therefore no longer be fulfilled. Students' answers did not and could not, given this deviation from the plan, express the general explanatory scheme in my meaning of the term, since the students were not told what that was. Their answers, on which they spent considerable thought and time, did express what they considered to be important in describing explanations systematically, it contained further examples of implicit use of the scheme whenever students explained or talked about explaining[3], but did not show the additional step of how they would have responded to an explication of their implicit use of the general explanatory scheme. A recurrent feature they mentioned was the (implicit) comparison of two situations, which is also one of the elements of the explanatory scheme. So although it was not explicitly mentioned as such, the examples and questions did at least instil this notion.

The homework (question 10) was 'discussed' the following lesson by merely[4] exchanging the various answers. No explication of the general explanatory scheme was attempted and no application of this scheme was announced. Whether the explanatory scheme had been recognised when it would have been explicated cannot be said, since it was not explicated. It might have been explicated in connection to students' input, since their input (answers to questions 7, 8 and to a lesser extent 9) was largely as expected. However, how they would have reacted to such an explication remains to be seen.

As was seen the execution of this episode deviated strongly from the plan. A number of factors contributed to this strong deviation. Some have a bearing on the design and are therefore important to discuss. The most notable factor is that the scenario does not state clearly how the explanatory scheme may be explicated based on students' responses to questions 7 – 9, although this is a crucial activity. Another factor explaining this deviation is the timing in lessons, that turned out different as planned. The lesson ended when students finished question 9, so it seemed straightforward to give question 10 as a homework assignment.

Answering the analysis questions

5. Indications for whether students understand the meaning of the elements of the general explanatory scheme were thought to be the kind of answers students give to questions 7, 8 and 9, whether the teacher is able to clearly explicate the elements in the evaluation phase and what kind of depiction of the general explanatory scheme students give themselves in response to question 10. The latter two sources can no longer be used in this way, given the mentioned deviations in the execution. The former source at

[3] Since several examples have already been pointed out in the description of what happened in episode 1.2, I think it is unnecessary to show instances of use of elements of the general explanatory scheme here. The point I tried to make then was that whenever people talk about explaining they necessarily use the general explanatory scheme, which can (not surprisingly) be pointed out. The question that remains is how this pointing out or explication of the scheme can be done in such a way that students recognise it and find it a natural or even familiar way of expressing what they do when they explain things. In order to answer this question students' reactions to attempts at explicating the scheme need to be investigated, for which question 9 was intended to provide data. Given the deviations in execution question 9 can not perform this function any more.

[4] Properly exchanging is already quite difficult. A teacher has to elicit answers from the students and therefore create a safe enough environment for this to happen. These answers need to be heard, understood and finally summarised in some meaningful way. In this case I mean with the slightly prerogative word 'merely' that the subsequent step of extracting from these answers the explanatory scheme did not take place.

least indicates that students have some understanding of the elements of the explanatory scheme.

6. An indication for whether the scheme would be helpful in clarifying explanations to students was thought to be whether students give a clearer answer to question 9 than to the similar question 3. My expectation was that students would have some notion of that Jostein and Els not necessarily disagree, not even about the speed of dissolving and that they would find this notion difficult to express. The explanatory scheme may be useful in expressing this notion of not disagreeing, for instance in terms of differing situations with which the explained situation is compared. Without this experienced difficulty in expression the scheme cannot provide this clarifying function. My expectation turned out to be false. Comparing answers to question 9 with question 3 does therefore not give any indication whether the explanatory scheme is helpful in clarifying explanations to students, unfortunately.

Suggestions for improvement

As was mentioned before the scenario lacks clear suggestions for the teacher how to explicate the scheme. What might those suggestions entail? After question 9 the teacher should point out the following elements in students' answers: the comparison of two situations, the factor in which these two situations differ, other factors that are the same and the regularity. The regularity is intimately tied up with the factor in which the situations differ or the 'cause'. The relation between the two is that the cause that we identify can only be a proper cause when we can call upon a plausible regularity which expresses that when the cause is present the result will follow. (And the result is the situation or event one wants to explain.) After explicating these elements the teacher should say that these can be found to underlie all (causal) explanations and that this underlying structure is called the (general) explanatory scheme. Students then can continue with question 10 after which the original scenario can be followed.

The example of an explanation of sugar dissolving in tea did not provide a reason for using the explanatory scheme in allowing to express clearly why the different explanations not necessarily disagree. This is a pity and might be remedied in two separate ways. The first way is finding an example that does perform this function as well as the other functions of the tea example like triggering all elements of the explanatory scheme. The second way is retaining the tea example and find another way of showing the scheme's use. One can even consider not remedying it. The scheme's main use is theoretical, which is emphasised throughout the course. Its practical use in clarifying the expected suspicion of students that Els and Jostein not necessarily disagree can be considered a bonus. Not cashing in on the bonus is not that important. In a revised scenario some choice in this matter should have to be made.

Concluding remarks

Since the general explanatory scheme has not become explicit the parallel between the general explanatory scheme and the explanatory scheme for motion (that will be introduced in the next episode) cannot be understood, for it was precisely in making explicit this parallel that the teacher was deemed necessary. This was later confirmed in interviews conducted at the end of the introductory course concerning the recognition (if any) of the main line of the course. Only Merlijn and to a slight extent Carlijn and Nicole indicated that they had recognised the link between general scheme and scheme for motion. Others failed to see this link. That the element of comparison of two situations was recognised as an important element in explaining by the students, suggests that at least this element might have been easily recognised as linking both schemes. This is an important point because it was precisely the difficulty in getting across the importance of comparison when starting with the explanatory scheme for motion in the first trial that triggered the idea of using the general explanatory scheme as a stepping-stone. This, I think, is an indication that using this particular stepping-stone might be a good idea.

4.4. Episode 1.4: Triggering the explanatory scheme for motion

What happened?

According to the scenario, in the introduction the teacher should make the transition to the explanation of motions by pointing out that since explaining motions is a particular case of explaining in general the general explanatory scheme may give ideas of how to look for the structure in explaining motions. The teacher said the following:

1. T : But we are going to make a theory of the moving of the bicycle rider. Not because that is so terribly interesting. And we do not look at riding with no hands and other things, just very simple.
2. T: And it concerns rather a kind of variation of question 10, of how to exactly put up a theory. Well, later we will apply this to heavenly bodies.
3. T: So it does not really concern that bicycle rider, it concerns, just for now that bicycle rider, but it concerns how we make a theory.
4. T: Which steps does it contain. Yes. And that is on the one hand things that you know, that you have observed. And on the other hand you try to mould them into a particular shape.
5. T: And that shape into which we are moulding it. That shape keeps returning. Yes? All right, then I will divide you into funny little groups that will stay the same all lesson. Namely, groups of two.

The connection that is made between the general explanatory scheme and the explanatory scheme for motion consist of calling what we are about to do a variation of question 10 (2) and a recurrent ‘shape’ (5) in which the things that we know or have perceived are moulded or organised (4). Furthermore the point is emphasised that not the particular example is important (1, 3), but the making of a theory (1, 2, 3) and that this will be applied to heavenly bodies (2). Since the general explanatory scheme had not been made explicit in the previous episode, it is more difficult to make the transition here to motion. On the other hand, this could have been an opportunity to try to repair this earlier omission.

In the main question and answer phase a number of questions, concerning easy examples in which two different motions of a bicycle rider are compared, should guide students in filling in elements of figures depicting explanations of motions. These question were indeed answered as expected. At first, students were a bit uncertain whether the given answers were in accordance with the meaning of the questions, given statements like ‘is that all’ or ‘have I done this correctly’. The given help by the teacher and me consisted mainly of guiding questions, without giving much away. The right elements of the explanatory scheme were put in the right places. One group of students was even able to do it correctly without reading the guiding questions 10, 11 and 12. Apparently this way of depicting explanations seems quite straightforward to students. The attention remained focussed on explaining instead of the explained phenomenon.

In the evaluation the teacher should take stock of the answers and point out the explanatory scheme for motion in them. The first formulation of the explanatory scheme for motion should then be extended to include all influences. ‘Influence’ should be distinguished from ‘influence affecting factor’. The teacher should then conclude that we have arrived at an explanatory scheme for motion and announce that in the next episode its uses will be explored.

The evaluation consisted of a long monologue of the teacher (not presented here) in which all elements of the explanatory scheme for motion were mentioned. He also indicated that a choice for a situation without the relevant causes or influences (the influence free motion in case of the explanatory scheme for motion) has got implications for the other elements of the explanatory scheme and that we were not interested in particular examples, but in a general ‘theory’. (It was recommended earlier in the scenario to repeat the latter point several times. To do so here is a good choice.) Here the teacher mentioned that the examples of the bicycle rider and the sugar dissolving in tea could both be depicted with the same abstract figure (figure 3 from chapter 5), which was intended for the previous episode, but used here instead. This was all done without using student input.

The teacher then started to continue with the next episode, skipping the more general notion of influence, the related question 16, the distinction between influence and influence affecting factors, and the preparation for the next episode, at which point I addressed the distinction between influence and influence affecting factors myself, of which only Jolien made notes. Others seemed not to understand this distinction. Aisha, for example, clearly did not get this point as can be seen from the following fragment:

1. T: And what is working, eh, which influences are working? What is the influence with Kepler?
2. Ais: Well, distance or something?
3. T: No, the distance in not the infl, the distance does not do anything. Who does something? Who does, who influences it?
4. Ais: The sun (…)
5. T : The sun. So, and what about the sun? The ...?
6. Ais: The motion of the sun. Eh, the rotation speed.

First Aisha calls the Keplerian influence the distance, which is an influence affecting factor (2). The teacher corrects this in (3) and asks about the influencer, which Aisha correctly identifies as being the sun. The teacher then hints at a further answer, probably intending something like ‘the drag of the sun’. Aisha, however, gives another influence affecting factor, rotation speed (6), which is not corrected. Although this is only one example, which I selected for being very explicit, more confusions of this kind arose with other students.

Answering the analysis questions

7. Students are able to point out most elements of the explanatory scheme for motion, for they gave the expected answers to questions 10 through 14. The distinction between influence and factor, however, did not become clear.

8. Given the relative ease at which students responded to the questions, the explanatory scheme for motions could quite easily be triggered. The teacher also explicated it more or less as intended, but it is at this stage difficult to say whether students find the scheme naturally underlying explanations of motion, since their answers to the questions were not explicitly used in explicating the scheme and their reactions to the explication that took place were minimal.

Suggestions for improvement

There are no indications that this episode could not perform its function of making students realise that the explanatory scheme for motion (as a special case of the general explanatory scheme) can be recognised in explanations of motion. However, there is certainly room for improvement, since the function of the distinction between influence and influence affecting factors cannot be clear at this stage. The same can be said of the distinction ‘regularity’ and ‘relation influence – motion’ (see also Figure 4 from chapter 5). The teacher explained that this distinction is useful for understanding motion, which the students are certainly willing to believe, but cannot understand. The scenario does not give additional answers and is therefore lacking in this respect. I will return to this point in the next section.

4.5. Episode 1.5: Making use of the explanatory scheme for motion

What happened?

According to the scenario, the teacher should introduce this episode by pointing out that one use of the explanatory scheme for motion may lie in solving the initial asteroid problem (and implicitly therefore also in explaining and predicting any motion). This did not happen.

In the main question and answer phase students should identify those elements that are needed to solve the asteroid problem by answering the question, with the help of figure 5 from chapter 5, what things one would have to know to be able to give an explanation, given the explanatory scheme for motion. I will here give a complete set of what students wrote down in response to that question. The mentioned figure is displayed again in Figure 1, only this time with numbered cells. These numbers will be used to indicate in which cells students wrote down their statements.

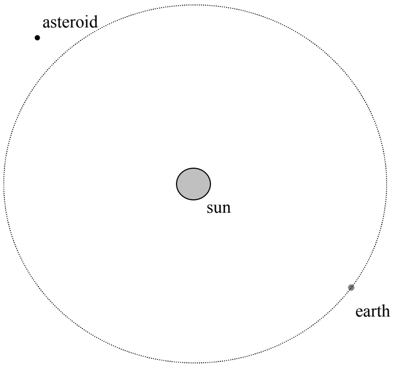
<table>
<tr><td>Motion of the asteroid: …
(1)</td><td>Influence free motion of the asteroid:…
(2)</td></tr>
<tr><td>
(3)</td><td>asteroid
(4)</td></tr>
<tr><td>Working is:
- …
- …
(5)</td><td>No influence is working on the asteroid.
(6)</td></tr>
<tr><td colspan="2">Regularities:
….
….(7)</td></tr>
<tr><td colspan="2">Relation influence - motion:
…(8)</td></tr>
</table>

Figure 1: Asteroid towards earth

This is what they wrote down:

Mick: (5) the earth attracts the asteroid just like a truck that passes by very fast

Christiaan: (5) attraction; a force forward/backward

(7) the closer to the sun, the larger the attraction on the asteroid, the larger the force forward/backward.

(8) the more the asteroid is influenced by forces the more and larger the motion

Aisha: (5) collision with object in space; speed at which it approaches earth

(7) when it for example collides with an object in space then the trajectory in which it comes can deviate

(8) when it comes in a straight trajectory to earth then it is faster than [not finished]

Nicole: (5) influence of other asteroids

Jolien: (5) steering of the asteroid; the asteroid also rotates around the sun

(7) without influence the asteroid remains approximately at the same place

Carlijn: (5) speed, trajectory/direction; attraction of the sun

(7) when the attraction is large, the asteroid abandons its trajectory

Merlijn: (5) sun; earth

(7) when the asteroid is close to earth, then you can determine where the asteroid is.

(8) The closer the earth is to the asteroid, the better you can see it.

Students were expected to be able to completely fill in this figure, but what they wrote down was incomplete. They found answering this question difficult and were unsure about their answers. Take for example Merlijn and Jolien:

1. Mer: When the asteroid is close to earth, then you can determine where the asteroid is.
2. I: Yes yes. For then you can see it or something like that, what do you mean?
3. Mer: Yes, look when the earth is turning then (...)
4. I: Yes.
5. Mer: Well, then one can probably see whether it is there, kind of.
6. I: Hm hm
7. Mer: I didn't really know. I tried something.

Merlijn indicated as a regularity that when the asteroid is close to earth, you can determine where the asteroid is (1), but indicates that this answer was more of a guess (7).

1. I: Do you find it difficult?
2. Jol: Yes.
3. I: What is difficult?
4. Jol: (4s) Just difficult.
5. I: Hm. But you did write something down.
6. Jol: Yes, but I don't know whether that is true.

Jolien found the question difficult (2), cannot even express what is difficult about it (4) and also indicates uncertainty about her answer (6).

In the evaluation the given answers should be discussed where the teacher should emphasise *that* the elements of the explanatory scheme are needed for an explanation and that we do not yet know *what* these elements look like precisely. The explanatory scheme for motion, therefore, is useful in the sense that it provides for a handle on the problem by pointing out the elements student still need to learn more about in subsequent episodes. This evaluation did not take place in this lesson (lesson 2) nor in the next. Although it became a point of attention for lesson 3, it was somehow overlooked.

Answering the analysis questions

9. Given the deviant way in which this episode was executed it is not surprising that students cannot be said to have understood that in order to explain the motion of the asteroid they would have to know how the asteroid would move without any influences, which influences were operating (and where they came from), and how these influences caused deviations from the influence free motion. They answered the main question

incompletely, so could not think of the answers themselves, which was unexpected from the point of view of the scenario, but given the earlier deviations and shortcomings is not that surprising any more. Their answers were not corrected and completed, because in the evaluation the explanatory scheme was not explicated at all, let alone clearly, which would have required substantial input from the teacher. Students could also not be expected to have realised which elements of the explanatory scheme for motion are still unknown, because they were not identified. Finally the agenda for the following lessons was not set at all, let alone clearly.

Suggestions for improvement

One point concerning the design of this episode is that the regularity has been distinguished from the relation influence – motion (see also Figure 1), but no reason was given for this. The reason I as a designer had for this distinction is that it prepared the ground for later introduction of influence laws as specification of the regularity and the rule deviation=influence/laziness as specification for the relation influence – motion. Students could of course not see this reason and should be provided one that they can understand and appreciate. A revision of the design should address this issue.

A similar issue involves the distinction influence – factor, where influence will later turn out to be force and factor a variable in a force law. Here the scenario does give an explanation of the difference, but no reason why this is important.

Concluding remark about the design of this episode

At face value the deviations in execution make it very difficult to draw some meaningful conclusions regarding the design of this episode. However, the answers students gave in response to the main question do give some concrete leads as to how the teacher might have responded. It is my claim that the test of this episode gives additional empirical information in support of the design besides the theoretical arguments already given in the scenario. To back this claim I will give a possible response to the answers students wrote down in which the goal of the episode may be reached. In this way, by 'reconstructing'[5] a teacher response I intend to illustrate that a proper response had been possible, given the student input, and might have resulted in the desired outcome of this episode.

The teacher could have responded in the following way, after the answers to the episode's main question were read aloud (or exchanged otherwise):

> *Although none of you have given a complete answer, you do mention a lot of elements. The most of what I hear/read is about what is working. The influences working on the asteroid. Mick mentions an attraction from the earth, Christiaan also an attraction, Carlijn an attraction from the sun, Christiaan also mentioned a force forward/backward, Aisha collisions with other objects in space and Nicole the influences of other asteroids. Nicole, do you think about collisions or maybe also attractions or something else? Merlijn, what do you mean by sun and earth?*

[5] This way of reconstructing a teacher response resembles the reconstruction method of Kortland, but is less strict in the sense that it does not follow all the guidelines he established.

I would expect that Merlijn would join the mentioned attraction by sun and earth, since she indicated at another instance that this answer was a guess.

Maybe you disagree whether some influence is or is not there, but we can agree on that when some influence is working, you have to know how it is working if you want to predict the trajectory of the asteroid, don't you?

The reason that influences matter is that they change the trajectory of the asteroid. Without influences the asteroid will move in some manner and with influences in some different manner. Comparing these two ways of moving leads to identifying influences. This is similar to the comparison of two situations that we saw in the explanations of sugar dissolving in tea. What counted as a factor accounting for the difference between slowly and quickly dissolving, e.g. the temperature, depended on what situation one had chosen as a reference. The same here: what counts as an influence depends on what motion one has chosen as a reference, that is what influence free motion.

What motion will the asteroid have when there are no influences working, do you think? There are several possibilities. Jolien mentioned that according to her the asteroid would remain in its place. Christiaan did not mention this, but implicitly he did. Christiaan said that there has to be a force forward/backward. Why do you think so, Christiaan?

I expect an answer like: otherwise it would not move in the direction it is moving, it would move straight towards earth because of the attraction of the earth.

Ok, so when we try to indicate which influences have to be working, we also say something about what would happen when these influences were absent. That is to say, we make an assumption for the influence free motion, here on the right side of the figure (pointing towards Figure 1 cell 2).

An influence has to come from somewhere. There has to be an influencer. You also mention something concerning this point. The attraction comes from the earth (Mick) or from the sun (Christiaan, Carlijn). Christiaan, where would the force forward/backward come from?

He might have some idea on the topic.

Or the influence comes from collisions with objects in space (Aisha) or from other asteroids (Nicole). In that case it is clear where the influence is coming from and what the influencer is. The magnitude of an influence depends on where it is coming from. It depends on the influencer. This can be expressed by a regularity like Christiaan did. Look here in the figure (points towards Figure 1 cell 7). He said, 'the closer to the sun, the larger the attraction on the asteroid, [and] the larger the force forward/backward'. The other 'regularities' by Aisha, Carlijn and Merlijn that were mentioned do not express the magnitude of the influence, which is the meaning of regularity used here.

Apart from the distance Christiaan mentioned, what could also determine the magnitude of his attraction by the earth or sun?

I expect someone to come up with the notion of size or mass, otherwise the teacher may put this forward without much resistance.

> *All right, suppose that we know now which influences are working (points to figure cell 5) and we have (therefore) also an assumption for the influence free motion (points to figure cell 2). And we also know the magnitude of these influences, because we know where they come from (points to figure cell 3 and 7). In order to predict the motion we would have to know how all those influences together cause a deviation from the influence free motion. What is the effect of the influences on that motion? (Points to figure cell 8). That is something we also need to know.*

Here the teacher might give an easy example illustrating that influence needs to be transformed into deviation (from the influence free motion).

In this way a teacher might have reacted to the written answers to the episode's main question. I expect that students would find most of this understandable and would be able to recognise their answers in my reading of them. The more difficult parts were explicating the implicit assumption of an influence free motion that is coupled to the identification of influences and the elements regularity and relation influence – motion. The relation influence – motion is now introduced as an element we need to know more about (in order to be able to predict the motion), without connecting it to student input.

To end this discussion of a hypothetical teacher response I like to note that this episode is a crucial activity in which all previous activities culminate in a structure which sets the agenda for the subsequent activities. It is therefore a pity that this was not executed properly. In theory this can be done clearly and using student input, as I tried to illustrate with my hypothetical teacher response above. In practice this proved very difficult given the kind of preparation that was offered.

4.6. Conclusion main theme 1

Before drawing some conclusions concerning theme 1 as a whole I will summarise the answers to the analysis questions related to the various episodes in the following table, see Table 1.

The ideas for triggering and explicating both the general explanatory scheme and the explanatory scheme for motion might work in the designed way, but they are (too) difficult to execute for the teacher without sufficient training. The important topic of teacher preparation, including the specific difficulties related to a problem posing design and ideas for approaching it were discussed in section 3 and will be further addressed in chapter 7. The test does not give further empirical information as to whether the schemes will be recognised or considered familiar or at least not considered strange after explication. This question remains unanswered here and will require further research for answering it in the future.

The asteroid problem might perform its intended function, when properly used. Using the general explanatory scheme as stepping-stone simplifies the introduction of the notion of comparing situations in explaining, but has not been used explicitly enough in the transition to explaining motion.

Main theme 1: The why and how of explaining motions.		
Function of main theme: It addresses the questions of *why* study the topic of explaining motions and *how* are motions explained. This should result in the notion that this is an important and interesting theme worth knowing more about and the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of the underlying scheme (theoretical orientation).		
Episode	Analysis Questions	Answers
1.1 Introduction to the topic of mechanics	1. What indication can be found that explaining or predicting motions can be desirable? 2. What indications can be found that students consider explaining not as a simple matter?	What is meant by explaining motions and also why that may be important is still vague. Students did get some impression in the introduction and did mention (implicit) reasons for the importance of what they thought to be the subject and seemed willing enough to engage in the subject. Students are aware that it involves numerous things. It is uncertain if its difficulty and that it involves calculations has been recognised.
1.2 Triggering the general explanatory scheme	3. Are students intellectually challenged by how explanations work? 4. Can the general explanatory scheme be triggered quite naturally?	Yes. The answers to questions 3 and 4 and especially the related discussions showed considerable participation and interest and the focus lay on explanations instead of explained phenomena. Yes. There are plenty of elements of the scheme that can be recognised and pointed out in students' responses to the questions.
1.3 Making use of the general explanatory scheme	5. Do the students understand the meaning of the elements of the general explanatory scheme? 6. Is the scheme helpful in clarifying explanations to students?	Students have at least some understanding of the used figures and elements of the scheme. Hard to say.
1.4 Triggering the explanatory scheme for motion	7. Are students able to point out the elements of the explanatory scheme? 8. Can the explanatory scheme be evoked naturally?	Yes, most elements. The distinction between influence and factor did not become clear. Yes, given the relative ease at which students responded to the questions. It is difficult to say whether students find the scheme naturally underlying explanations of motion.
1.5 Making use of the explanatory scheme for motion	9. Do students understand that in order to explain the motion of the asteroid, they would have to know how the asteroid would move without any influences, which influences are operating (and where they come from), and how these influences cause deviations from the influence free motion?	No. They could not think of the answers themselves and their answers were not completed by teacher input.

Table 1: Summary of answers to analysis questions of main theme 1

Students did not see the explanatory scheme for motion as a special case of the general explanatory scheme. This was not pointed out and the general explanatory scheme as such was not established.

Students did not realise that for a complete explanation of motion further specification of the elements of the explanatory scheme would be necessary, but they might have realised it in a proper execution of the design, since their input allowed for a natural explication.

The students developed a theoretical orientation in the sense that they understood the goal of understanding explaining motions to be to arrive at some theory of motion, had some impression (however vague) of what such a theory might be, and were somewhat challenged by it.

Apart from the few scenario improvements that have been suggested in the course of section 4, this test did not provide empirical grounds for changing the design of main theme 1 in a major way. The encountered difficulties seemed to lay mainly in the execution and therefore the teacher preparation.

5. Extending students' knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining planetary motion.

The following sections, section 5.1 through 5.5, concern the results related to the second main theme, extending students' knowledge. The same presentation format as was used in section 4 will be used here. Section 5.6 contains conclusions regarding the second main theme.

5.1. Episode 2.1: Transition to Kepler and Newton

What happened?

According to the scenario, the main thread that is followed is that all subsequent activities can be seen as further specifications of the explanatory scheme for motion. Students should be oriented towards the texts on Kepler and Newton as examples of such specifications of the explanatory scheme for motion. In the introduction (which took place at the end of lesson 2) the teacher gave a gripping human interest account of Kepler and Newton and pointed out that the following assignment (assignment 18) is about recognising the explanatory scheme in the texts. He did not mention oral presentations, which were mentioned in the student booklet. A kind of main thread was indicated, as can be seen in the following fragment from the introduction:

1. T: But everyone has to understand really well what the meaning of this is. I think you have lost the thread a bit.
2. Ll: Yes (…) [intonation suggests 'not really']
3. T: Shall we precisely explain the meaning once more, or shall we ask her to explain?
4. Nic?: Ask away.
5. T: You, explain very shortly what precisely the meaning is and what we are doing now.
6. Ais: (…)
7. T: Louder, louder.
8. Ais: (…) real earth and the earth (…) together (…).
9. T: Actually, I mean all lessons together.

10. Ais: Oh. Ehm then eh, then the general, say, so the explanatory (...) eh influence is of motion, sort of.
11. T: Yes. We are engaged with a general explanation, we apply it to motion, yes? So we divided [it] a little in parts. We got two people who had two different theories. Those two theories we are going to specify.
12. T: We are going to apply them later and next lesson we are going to look who of these two has got the best explanation and after that we are going to further detail it, like, filling in. Yes. The text says that the distance has an effect, but not how large that effect is.

I do not think that this makes the main thread much clearer to students, e.g. they cannot be expected to have a clear picture of what 'applying' and 'specifying' is (11). The last sentence does give some lead: The further detailing or filling in of 'it' (meaning the theory of Kepler and Newton respectively) means making it more precise, like estimating how large the effect of the distance on the influence is (12). He did not use Figure 5 from chapter 5 in this introduction.

In the main question and answer phase students should read two texts on Kepler and Newton in which their use of the explanatory scheme for motion should be easily recognisable. This is guided by the question whether they recognise the explanatory scheme in the texts, on which they should give an oral presentation. What happened was that most students read the texts as homework, but did not prepare an oral presentation, which was in agreement with the teacher's intentions, but not with the written assignment in the student booklet.

According to the scenario, in the evaluation the teacher should discus several presentations of students and try to elicit answers to the following questions:

1. What were the facts that Kepler and Newton tried to explain?
2. Do you recognise the general way of explaining? How was it applied by Kepler? How by Newton?
3. Why did Newton come up with assumptions for the influence law, which differed from those of Kepler, in particular with respect to the direction of the influence?

In connection to their responses the teacher should emphasise that Kepler and Newton explained the same phenomenon in the same structural manner, but differently in respect to the specifications of the elements of the scheme and address the difficult point of the connection between assumed influence free motion and identified influences. This should then result in the further filling in of the status diagram. Finally the teacher should state that some of the elements of the status diagram ought to be made more precise and that this will be the topic of the following couple of episodes.

In the evaluation the next lesson the students were not asked to give an oral presentation, but were asked factual questions like 'what is the influence free motion according to Kepler?' by the teacher. Their answers to these questions together with their filling in of the status diagram gave indications for the extent to which they recognised the elements of the scheme. Filled in status diagrams were correct, in the sense of answered as expected, except for the element of the influence free motion, which was either lacking or put at a different place. The model of Kepler appeared to be intuitively clear to students. Take for example the following response to a question of the teacher during the evaluation:

1. T: Well. Ehm, let's take another question. You'll know this one. What is with Kepler the influence free motion?
2. Mic: Well, eh, hm.
3. T: You have done it, I hope.
4. Mic: Yes. Then the object is totally standing still, when it is not influenced.
5. T: Look, that's what I like to hear. When there is no influence, it is standing still. Very simply put: When the sun stops turning, the earth will ...
6. Jol/Ll: Stand still.
7. T: …stand still. When the sun turns in the other direction, it will ...
8. Jol: In the other way.
9. T: …turn in the other way. That's the idea. Yes? (2s) Yes. What do you think of that idea of Kepler?
10. Mic: Yes, a bit simple. It appears that he did not really think about it, but it is rather clear.
11. T: Rather clear.
12. Mic: Yes.

The model of Newton seems intuitively less clear, as expected:

1. Jol: That "gravity" [said as something revolting]
2. T: Gravity. Yes, how should I picture that?
3. Jol: Yes, that I did not completely understand. But according to me is that the sun also attracts that planet, or something. That it turns because of that.

[...]

4. Nic: Eh, the larger the heavinesses, so heaviness of planet and heaviness of the sun both, the larger the influence. And the larger the distance between the sun and the planet, the smaller the influence.
5. T: Yes. And then he does say how it is, but what that gravity really is...
6. Nic: That is unclear.

The elements of the status diagram did surface in the discussion and, as said before, students were able to write them down afterwards. However, it was not explicitly pointed out during the discussion that an element *of the status diagram* had been discussed, thereby a chance was missed to point out its use as a tool for keeping track of the main thread.

The point that the described regularities still are somewhat vague and in need for specification, which prepares for the next episode, was not emphasised. What the facts were that Kepler and Newton tried to explain was not mentioned. Also the question why Newton had other assumptions for the direction of the influence than Kepler was not discussed. These omissions were probably the result of a derailment of the discussion in which the threat of a premature introduction of laziness and the third law (they were mentioned but recognised in time, before elaborating on them) caused a distraction from the intended course.

Answering the analysis questions

10. The question 'are the given examples (of Kepler and Newton) recognised as specifications of the explanatory scheme' has two aspects. The first is whether the activities in this episode are seen as being part of the process of further specification of elements of the explanatory scheme. The second is whether the examples themselves are clear, so that the explanatory scheme is recognised in the texts on Kepler and Newton.

Regarding the first aspect I think that the main thread of specifying the elements of the explanatory scheme was not recognised, because this thread had not been made explicit and in the final interview nobody indicated to have seen this episode (or any) as part of such a thread. I will elaborate (slightly) on the second reason. (The first has been shown in the first part of this section).

The interview after the introductory course concerned with the recognition of the main thread consisted of shortly reminding students of the consecutive sections of the course by flipping through the student booklet and recalling some noteworthy aspects[6] and asking after each section why that section was done, if they found the transition to that section understandable at the time and if they found the transition to that section understandable in retrospect. All seven students were asked these questions individually in interviews that took about 15 minutes.

The only student that saw the intended reason for investigating Kepler and Newton was Jolien:

1. I: Then a kind of diagrams turned up. Then all of a sudden it was about Kepler and Newton. Why did we do that?
2. Jol: To learn different explanations of motions. How they thought about that. And then to look who was right or was closest to it.
3. I: Why did we do that here?
4. Jol: To.
5. I: Why here I mean? Why after that cyclist?
6. Jol: Well, that we can continue with something like planets and stuff after this.

Merlijn seems to come very close as well:

1. Mer: Ehm, because they have found a way to explain everything what is going to happen. And yes, you showed these diagrams. And with these diagrams you can explain their ideas a little.
2. I: You mean these diagrams, or?
3. Mer: These. But this is rather kind of, this is rather the same. And this they used with Newton and Kepler too.

The reason for investigating Kepler and Newton was that 'they had found a way to explain everything what is going to happen', which means 'explain what is going to happen with moving things', i.e. 'explain motions'. The schemes she refers to in (1) and (3) were two figures from the student booklet. One is the same as figure 5 from chapter 5, the other is a filled in version of figure 4 from chapter 5. She considers them to be

[6] I chose to remind students by noteworthy aspects instead of a short summary of the section, because a summary might already give some insight in the main thread away.

rather the same (3), which means that she recognised that they express the same thing (namely the explanatory scheme for motion), although she does not mention in what way they are the same.

Other students expressed various reasons, e.g. Aisha and Rosa mentioned calculating the trajectory of the asteroid. Carlijn saw a thread from small topics like tea to larger topics like the bicycle rider and finally the largest: motion of heavenly bodies.

As part of the booklet section in which episode 2.1 took place I asked about why the status diagram was used. Most students responded by indicating its use as providing an overview, e.g.

> Car: I think so that you precisely know what Kepler and Newton were really thinking. What their theory was. And that it was just briefly put there.

> Mer: Eh, then I thought, this is convenient to put Kepler and Newton in. That you don't have to go looking for their stories how they, ehm yes. That you just could look back at any time whenever you really couldn't remember how things were: Whether it was rotation or heaviness.

In addition some mentioned its use for displaying the difference between Kepler and Newton:

> Ros: Yes, I don't know what I thought, but eh to clarify it. That you can see the differences and, more orderly.
> Mic: To eh, you can see differences well. It is clear, you know.
> I: Differences between?
> Mic: Between Kepler and Newton, influence free not in, eh, like motions. Yes, I think that it eh, well...

> Nic: Very clear overview. You also could compare on (...)
> I: Yes. What do you compare?
> Nic: Well, his assumptions with those of his. Difference.

Jolien was the only one who mentioned some reflective function, namely noticing what you have learned:

> Jol: Well, to fill in the things you knew then and to add things whenever you learned something new. To notice what you have newly learned.

To complete this account, Aisha mentioned also some use for calculating influences:

> Ais: Yes indeed. That is in order to summarise a little how you do that and eh, to distil the important things. And with what you could calculate these influences.

From these responses I conclude that most students did not recognise the investigation of Kepler and Newton as a first step in specifying the explanatory scheme for motion as depicted in the status diagram. They can see the use of Kepler and Newton in light of the initial asteroid problem, since both investigated motion of heavenly bodies and seem therefore relevant for the asteroid problem.

Regarding the second aspect of analysis question 10, whether the explanatory scheme is recognised in the texts on Kepler and Newton, I think the separate elements were correctly recognised and identified, but their interrelation had not become clear. Except for the influence free motion, the elements of the explanatory scheme were correctly filled in in the status diagram in assignment 18, but in the evaluation several important points were not made clear: If and how Kepler and Newton applied the explanatory scheme for motion and why Kepler and Newton had different explanations. The use or importance of the influence free motion is not sufficiently clear at this stage. This is in agreement with findings from earlier episodes in which the difficult point of the coupling between influence free motion and identification of influences, from which the use of the notion of influence free motion surfaces, did not become clear.

Since what students filled in in their status diagrams was largely correct, I am inclined to think that a similar discussion of their answers as I suggested before in relation to the responses to the main question of episode 1.5 (see section 4.5) would have been quite possible and appropriate. It would have been possible therefore to point out the implicitly recognised structure of the status diagram in connection to students' input.

Conclusion and suggestions for improvement

The accounts of Kepler and Newton were recognised as having to do with motion like the asteroid problem and possibly as 'theories' in some vague sense about motion, but not as *examples of specifications* of the explanatory scheme for motion. Although elements of the explanatory scheme were recognised in the texts on Kepler and Newton, their interrelations were not. The function of the explanatory scheme for motion as guiding the subsequent programme of further specification of elements of the explanatory scheme (with use of the status diagram as guiding tool) did not become clear. Therefore, from now on a *new* project is unintentionally started for students in which Kepler and Newton will be investigated using a computer modelling environment, instead of the intended continuation of the same project of detailing the explanatory scheme for motion.

The test does not suggest revisions in the design of this episode, only in the execution.

5.2. Episode 2.2: Introduction to the matching problem

What happened?

The episode was not introduced. In the main question and answer phase the computer model should be demonstrated requiring a formula or influence law and illustrating Kepler's assumption for an influence free motion, his notion of influence including his spokes explanation and a Keplerian influence law. The teacher should then invite suggestions for effecting a 'match' from the students. This demonstration happened largely as intended. Students did not suggest any formulas, instead the teacher quickly went from I=0, through I=R, I=R*r and a short discussion why this one cannot be right to I=R/r. One student found this curious:

1. Chr: Why do you have to divide R by r, that I don't get.
2. T: Well, I don't know either. One simply tries something. No, but you have to think of something.

3. Chr: The R stood for rotation of the sun, didn't it?
4. T: I is the influence, R is the rotation of the sun, yes. When the rotation of the sun increases, what will happen to the influence? (3s)
5. Mic: Will increase.
6. T: So, I am looking for a formula that does what I want it to do.

[...]

7. Chr: But why are you going to divide the rotation speed of the sun by the distance to the earth?

The necessity for an influence law for determining the motion was probably mentioned too quickly and too implicitly in the demonstration. The idea that the regularities of Kepler (as they were mentioned in the text students read about him) are still somewhat vague and imprecise and need quantification was not mentioned. Instead it seemed that the context of using a computer model dictated the need for a mathematical formula. The teacher then suggested $I=R^2/\sqrt{r}$ and asked how one can find out whether such a formula is right.

Jolien provided the right answer:

Jol: When the model is moving the same as the earth.

Also Merlijn recognised that trying several values for R was done in order to effect a match, although the fact that she asked about it suggested that she was unsure about it:

Mer: What is the meaning of all this? That it goes the same with the real earth?
T: Yes!

I considered the given explanation understandable for the students. Jolien and Merlijn expressed the idea of 'matching' as a way to know whether a particular influence law is right. It seems fair to think that most other students would agree with that. The teacher was very enthusiastic about this model and also the students were very much involved in whether the 'model planet' would catch up with the 'observed planet'.

Rosa raised an important issue:

1. Ros: But sir, with that formula you only do the influence...
2. T: Yes.
3. Ros: …you only calculate the influence. So really, but [with] the earth you do not see a [difference in the] arrow, so you cannot know whether you were right.
4. T: On the real earth you do not see an arrow. No. So the real earth does not have that, because that influence is in the model. You come up with that influence. Or Kepler came up with that influence. He thought of that.
5. Ros: How can you know whether it is right or not?
6. T: Well, you can't. Only, imagine that it is right, yes? And it all fits beautifully. Then you can say that the best model is a model that... Yes, when is a model the best?
7. Mic: When it has the best effect.
8. Jol: When it most resembles the real.
9. T: When it most resembles the real.
10. Jol: Yes.

11. T: And of course also when I have six planets that result in six different rotation speeds of the sun. Yes, that would be a bit complicated, how things can fit together then. So you want to arrive at one rotation speed of the sun, right? And you also want that once you got the rules, that they also apply to a meteor, that the meteor also fits. So I really want one theory for everything. That I would like. And that is what we are looking for.

[Later this exchange was continued:]

12. T: Aah, you don't get it. Good, good. Tell me, what do you don't get?
13. Ros: So, you have to look which arrow is best?
14. T: No. Not which arrow is best, because you cannot see that. You can look which ... motion is best. You know how the earth is moving. You make a theoretical construction, because you say that the rotation speed is involved, the distance is involved, I think of something with those. Yes? And then I look whether they are moving in the same way. And the best model will fit the best. You have to choose both the best model as well as for instance the best rotation speed within that model. So you have to think of both the best model, which is your theory, and you have to get the right value in your model. So that involves quite a lot of steps. Yes? So that is what we are going to do.

Rosa was thinking of matching the modelled influence to the real influence (3, 13). The teacher explained why motions instead of influences are compared by telling that the 'real influence' cannot be observed, only the resulting motion (4, 14). The teacher does a pretty good job here, but it is a rather difficult explanation, which suggests that the design may be improved on this point. The teacher also uses an argument based on the criterion of broad applicability (11) which is strictly speaking not necessary here, but can be used. The fact that 'influence' is a theoretical construct that cannot be observed in the context of heavenly bodies is somewhat confusing, since it had also been related to observable influences like pedalling or braking.

Perhaps the best response to Rosa's question would have been the first part of what the teacher answered, namely that the 'real influence' is not observable in this case, leaving more fundamental considerations aside whether this is in principle impossible because it is a theoretical construct, or in practice difficult or even impossible. Such a discussion can perhaps at a later stage be meaningful, but not now for it will complicate the introduction.

The intended evaluation was lacking.

Answering the analysis questions

11. It is not very clear for students how a detailed explanatory scheme may lead to predictions of motions, because although the meaning of the matching problem did become clear, the necessity for an influence law did not.

Suggestions for improvement

To the introduction of the matching problem can be added, e.g. when demonstrating the model, that the influence on the observed earth is not depicted because it is unknown, whereas its motion is known.

5.3. Episode 2.3: Influence laws

What happened?

In the introduction students should be able to think of several correct Keplerian and Newtonian influence laws (and possibly one of their own). The question how one can choose between the given alternatives should trigger a recollection of the earlier demonstrated matching problem as a way of approaching this. In the introduction the students read a short introductory paragraph and all came up with several alternative influence laws in question 20 and 21, which were almost all in agreement with the regularities. They mostly varied on the form $I_{Kepler}=R^a/r^b$ and $I_{Newton}=H^a/r^b$ with a and b integers. Most students could not think of additional factors affecting the influence, as was expected. The subsequent investigation of alternative influence laws with computer models was introduced at the beginning of the next lesson (lesson 4) roughly as intended.

In the main question and answer phase the students should test three Keplerian and three Newtonian influence laws (question 23), describe how one can see if some model is Keplerian or Newtonian (question 24) and add the best influence laws to their 'status diagram' (question 25). I expected effecting a match to be fairly easy. Differences between Keplerian and Newtonian models I expected students to come up with were the kind of influence law, the direction of the influence, and the observed motion after the 'test' of making the influence zero by making the relevant parameter (R or H_{sun}) zero.

Students were able to apply a correct matching procedure and came up with correct conclusions concerning which influence law could be suitable. Students did not see influence laws as specifications of regularities, because although this was indicated by the teacher, this was not emphasised (e.g. by using student responses to questions 20 and 21) and is hard to come up with for students on their own. Furthermore no fragments were found in the protocols that indicate otherwise. The only two students that added an influence law to their 'status diagram' did not do so in the box 'regularity', which indicates that they did not think some relation between the found influence law and a regularity was obvious.

Students seemed to have an operational understanding of the function of the parameters in the influence laws, but found it difficult to explain why these parameters showed this functionality. With an operational understanding I mean that students realised the effect of a parameter on the motion simply in terms of some easily observed feature[7]. An example in which a student developed (with some help) a slightly deeper insight into the functioning of a parameter is the following:

In response to a suggestion of the interviewer Merlijn and Mick changed the value of the rotation speed of the sun R by making it negative and later zero. They were asked to explain the motion they observed.

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[7] Operationally matching would follow a line of thought similar to the following: 'In order to keep up with the real planet the model planet should move faster, therefore this number has to increase, because I have seen that increasing this number makes the model planet move faster.'

1. Mer: Because it doesn't move. The rotation speed is 0.
2. [Mic: He is not forced to go backwards in time and also not further.]
3. I: But what you also see with 0 is that that red arrow is gone. What did the red arrow signify?
4. Mer: But this [points towards R?] is the rotation speed, isn't it?
5. I: Yes, correct.
6. Mer: Yes, he hasn't got any more rotation speed, is zero.
7. I: Yes, but who hasn't got any more rotation speed?
8. Mer: The earth.
9. I: But what does that, what rotation speed does that R signify? That is not the roation speed of the earth.
10. Mic: Of the sun.
11. I: Yes.
12. Mer: Ooh. [Because] That the sun is turning in the other way, of course, the earth is turning the other way too.
13. I: Yes, precisely.

At first Merlijn thought R indicated the rotation speed of the planet (5,7). This confusion is indeed obvious and should be prevented in a revised design. By making R negative and later zero and pointing out that R indicates the rotation speed of the sun she got the picture (12). Without such guidance their understanding of the parameter R would have remained rather poor. What this example also illustrates is that students sometimes not remember the meaning of the letters indicating variables (R, r or H). More of such instances can be found. If one does not even know what a particular parameter stands for, one probably does not know its function either. At the most one has an operational understanding, which suffices for the matching procedure as such, but falls short of the intended insight.

Students showed obvious enthusiasm and spent a large amount of time on the modelling assignments. Because of time restrictions only Nicole and Rosa finished all questions (up till question 24) in the lesson, the others did not think about the last questions concerning the differences between Keplerian and Newtonian models. In the next lesson this omission was overlooked and not remedied. I discussed the differences between Kepler and Newton with Nicole and Rosa. These discussions led me to believe that the differences between Kepler and Newton may be quite naturally (that is in close relation to student input) put forward in a evaluative discussion of the relevant question (question 23):

1. I: Ok. You are looking at a model of Newton. Ehm. Mention a couple of differences with Kepler. You have seen now three of Kepler. This is probably the first of Newton. Do you notice any differences?
2. Ros: This is different.
3. Nic: Yes, but that is with...
4. I: That is different.
5. Nic: ...Newton the heaviness.
6. I: Yes. It concerns now heaviness.
7. Ros: That other one talked about eh ...
8. Nic: Yes, that was the eh...
9. Ros: What was R again?

10. I: Rotation speed of the sun.
11. Nic: Yes, rotation speed.
12. I: Yes. So that is a difference. What else?

[They mention different values for the used parameters and different matching results.]

A difference between Kepler and Newton these students easily come up with is the difference in the used parameters in their respective influence laws (5, 7, 9, 11). The other expected differences of the direction of the influence and the test of which influence free motion is used (by making the influence zero) did not surface spontaneously. I rephrased the question now more in line with question 23.

1. I: Suppose that, look now you know that this is a model of Newton. But suppose that you don't know that and you wonder: Would this be a model of Newton or Kepler or maybe something else? How could you find that out?
2. Nic: By looking at, yes, the difference we just mentioned. Whether they look at heaviness or rotation speed. That was a difference wasn't it?
3. I: Yes, exactly. Yes, that is one difference.
4. Nic: And, yes I don't know whether you can see it in these models, but what they eh, when there is no influence.
5. I: Hm hm
6. Nic: Ehm
7. Ros: When you make this zero.
8. Nic: When you make that zero.
9. I: Yes, what would you then expect?
10. Ros: With Newton it would go through and with Kepler (…)
11. Nic: Yes, it will go, no with Kepler nothing will happen. And with Newton it will continue straight with the same speed.

The first difference is repeated (2), but after that the expected test of the influence free motion surfaces (4) in which Rosa adds a way to do that by making R zero (7). They also formulate a correct expectation of the outcome of this test (10, 11). The third expected difference of the direction of the influence did not surface after prompting. It may come as a surprise that these students did not notice themselves the difference in direction of the influence although they had investigated already three Keplerian and one Newtonian model and had read the texts on Newton and Kepler in which this is specifically mentioned. I will explain why I think it is not surprising in answering analysis question 12.

In the evaluation the teacher should take stock of several answers and makes sure the main points surface clearly: a quantification of the regularity is necessary in order to predict motion, an influence law is testable by matching, and some feeling for the effects of R and H. This did not happen. The episode was not evaluated.

Answering the analysis questions

12. Students' insight in motion models has deepened somewhat, although not as much as expected or possible. This conclusion is based on the following interpretations of the presented results:

- Students could correctly translate assumptions of Kepler and Newton concerning influences into an influence law.

- Students realised that an influence law is needed to calculate the motion of a planet around the sun, but did not see that it is a specification or quantified expression of the earlier seen regularities of Kepler and Newton.
- Students saw that alternative laws are possible, because all students could come up with several alternative influence laws, although these were mainly unimaginative variations on one form.
- Students did not understand the role of parameters in the models. Their understanding remained on the level of what I called an operational understanding. For deeper understanding some reflection would be needed, which was planned to take place in the evaluation phase, but as was mentioned before did not occur properly.
- Students understood what testing a model entails. The notion that the two moving things should be on top of each other was clear to everyone. I think that students realised that this means that the model should predict the observed motion. They probably attributed some meaning to this activity given their obvious enthusiasm and large amount of time they had spent on this activity. If they had seen this activity as merely a meaningless game of changing a number until two things are on top of each other they would have become bored quite quickly. This is also in line with an earlier result from episode 2.2 indicating some understanding of the matching problem.
- Students could have acquired more feeling for the difference between Kepler and Newton. Although this was not observed to arise without prompting, the ease with which two differences (different parameters in the influence law and different motion in the situation with influence put to zero) could be triggered in the only students that had progressed sufficiently far in the episode in the given time suggested that in a proper execution of the evaluation these differences would have surfaced in most students.

  The apparent difficulty in prompting the third difference (it was not mentioned spontaneously, but had to be introduced), the different direction of the influence, can also be understood. Seeing the direction of the influence as a telltale indicating whether the model is Keplerian or Newtonian requires insight in the difficult point of the coupling between the assumption of an influence free motion and the identified influences accounting for deviations from this motion. Merely mentioning this difference or letting students read about it is not sufficient. This coupling had unintentionally not been addressed so far, thereby making it difficult to appreciate the significance of the direction of the influence. This might also work the other way around: discussing this difference in direction of the influence between Kepler and Newton can clarify the mentioned coupling.

13. The question which type of model is fruitful was not seen to pop-up occasionally.

Suggestions for improvement

What can be done to deepen the operational understanding of parameters to understanding their function and 'background' besides the suggested evaluation of the main activity? Now too much emphasis lies on the evaluation. It would be preferable when the main activity itself fulfils a weightier role in the functions of 'deepening the insight in the what and how of explaining motions, limited to the relevant factors in the influence laws'. Can the main activity be designed in such a way as to prevent mere operational matching? Finding answers to these questions would improve the design of this episode.

The parameter R, the rotation speed (of the sun), is confusing when it is used without its suffix 'of the sun' since rotation speed can mean the speed at which the sun rotates around its axis and the speed at which a planet moves around the sun. This confusion might be prevented by adopting some other term for this parameter.

5.4. Episode 2.4: Laziness

What happened?

The introduction consists of three parts: an introduction (of the introduction), a main question and answer phase (of the introduction) and an evaluation (of the introduction). In the introduction of the introduction students should read about laziness in the context of further specifying the relation influence – motion. Instead of ensuring that students read and understood this part the teacher gave another introduction himself which was largely incomprehensible.

In the main question and answer phase of the introduction a simple Keplerian and Newtonian model including laziness as a parameter should be investigated guided by questions asking to vary the laziness of the earth and look for what happens with the influence on and the motion of the earth, match the motion of the earth by finding suitable sets of parameters and explain why several sets are possible. I expect students in this way to easily observe the effect of laziness on the motion and notice the balancing effect of influence and laziness.

What happened was that the investigation of simple models with the added parameter laziness went well. There were no signs of students getting stuck, like asking questions about the meaning of assignments, but it took a lot of time because students started freely exploring the models instead of directly focussing on the guiding questions, which they only did after being told to by the teacher. Interestingly one group performed all the required tasks for answering the guiding questions during their free exploration, but repeated those tasks when answering the guiding questions. Apparently they did not realise that they had already seen all the ingredients for answering the questions.

As was the case with 'influence' students also tended to understand 'laziness' merely in an operational way. Take as an example of this operational use the following excerpt:

1. I: What does that laziness do. When you change it?
2. Mic: When it is smaller, the smaller the laziness, the faster.

3. I: Yes.
4. Mer: And the larger [laziness is], the slower [the object moves].
5. I: OK. Is that logical or eh, can we understand that?
6. Mer: Yes, we can. It is kind of hard to explain. What Carlijn mentioned about the ball.
7. I: Hm hm.
8. Mer: When it is heavier, it will simply move slower.
9. I: Yes.
10. Mer: So, I see laziness more as heaviness.

Some found laziness difficult to express, some were uncertain about its effect and some identified it with heaviness (like Merlijn did in the last example (10)) or influence. The distinction between influence and laziness was correctly written down and expressed by only two students. When seen strictly operationally, influence and laziness are indistinguishable, of course. Their effects on the motion are similar and can balance.

Although students observed the phenomenon of balancing, they could not explain why this occurred. Their written answers indicated that the phenomenon of R and L (Kepler) and H and L (Newton) as balancing numbers was slowly remarked. Some students chose sets of values for parameters R and L that differed precisely in the same factor. (If R_1 and L_1 resulted in a match, also did $f \cdot R_1$ and $f \cdot L_1$, with f some constant). This suggests that they at least had an implicit notion of balancing. From the protocols the only example of a developing notion of balancing was the following in which some light dawned on Christiaan. (What Mick was saying here is irrelevant).

1. Chr: I am still only working with the influence. I am changing the influence until it goes right. Not the laziness, you know. With the laziness I don't have to do anything.
2. [Mic: I am changing the laziness.]
3. Chr: Wait a minute. I'll try again. Suppose I increase this one. Than it will have to go slower. This is much slower. But then I can change this again. So, that smaller again, if I am right, no larger, eh, 0,8...
4. [Mic: Oh, he is going to look at his neighbour.]
5. Chr: I turns out the same. Then you can make it the same eventually in that way.
6. I: Hm hm. Yes, so you can choose.
7. Chr: Yes, you can simply choose, You can say: I am going to keep the influence like this, but I do with the laziness, I change the laziness so that it turns out alright.

Christiaan was working on a model in which both the influence (by means of the rotation speed of the sun) and the laziness can be changed. He indicated that he was only changing the influence, letting the laziness unaltered (1). He then decided to increase the laziness, making the correct prediction that the motion should decrease speed (3). He also observed that by changing the influence again (to 0,8) (3), the motion remained the same (5).

Important for explaining the balancing phenomenon is being able to sharply distinguish between influence and laziness, which students found difficult. An example of failing to sharply distinguish between laziness and influence is the following:

1. Mer: Yes. When you increase the laziness, the influence increases too.

2. I: How can you see the difference between influence and laziness in such a model? Can you see that at all?
3. Mer: The influence is this red arrow (...)
4. I: Yes, yes.
5. Car: And the laziness is…
6. Mer: I perceive laziness as kind of the speed of the planet, the ehm earth.

The reasoning during matching did not show arguments from basic ideas. In matching a Newtonian influence law Rosa, for instance, applied the same operational procedure as she did in the case of Kepler by looking at the speed of the planet. Nicole used a new operational procedure by looking at whether the model planet curved too much inward or outward. ('Increasing this number (the laziness) makes the planet curve more outward'). Such a correct operational procedure sufficed of course for these matching assignments, but did not indicate understanding of why the motion is as it is.

After discussing their answers in the evaluation of the introduction the teacher should recapitulate that Kepler and Newton both attributed various lazinesses to various objects and that the laziness of an object indicates how strongly the object reacts to an influence. He should then introduce the next part by stating that Kepler and Newton tried to establish the laziness of different planets and that the topic of the next part is to investigate how they did this.

During the evaluation of the introduction, which took place two lessons later, in lesson 7 (lesson 6 was used for a test), it became clear that students could not tell what laziness is. This main point was therefore repeated, which at least provided students with a proper definition of laziness given by the teacher and later correctly repeated by Mick:

1. T: No example. What is laziness?
2. Mic: Laziness is how an object reacts to an influence. When it react steeply and moves a lot, than the laziness, it is not very lazy. When it reacts little to an influence, it is lazy.

Unfortunately the vagueness in the original definition was also repeated: It remains unclear what exactly 'a reaction to an influence' is or what 'much movement' is. The subsequent main activity and answer phase was sketched as a continuation of an investigation into laziness with an extension to more planets. Its main purpose of finding out how laziness can be determined was not mentioned.

This evaluation (of the introduction) illustrated in a way the use of a proper evaluation. It became clear what students had understood of the preceding part (namely little) and gave an opportunity to do something about it (in this case once more explaining what laziness is).

In the main question and answer phase students should determine (the ratio of) laziness(es) according to Kepler, using a model of two planets, guided by a matching assignment that asks for several solutions. A similar application of a Newtonian model of two planets should lead to the conclusion that in this way the ratio L_{earth}/L_{venus} or H_{earth}/H_{venus} cannot be determined. They should then apply a newly introduced way of determining laziness with a Newtonian model of sun, earth and moon, guided by some preparatory questions asking to calculate the ratio L_{earth}/L_{sun} and whether with this model the laziness of the moon can be determined. These prepare for the question of which planets the laziness can be determined in this way, which is meant to lead to the conclusion that in this way only the laziness of heavenly bodies can be determined if they have another object circling around it. I expect students, guided by several questions, to arrive at the conclusion that Newton's assumption (that laziness equals heaviness equals mass) was right, whereas Kepler's was not.

The main question and answer phase took more time than expected. Many students first had to finish earlier questions. Students were restless. Although they remained mostly on-task, they were less concentrated.

All students could find one correct solution for a match in the Keplerian model for two planets. Only some mentioned a second solution, which underlines the earlier finding that the notion of balancing was not clear. If it had been clear at this stage, a second solution would have been easier to find and write down. All students found a correct ratio for L_{earth}/L_{venus}.

Five students found a correct solution for a match in the Newtonian model for earth and Venus. Nicole and Mick even mentioned the right condition for a solution, $H_{sun} = 900$ and $H_{planet} = L_{planet}$, together with an example. The other students did not answer this question. Four students seemed to understand the idea that the ratio L_{earth}/L_{venus} could not be determined with this model. Two did not answer the related question, one answer I found incomprehensible:

> Mer: No, when you look at his results you don't see any similarities.

And one answer was not true:

> Ros: Yes, the laziness of the earth is 2x as big as that of Venus. You can simply see that.

Most students arrived at correct values for the ratio L_{sun}/L_{earth} in their matching of the Newtonian model for sun, earth and moon. The intended conclusion that the laziness of heavenly bodies can only be determined by matching motions when they have some object circling around them seemed to be reached, for students gave correct answers to the relevant questions. In response to the question whether with the Newtonian model for sun, earth and moon the laziness of the moon could be determined four students were able to write down a correct answer. Take as a typical example the answer of Rosa:

> Ros: You know something of the sun by looking at the earth that circles around it. And information on the earth by the moon that circles around it. The answer is therefore 'no', because you need a planet that circles around the moon.

And also most students correctly stated that only of planets with a moon the laziness can be determined in this way. However, both responses were not given without help of the teacher and in fact echoed the given help.

Most students that managed to get this far in the episode (5) arrived at the conclusion that Keplerian laziness does not equal mass. Three students drew a conclusion regarding the Newtonian idea that laziness equals heaviness equals mass. Jolien concluded that

Newton's assumption is correct (but she did not add this to her summarisation figure), Aisha concluded that Newton's assumption is incorrect because the ratios of H did not precisely equal the ratios of m (there was less than 1% difference) and Nicole concluded that Newton's assumption was incorrect because of a calculation error she made.

In the evaluation the answers should be discussed. The teacher should emphasise the main point, which is the role laziness plays in relating influence to motion. This relation is finally quantified in a text students should read in which the rule 'deviation = influence/laziness' is introduced. I expect in the discussion the question 'which type of model is best?' to slowly surface. This evaluation did not take place. The class continued with the next episode, episode 2.5, omitting the questions most had not finished. The introduction of the rule 'deviation = influence / laziness' was skipped altogether at this stage. The point that this rule is a specification of the relation influence – motion was not addressed. At an earlier stage the question whether one type of model was better than the other surfaced explicitly:

1. Ros: Has already been proved who is right?
2. T: Well, that is really the question for you. Do you have an idea who is right? Which one fits best?
3. Ros: I'd say, I find Kepler quite logical.
4. T: Yes, yes. You find Kepler quite logical and I do so too. And Newton especially with that 2, that ... seems to fit better...
5. Ros: Yes.
6. T: …but he has that illogical story. So that is a bit of a problem...
7. Jol: But when I was at home, before I read about Newton, I thought it would come to a stop, when I hadn't read about Newton. Then I thought it might as well go straight on. That seemed more logical.
8. T: Ah, yes.
9. Ros: Yes, but I find, I don't know. Kepler on that bit about these spokes and stuff, that I find quite logical, but ...
10. T: Yes.
11. Ros: …only, I might also say that they would continue on, but it seems like Kepler did not think things through. Like he wanted to give a kind of too simplistic answer.
12. T: Yes.
13. Jol: He came before.

[...]

14. Ros: But is it the case that one of these two is right? Or is it someone else? Or is it undecided, does one not yet know at all?
15. T: In the end, when you look back with current knowledge they both are not completely right, unfortunately.
16. Ros: But they do know now? Or are these other...
17. T: They know now much better. When you apply the theory of Kepler or Newton, you will encounter errors, deviations. I think the deviations in the case of Newton are a little smaller than those of Kepler. That we also have seen, haven't we?
18. Jol: Yes.
19. T: And I think it is a bit mixed, isn't it. I think the story of Kepler is somewhat more logical and Newton fits somewhat better, so yes.

The question if already had been proven who was right (1) is later sharpened by expressing all possible situations in (14). The question is not answered by the teacher resulting in a discussion about the strengths and weaknesses of the two types of model.

Answering the analysis questions

14. Students' inability to explain why influence and laziness exhibit a balancing effect on the motion and what laziness is, was disappointing. This meant that students did not acquire a clear picture of the different functions of influence (or indirectly the parameters R or H) and laziness.

15. The rule deviation = influence / laziness had not been introduced at this stage. Some students might have read about this rule in the student booklet. However, given the earlier seen result that students did not really understand influence and laziness, their grasp of this rule cannot be firm.

16. The question which type of model is fruitful was seen to pop-up explicitly only once. What was apparent from their investigation of the Keplerian and Newtonian models is that students had not yet decided which type was to be preferred. Although sometimes students arrived at some conclusion regarding the plausibility or validity of some model, this did not yet tip the balance in favour of one or the other. E.g. the idea to assume rest as influence free motion was considered more plausible than the Newtonian equivalent by some and Kepler's assumption that laziness equals mass was considered invalid by others. Since both Newton and Kepler were therefore still in the race one can say that the question which type of model is fruitful had not yet been answered. Whether most students really wanted this question to be answered is hard to say.

Suggestions for improvement

In answering the guiding questions related to the investigation of the computer models the same actions were performed as were done before in a free exploration of the same models. I think this repetition of tasks suggests that the designed guiding questions are indeed necessary to force students to articulate their findings and also that these guides are not too far from the path students would have taken by themselves. The questions seem 'logical' or natural, which is a good sign.

Something should be done to enhance the understanding of laziness beyond the operational level. The matching assignment as it is now can be accomplished with an operational procedure, putting too much emphasis on the guidance from the teacher during the assignment and its evaluation afterwards to raise this to a more meaningful insight. It would be preferable if the assignments themselves already require deeper understanding. How this can be done remains an open question for now.

5.5. Episode 2.5: The precise relation between influence and motion.

What happened?

In the introduction the relation with the main thread should be addressed using the status diagram. What happened was that no introduction took place.

In the main question and answer phase an example of the Newtonian or Keplerian graphical way of constructing subsequent positions should be explained and demonstrated by the teacher, read about in the booklet, illustrated with a computer model depicting a quick succession of constructions of positions of a planet, and applied in one Newtonian (question 89) and one Keplerian (question 88) linear case. The teacher should emphasise the main point, that it is possible in principle to construct the motion from a given influence law, not the specific details.

Students read the complex text on constructing motion from known influences as homework. The next lesson this text was discussed where it became clear that students understood some details, missed other details and one student explicitly asked what its meaning was. These details (amongst which the use of the rule deviation=influence/laziness that should have been introduced in episode 2.4, but was skipped) and the meaning of the episode (in this way any type of motion can be constructed) were discussed. After this the topic of constructing motion from a given influence law was extensively explained by the teacher[8] using the blackboard.

The explanation largely followed the text in the booklet and scenario, but was in some ways confusing. The teacher talked unnecessarily about ‘velocity’ and used the word ‘change’ as a synonym for ‘deviation’ (from the influence free motion). The term influence free motion itself was not used, neither was the explanatory scheme for motion explicitly mentioned, although there were opportunities to repeat it. The concepts laziness and influence were still not clear, as was seen in earlier episodes. Take for example the following response to a teacher question:

1. T: [...] What is laziness again?
2. Car: Laziness?
3. T: Just, in plain... What do you feel with the notion of laziness? Something is very lazy...
4. Ais: Heavy...(...influence...)
5. T: Yes, and when something is very lazy, it will react very ...
6. Car: Bad.

The two students who reacted, Carlijn and Aisha, did not come up with the answer themselves. Carlijn merely filled in an answer of the teacher (6). It is apparently still quite difficult to come up with a description of laziness.

Next the students investigated in pairs a model depicting a quick succession of constructions of positions of a planet guided by an assignment. They found interpreting what they saw on the screen difficult and needed a lot of help in doing so.

Students applied the demonstrated graphical construction technique in the next two assignments (88 and 89). Eventually students were able, with quite some help, to give fairly correct answers to these assignments. Applying the rule

[8] The teacher later indicated that part of the reason for setting this text (which was expected to be too difficult to be comprehended without proper introduction) as homework was to provoke the need for his explanation. Giving students an assignment with the expectation that they will not be able to do it at all is of course in sharp contrast with a problem posing approach.

deviation=influence/laziness to these simple linear Keplerian and Newtonian constructions succeeded quite well.

The meaning of these assignments was not clear at first. Take for example the following two fragments:

1. Car: No clue how to do this.
2. Car: I have no clue how to do this.
3. Mer: No, me neither.
4. Mer: I don't get at all what I am supposed to do.
5. Car: Is that the influence? (10s) So what do you have to do? (4s) Oh, this arrow indicates deviation. (20s)
6. Car: Is this arrow 2 centimeters? Otherwise I won't know too... I think this... How can you draw a deviation arrow?
7. Mer: That's the influence, isn't it? Influence is always in that direction, isn't it. Then these arrows also go in that direction? That is only going straight on.

[...]

8. Mer: Sir, why are we skipping steps?
9. T: Yes?
10. Mer: Why are we skipping steps?
11. T: We do not skip that much. You are doing this now, so that you can understand how the program works, after which you will wonder about other things. I found out that you were filling in these things, but did not undestand what happened with such a program.
12. Mer: Now I don't get at all what we are doing.

Both the meaning and certain details of the assignments were not clear. These students did not know what they were expected to do (1, 2, 3, 4, 12) and wondered about specific details (5, 6, 7). Merlijn asked why steps were passed over (8, 10), which indicates that the assignment apparently did not fit in the main line that she had perceived.

Although these and other difficulties were encountered, students remained on-task and did not abandon their work in frustration.

The main point that motion can in principle be constructed when the influence (law) is known was not emphasised by the teacher during these assignments and was not spontaneously recognised by the students since none mentioned it during the lesson or in the interview about recognition of the main thread at the end of the course.

In the evaluation the questions should be discussed and the main point again emphasised. The quick and bright students should continue with investigating the effect of the time step size (question 90). This did not take place. Not everyone finished the questions. Some students did manage to get as far as the last question (question 90). In relation to that question students noticed that decreasing the time step size gave better results in the sense of a more fluent and exact motion. They could not explain this in detail, as was expected.

As was seen, the execution of this episode differed strongly from the intended design. Apart from the reason encountered before (my inadequate preparation of the teacher) here this was due to a lack of clear instructions in the scenario. These were not worked out to the same extent as for other episodes, because of the optional character of this episode. Furthermore the teacher and I explicitly differed in our goals for this episode. My aim was that students should arrive at some confidence in that given influence laws can lead to motion (by means of a detailed technical exercise), whereas the teacher found the details involved in this exercise itself important. This had a large impact on the outcome of this episode.

Answering the analysis questions

17. Students cannot be expected to fully understand how a motion model may lead to prediction/explanations of motion, because of two reasons. Firstly, this is a new and difficult topic that only after an explanation, reading a text, watching a computer demonstration, working trough some examples and discussing their answers can be expected to be somewhat clearer. Since the execution deviated from the plan, this could no longer be expected. The main point of this episode was not clearly emphasised and no indications were found that students recognised it by themselves. Secondly, students lost themselves in details, which is in stark contrast with the episode's goal that they should trust that the motion of an object can in principle be determined from given influences and type of model, not how this is precisely done. Results from earlier episodes had already shown that the concepts of deviation, influence, laziness and influence free motion were shaky. Getting lost in details in this episode was also related to this unstable grasp of these basic concepts.

18. The question which type of model is fruitful did not explicitly come up. A similar account as was given in section 5.4 in the answer to analysis question 16 can be given here as well: both type of models are still in the race.

Suggestions for improvement

The execution of this episode does not give additional empirical evidence for the claim that this episode can fulfil its function. I still believe that it can, based on the arguments from the scenario, but these were not tested. This episode suffered from 'fall out' from the previous episodes, in the sense that earlier shortcomings were also felt here. It is therefore hard to find suggestions for improvement.

5.6. Conclusion main theme 2

Before drawing some conclusions concerning theme 2 as a whole I will summarise the answers to the analysis questions related to the various episodes in the following table, see Table 2.

Students knowledge is somewhat extended, but not by detailing the explanatory scheme for motion. This main thread was not recognised. Understanding the mechanics content, notably the concepts influence, laziness, influence law, and second law (or the rule deviation=influence/laziness) turned out to be disappointing. This is not that surprising because of the faults in making the main thread clear and explicit. A good execution would have resulted in better results concerning the mechanics. Some indications were found to justify this claim, notably those instances that in students' responses elements were found allowing a natural (meaning in close relation to student input) continuation in the desired direction. Even so, it remains to be seen whether students would have recognised and responded in the expected way to such a 'natural continuation'.

Main theme 2: Extending students' knowledge.		
Function of main theme: Extending students' knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining the motion of heavenly bodies, resulting in a question concerning the fruitfulness of the specific schemes and models.		
Episode	Analysis Questions	Answers
2.1 Transition to Kepler and Newton	10. Are the given examples (of Kepler and Newton) recognised as specifications of the explanatory scheme?	The main thread was not recognised. Most elements were correctly recognised and identified, but their interrelation had not become clear. The use or importance of the influence free motion is not sufficiently clear at this stage.
2.2 Intro-duction to the matching problem	11. Is it clear for students how a detailed explanatory scheme may lead to predictions of motions?	No, because although the meaning of the matching problem did become clear, the necessity for an influence law did not.
2.3 Influence laws	12. Has students' insight in the *what* and *how* of specifications of the explanatory scheme for motion deepened, or more concretely:	Students' insight in motion models has deepened somewhat, although not as much as expected or possible, because:
	- Can students translate assumptions of K and N concerning influences into an influence law?	Yes
	- Do they understand the function of an influence law?	Students realised that an influence law is needed to calculate the motion of a planet around the sun, but did not see that it is a specification or quantified expression of the earlier seen regularities of Kepler and Newton.
	- Do they see that alternative laws are possible?	Yes.
	- Do they understand the role of parameters in the models?	No. Their understanding remained on the level of operational understanding.
	- Do they understand what testing a model entails?	Yes.
	- Do they get more feeling for the difference between K and N?	No, but they could have.
	13. Does the question which type of model is fruitful slowly start to pop-up?	This was not seen.
2.4 Laziness	14. Do students know what laziness is and does?	No.
	15. Do they know the rule deviation = influence / laziness?	No.
	16. Does the question which type of model is fruitful slowly start to pop-up?	Yes, although seen only once.
2.5 The precise relation between influence and motion	17. To what extent do students understand the method of graphically constructing motions from given influences?	Students have little sense that the motion of an object can be determined from the given influences and type of model. They were rather lost in the details, which use did not become clear.
	18. Does the question which type of model is fruitful come up?	No.

Table 2: Summary of answers to analysis questions of main theme 2

The project of comparison of alternative types of model was successful in the sense that students did manage to use the criteria of empirical adequacy and plausibility for choosing between models and both types of model remained feasible as alternative. The question concerning the fruitfulness of these types of model was hardly ever explicitly raised, but seems to be still relevant because students have not yet decided which type of model is more fruitful.

6. Evaluation of models and *types* of model in the light of achieving broader applicability.

6.1. Episode 3.1: Reflection on types of model

What happened?

The teacher should introduce this reflection by remarking that in order to decide how to continue it would be useful to look back for a moment. There was no such introduction.

The questions (question 44 - 49) of the main question and answer phase, in which all previous main points of the introductory course are captured, were supposed to be done in the thinking-sharing-exchanging format. The thinking phase was done as homework and students were given a procedural reason for paying much attention to this homework, which they did.

In the sharing phase of the evaluation the students should share in small groups their answers to questions 44 – 49. Here they were expected to complete missing elements in their answers and try to reach agreement within their groups on what proper answers should be. What happened was that the homework was shared in groups of three or four students. Sharing consisted mainly of reading out one’s answers and adding or completing one’s own answers when one agreed with another answer. Earlier written down text was seldom changed nor challenged. In the conversations students seldom disagreed, although they sometimes should have when answers diverged.

In the exchanging phase of the evaluation the findings of the groups should be exchanged in the class. Possible wrong or incomplete group answers can now be corrected or completed. The conclusion that both kinds of model can be argued for at this stage also can provide the basis for the continuation in the next episode. The teacher should ensure that the mentioned conclusion surfaces in as close a connection to the students input as possible, which is, needless to say, quite a challenge. He also should introduce (or if possible even point out in some group response) the additional criterion of broad applicability that will allow for a feasible test of the types of model by applying them to other motions, e.g. motions on earth. In that way the still open question of which kind of model is to be preferred can perhaps be answered as will be tried in the next episode.

It followed from the written answers that the central question of the introductory course (question 44) and the function of the explanatory scheme in answering that central question (question 45) had not become clear. Only one student mentioned the explanation of motion in response to question 44, others mentioned for instance ‘what is motion' or 'what is the connection between influence and motion'. No one could clearly state what the explanatory scheme is. Two examples are:

> Mic: A scheme with the regularities and the change. The difference between the influence free and the influence.
>
> Jol: A scheme in which a situation of a motion is depicted and all factors that are relevant.

The students seemed to equate the explanatory scheme with the figure depicting the scheme (which is not surprising given that the word 'scheme' already suggests some depiction), and not with the three lines stating the scheme in the student booklet I would have expected as an answer.

The subsequent investigation of Keplerian and Newtonian models had come across better, since students could correctly point out differences between these types of model (question 46) (mainly the different influence laws were mentioned, but also other differences) and they fairly well understood why and how that investigation took place and with what results (questions 47 and 48). Amongst the students some implicit criteria like plausibility and empirical adequacy for estimating the value of a type of model (question 49) could be found. Mick and Merlijn mentioned the plausibility of the influence law:

> Mic: And I found about the rotation speed of the sun of Kepler and the mass [he means heaviness] of Newton, I found both good arguments, you know.
>
> Mer: Also Newton is talking about heavinesses, the laziness and Kepler about rotation. I don't believe that the rotation of the earth has got anything to do with the influence, unless the earth would start rotating real fast.

They argued that Kepler's and Newton's ideas about what the influence depends on are both credible (Mick) or one is not (Merlijn), which is important for an influence law.

Empirical adequacy could be recognised in the following statements by Mick, Merlijn and Aisha:

> Mic: But Kepler [he means Newton] had a better mathematical influence law, one that matched exactly on that computer.
>
> Mer: I am for Newton, with power of r is 2, because it fitted best in that assignment.
>
> Ais: I would choose Newton, because these models match better [with reality] than the models of Kepler.

The same students used the argument I expected to be difficult, namely that Newton's assumption that laziness equals heaviness equals mass is right while Kepler's that laziness equals mass is not, and that this suggests that Newtonian models are preferable. Nicole further qualified this argument:

> Nic: Well yes, in certain aspects I think he is right, but for example Kepler, that laziness equals mass which turned out wrong, his assumption, that does not say that much, because that was with one influence law, so it might be right for another influence law. So that is why I was still vacillating.

I think this is quite a subtle argument. The fact that she picked it up from the teacher slightly diminishes but in no way negates her achievement.

Apart from these intended criteria students also mentioned as criterion the believability of the assumption for an influence free motion, which was also slightly encouraged by the teacher. The criterion of broad applicability was not mentioned.

In the evaluation/exchanging in the class only question 49 was discussed, with an emphasis on which model was best. As was seen, students made use of expected criteria in their written answers, but these were not emphasised and made explicit by the teacher. A clear summary of the answers to the preceding questions was not made.

Students were uncertain about which model is preferable (and why!), which is good. Both types of model are still in the race. Mick and Nicole wrote:

> Mic: I can't choose

> Nic: I really don't know yet where my preference lies.

Aisha indicated for both Kepler and Newton why she would choose for either. Merlijn argues extensively for Newton. Carlijn prefers Newton based on the laziness equals heaviness equals mass argument. Jolien and Rosa did not answer question 49. So only Merlijn had at this stage made up her mind. The teacher mentioned that there seemed to be a slight preference for Newton because of the more precise matching results (empirical adequacy). The message that both kinds of models are still in the race remained implicit, but seemed clear. Otherwise students would have expected some conclusion indicating Newton as the winner. An idea for further investigation was now introduced without relating to student input and without it being clear that it was an idea for further investigation.

Answering the analysis questions

19. The criteria for valuing models and types of model did not surface clearly. Although implicit use has been made of the criteria plausibility an empirical adequacy, this use was not made explicit. The fact that students made use of the intended criteria at all is encouraging, given the earlier shortcomings and difficulties and the deviations in the execution of this episode. This indicates that these criteria are quite robust and intuitive, as was also seen in the first trial (see chapter 4, sections 2.2.2 and 2.3.2).

20. A strategy for further investigation did not surface at all, but could have surfaced in the way I will describe in the part 'suggestions for improvement' in this section.

Concluding remarks

Apart from the expected criteria students used another criterion, namely the believability of the assumption for an influence free motion. This is not a correct criterion, for this assumption cannot be separated from the identified influences. To realise that this is a mistake would require understanding of the difficult and subtle point of the coupling between assumption for influence free motion and identified influences, which is the basic idea of the explanatory scheme for motion. In the first two themes was already seen that this idea had not come sufficiently across, which was confirmed by the students' responses to the reflective questions in this episode. It is therefore not surprising that this particular mistake was made here.

The central question of the introductory course and the function of the explanatory scheme in answering that central question have not become clear. The subsequent investigation of Keplerian and Newtonian models has come across better, since students can correctly point out differences between these types of model and they fairly well understood why and how that investigation took place and with what results. Amongst the students some implicit and explicit criteria for estimating the value of a type of model were used. Unfortunately this was not clearly summarised in a class discussion at the end and it did not function as a guide for further investigation although it might have, as I will try to show in the next part of this section.

Suggestions for improvement

The exchanging could have been done more naturally, i.e. using student input, but the scenario was also not clear or lacking on this point. This episode might have been evaluated in a way that summarised and emphasised the main point of how to choose between types of model, addressed the mentioned wrong criterion, introduced the criterion of broad applicability and provided for a perspective on or even motive for the next episode. A possible way would have been the following:

> *We agree that it is not decided which kind of model (Keplerian or Newtonian) is preferable. We have seen some criteria (assuming that the mentioned criteria have been highlighted in an earlier exchanging of students' answers) with which we could look at the quality of a model. Who has got some idea of how to continue? What can we do to find out which kind of model is to be preferred?*

When this proves to be too open, the following question might be helpful:

> *We could look to other influences and/or other motions. Has someone got a suggestion?*

Then a discussion could follow of how some given concrete suggestion would shed light on the question whether Keplerian or Newtonian models are to be preferred. For example when someone suggests investigating some other motions, it can be shown that when a model describes and predicts this motion also correctly (as it did in the case of planetary motions) this model would rank higher on the criterion of broad applicability (as well as the criterion of empirical adequacy).

In retrospect the lack of critical sharing of answers amongst students is not surprising since the design did not provide an additional assignment related to the sharing although the used interaction structure 'thinking – sharing – exchanging' (see chapter 4, Table 7) explicitly calls for some 'deepening' assignment. The task to try and reach agreement about the answers is not enough for students to critically evaluate each other's answers. This omission in the scenario should be corrected in a revised edition.

6.2. Episode 3.2: Introduction to a choice between types of model for a situation on earth

What happened?

In the introduction the main thread should be emphasised, that by applying Kepler and Newton to situations on earth we try to find out more about the value of these two types of model. The introduction failed to make the relation with the previous episodes clear. The reason for applying Kepler and Newton was not introduced, which was very unfortunate since the previous episode failed to result in a plan for further investigation consisting of an application of Kepler and Newton to situations on earth. This failure might to some extent have been repaired by a proper introduction here.

In the main question and answer phase students should work in a group on one example guided by questions asking to apply step by step a Keplerian and Newtonian model to the example. One group worked on the bicycle example (with the related questions 50 - 54), another group on the hovercraft example (with the related questions 60 - 64).

With some help, which included a graphical construction showing the resulting motion of one opposing influence, questions 50 - 53 were answered as intended. The response to question 54 showed a notion that Kepler's model might be improved by changing its assumption for an influence free motion. Take as an example the following answer, which is typical for this group:

> Mer: Kepler is not right. You could make it right by changing the influence free motion.

The other group also answered questions 60 - 63 as intended. Their answer to question 64 reflected the 'help' given to these students. This group was by a confusing explanation mistakenly led to believe that Newtonian models had to take account of some aftereffect of the push the moving object had received in the past[9]. Before this explanation they did not show any signs of thinking in this direction. These students were now led to believe that Newtonian models exhibit problematic behaviour, whereas they did not mention any problem with the Keplerian model. The same opinion was also expressed by one of them (Mick) in the FCI items interview at the end of the course: an unfortunate explanation indeed!

In the evaluation the groups' findings should be exchanged so that everyone has seen two examples. Students should then answer questions why Keplerian and Newtonian models have been applied to motions on earth (65), what their conclusion was concerning the applicability of Newton and Kepler on a situation on earth (66) and what they could say about the value of these two kinds of models in general (67). I expected that these questions would guide students to the conclusion that applying Kepler to the used examples of motion lead to a problem in the sense of that it predicted a motion that is known not to occur. Newton did not give such a problem and is therefore broader applicable. The teacher should sharpen the answers keeping the criteria plausibility,

[9] The idea of introducing some way of taking account of aftereffects of influences from the past might be a way to repair *Keplerian* models.

empirical adequacy and broad applicability in mind. He should then end by stating that since we now value Newtonian models more than Keplerian, we can try to solve the initial asteroid problem using a Newtonian model (with the best influence law we encountered).

In the evaluation the group work was exchanged in a class discussion, which also showed that the problems that applying Kepler led to had not come across in the hovercraft group. This was at this stage not addressed nor repaired. The following fragment illustrates the misapprehension of Newton and uncertainty of Kepler. Mick reported the findings of his group, which is the hovercraft group:

1. Mic: Yes, what did we find? I was about to say that. That… so it moves with constant velocity straight on, so it would appear that this Newton is right, but he first gave a push before it moved with constant velocity straight on, so there had been an influence in the beginning.
2. T: Can you follow this?
3. Ais?: Yes… a little bit.
4. Mic: And yes… so it surfaced that, one should not only look at the moment itself, but also what had happened in the past, for example looking at that push, which made it move straight on.
5. T: Okay, and when you look at the conclusion, what is your conclusion?
6. Car: That … of Newton is kind of right, but in the beginning … it is not totally complete. He only looks at what happens after, but not before.
7. T: So Newton is right, but you have to properly look at the past. And Kepler … is right or not so?
8. Car: Ehm … well…
9. Mic: Yes.

So according to this group Newtonian models are incomplete (6) taking no account of aftereffects of earlier influences (4) and Keplerian models trigger some uncertainty (8). Although the bicycle group did find the expected problems with Kepler and these were reported in the class, this was not emphasised and did not result in revising the written answers of the hovercraft group (it literally did not register).

During the same discussion the concluding question 65 was answered collectively. Although questions 66 and 67 were skipped in this discussion, most students had written down their answers. The responses to the question of why it was tried to apply Keplerian and Newtonian models to motions on earth (65) did seem to indicate the expected reason, since they all mentioned something like ‘universal theory’, but these answers echoed the answer given by the teacher.

Students’ written conclusions concerning the applicability of Newton and Kepler on a situation on earth (question 66) indicated that the notion that the model of Newton is better applicable to situations on earth had not clearly surfaced. It could only be recognised in three written answers. Only one student explicitly stated that the Keplerian model led to problems.

None of the students gave the intended reason for preferring Newton over Kepler (question 67), which is that since Newton is also applicable to earthly situations it is more broadly applicable than Kepler.

Students were clearly involved in the project of deciding who is right, Kepler or Newton.

Answering the analysis questions

21. Students can not give the intended reason to value Newton above Kepler. The group involved in the bicycle assignments did notice that applying Kepler to the motion of a bicycle encounters (perhaps solvable) problems and that applying Newton does not. However, since they did not state this in their concluding answer to question 67, it is doubtful whether they recognised the importance of this observation. The group involved with the hovercraft, in contrast, saw mainly problems with applying Newton, which can be attributed to the unfortunate explanation of the teacher and to a shortcoming in this example that will be discussed below. Some intended criteria, as well as a not intended criterion, for valuing models were used, but these were not highlighted and explicitly discussed and therefore did not function clearly enough as a basis for a reason for preferring Newton above Kepler.

22. Students did not see the reason for applying Kepler and Newton to a situation on earth. Although they were able to write the intended reason down, this answer could have been merely an echo of the answer supplied by the teacher. Additional information is provided in the interviews at the end of the course. In these interviews none (with the possible exception of Nicole) could explain why the transition to situations on earth had taken place. I surmise that if the written down response to question 65 had been students' own response, more students would have remembered this answer during the interview.

23. The application of Kepler did not recognisably (for the students) lead to problems. See also my earlier remark in response to analysis question 21.

Conclusion and suggestions for improvement

Answers to the analysis questions briefly recapitulated here:

- Students cannot give the intended reason to value Newton over Kepler.
- Students do not see the application to situations on earth as an additional way to find out more about the value of the two types of model.
- The application of Kepler did not recognisably (for the students) lead to problems.

show a lack of success of this episode. This can be attributed to earlier malfunctions in the design that made itself felt here, deviations from the planned execution and omissions in the scenario.

The earlier failure to elicit a strategy for further investigation in episode 3.1 made itself felt here. In section 6.1 I argued that this strategy might have been elicited because the condition was present that both Kepler and Newton were considered to be still in the race. Even without students coming up with a strategy themselves, a proper introduction of episode 3.2 might have repaired to some extent the failure of episode 3.1. Students are visibly involved in the project of deciding who is right, Kepler or Newton, from which a further investigation can be motivated by using or introducing the criterion of broad applicability. The scenario was unclear in this particular point of explicitly applying the criterion of broad applicability.

Another earlier failure that was felt here was that the coupling between influence free motions and identified influences has not been understood. This resulted here in the unintended use of the criterion of 'implausible assumption for the influence free motion' that Newton had been accused of.

An omission in the scenario was how to use, and the importance of using, criteria to determine the value of the two types of model. Students did use (intended and not intended) criteria. It therefore seemed not too difficult to highlight these criteria and use them more explicitly in answering the questions, as was also discussed in section 6.1. This could also clarify the main thread: Application to earthly situations can be seen in light of the criterion of broad applicability. I expect that when the scenario is revised in this direction this episode can better fulfil its function.

A shortcoming in the scenario was a confusing element in the hovercraft example, that did not occur in the bicycle example. In the case of the bicycle rider the Keplerian model led to an obviously wrong prediction of the motion after the bicycle rider stops pedalling (namely an instantaneous reversal of direction and speed). In the case of the hovercraft the motion the Keplerian model predicted after switching on the propeller could be 'continuing in the same direction with greater constant speed, for which some acceleration (instantaneous, very quick, …) would be needed. Newton would predict continuous acceleration. When one does not look at what happens the moment the propeller is switched on, but some moments later, one sees that the motion predicted by Kepler is more like the actual observed motion than the one predicted by Newton. So Kepler appears to be in better shape than Newton (which is of course due to the no longer negligible air friction balancing the force of the propeller). This interpretation of the situation depicted in this assignment was not intended but seems quite obvious in retrospect. This question should therefore be revised to account for this unintended possibility, in such a manner that students are unavoidably led to the conclusion that applying Kepler to some well chosen situations on earth leads to problems, whereas Newton does not.

6.3. Episode 3.3: Asteroid problem, mechanicism and transition to the regular course

What happened?

In the introduction the teacher should recall the initial asteroid problem and the (implicit) promise that this problem would be solved in this introductory course. He announces that this will now be done using a Newtonian model with the best influence law. He also announces that an additional argument for why mechanics is important will be encountered that returns to the earlier seen example of the dissolution of sugar in tea.

What happened was that the teacher did not indicate that students were returning to the asteroid problem, but that they were to continue with an application to an asteroid. The mechanicism part was not introduced here nor as wrapping-up of the asteroid problem part of the episode. Instead the teacher directly started to give an explanation of mechanicism.

In the main question and answer phase students should investigate a Newtonian computer model of an asteroid, the earth and the sun in which they are meant to recognise the various elements of the Newtonian specification of the explanatory scheme for motion. The conclusion students were expected to reach was that whether the asteroid hits the earth depends entirely on the starting conditions. The relevant questions 68, 71, 72 and 73 were answered as expected and with little help from the teacher or researcher. Students can therefore recognise the elements of the explanatory scheme in the code of a Newtonian model of an asteroid. The expected conclusion was not found in response to the relevant question (77) nor in students' conversations and also not in any discussion of these answers (since that was lacking). In response to question 77 (the students who managed to get that far) gave 4 or 5 values for the mass of asteroid and earth with which they collide. In retrospect this was not surprising since varying other initial values like velocity or position was a new aspect in this computer model, that had not been emphasised enough (it was only mentioned in the booklet). This made the intended conclusion more difficult to surface.

Next the topic of mechanicism should follow as part of the main question and answer phase.

Students should read a text in which mechanicism is introduced. That matter can be though of to consist of moving and interacting particles and that macroscopic change can be understood in terms of unchanging particles is illustrated with the example of sugar dissolving in tea. Students answer questions about what they imagine these particles to be like (question 82), what will happen with the particles during dissolution (question 83), why this would explain the observed phenomenon that solid sugar 'disappears' (question 84), why dissolution would go quicker when the tea is stirred (question 85) and why the dissolution would go quicker when the temperature is higher (question 86). I expect the students to come up with perhaps ingenious answers to questions 82 – 85. The last question is probably too difficult. It is meant to show that a plausible answer is possible, although it may have to be brought in by the teacher.

Unfortunately the teacher did not clarify what microscopic explanations of macroscopic phenomena entail, let alone the role the mechanics of particles plays in those, but jumped to the philosophical consequences regarding free will that a mechanicistic or deterministic perspective may lead to. The given explanation on mechanicism focussed on different points than the intended role mechanics might play in understanding all change. It glossed over ideas I would expect far from obvious, namely that matter can be thought to consist of moving and interacting particles and that macroscopic change can be understood in terms of unchanging particles (that is to say the only thing that changes in the particles is their position and velocity). Students can not be expected to have picked up these ideas from the explanation.

In the evaluation the teacher should take stock of the students' answers concerning the asteroid problem, check whether they consider this solved, take stock of some answers concerning the mechanicism and bridge the introductory course to the regular course. This was not done.

Answering the analysis questions

24. Students have little appreciation for the power and range of Newtonian motion models. Appreciation was supposed to increase in this episode by the mechanicism account, which, given the way it was executed, cannot be expected to have fulfilled this function. Additional information related to this analysis question can be found in the interviews at the end of the course in which I asked students specifically about their recognition of the main thread. From these interviews (that will not be further reported) it became clear that most students were unable to explain why they did the bit on mechanicism. Only two students could say something correct about mechanicism. Expectations of what they will be learning later on in the regular course on mechanics were vague and uncertain. Students therefore did not arrive at a notion of mechanics as being far ranging or having great scope. This did not hinge on appreciating the mechanicism argument (although this also contributed), but is an effect of continually failing to make the main thread clear enough to be recognised. When students do not really know what mechanics is all about it is hard to appreciate its power and range.

25. Students considered the asteroid problem solved, when asked[10] in the interview concerning the recognition of the main thread at the end of the course. All students considered that the implicit promise at the beginning of the course that at the end of the course the asteroid problem would have been solved was met. None felt cheated in this respect. All students except one had the idea (justified or not) that they were able in principle to calculate whether the asteroid would hit the earth or not.

Suggestions for improvement

The additional feature of the computer model of the asteroid, it allowed changing the initial values for the position and velocity of the asteroid and earth, needs more explicit introduction when retained or can be skipped altogether. Its function was to show that a collision depends entirely on such starting values. In retrospect the function of the asteroid problem at this stage is merely to show that it can be solved with a proper model, for which varying initial values is not essential.

The mechanicism account did not function as expected. It is hard to say whether it would have functioned when it would have been executed as intended. I think it is weak even in a proper execution. Although it shows how some macroscopic phenomenon can be explained and understood in terms of moving and interacting particles, it does not show how actually calculating the motion of these particles adds up to a macroscopic phenomenon. The point that since particles are moving, mechanics would be applicable and therefore important glosses over the question how mechanics would help understanding/explaining/predicting the phenomenon. Calculating the motion of sugar and tea particles does not help in any way to understand better the common phenomenon of dissolution of sugar in tea. I am afraid that another example which actually shows how microscopic calculations add up to some macroscopic phenomenon will be too difficult.

[10] Without such a question I think none would have remembered that such an implicit promise had been made.

6.4. Conclusion main theme 3

Before drawing some conclusions concerning main theme 3 as a whole I will summarise the answers to the analysis questions related to the various episodes in the following table, see Table 3.

<table>
<tr><td colspan="3">Main theme 3: Evaluation of models and types of model in the light of achieving broader applicability.</td></tr>
<tr><td colspan="3">Function of main theme: Both a reflection on criteria to determine which type of model explains best and subsequent application of these criteria should result in an appreciation of Newtonian models and an outlook on the regular course.</td></tr>
<tr><td>Episode</td><td>Analysis Questions</td><td>Answers</td></tr>
<tr><td rowspan="2">3.1 Reflection on types of model</td><td>19. Do the criteria for valuing models and types of model surface clearly?</td><td>No. Although implicit use has been made of the criteria plausibility an empirical adequacy, this use was not made explicit.</td></tr>
<tr><td>20. Does a strategy for further investigation surface naturally?</td><td>No, it did not surface at all, but it might have.</td></tr>
<tr><td rowspan="3">3.2 Introduction to a choice between types of model for a situation on earth</td><td>21. Can students give reasons to value N above K?</td><td>No. Some intended criteria for valuing models were used, but these were not highlighted and explicitly discussed and therefore did not function clearly enough as a basis for a reason for preferring Newton to Kepler.</td></tr>
<tr><td>22. Do students see the reason for applying K and N to a situation on earth?</td><td>No. In the interviews at the end of the course none could explain why the transition to situations on earth had taken place.</td></tr>
<tr><td>23. Does the application of K recognisably (for the students) lead to problems?</td><td>No.</td></tr>
<tr><td rowspan="2">3.3 Asteroid problem, mechanicism and transition to the regular course</td><td>24. Do they have some impression of the power and range of Newtonian models?</td><td>Very little. Students did not arrive at a notion of mechanics as being far ranging or having great scope. This is an effect of continually failing to make the main thread clear enough to be recognised. When students do not really know what mechanics is all about it is hard to appreciate its power and range.</td></tr>
<tr><td>25. Do they consider the asteroid problem solved?</td><td>Yes.</td></tr>
</table>

Table 3: Summary of answers to analysis questions of main theme 3

Criteria to determine which type of models explains best can be used and were used, but should be made more explicit, especially ‘broad applicability’.

Appreciation of Newtonian models can be expected to be better when the main thread is more used and explicated. Now the design suffers from cumulative effects of earlier failures in main theme 1 and 2. The mechanicism part seems now not very strong.

An outlook on the regular course has hardly been achieved. Such an outlook would have been provided by a clear perspective on the main thread of ‘this is mechanics’, which was now lacking.

7. Choices for interaction structures

The recurrent phenomenon in the episodes was that an important question to answer in the analysis of each episode, namely whether the choice for the used interaction structure was good, was difficult to answer. The difficulty lays in the fact that most episodes were not executed as intended mainly in respect to the interaction (an exception was episode 1.4 that went largely according to plan). Usually the main activity went all right, but was not properly introduced and evaluated. Since the difference between the used interaction structures mainly lay in the evaluation part, it became very hard to find any empirical backing for the choices that were made. What *could* be seen sometimes was that an evaluation might have taken place as intended given the kind of student input from the main activity (examples are episode 1.1, 1.2, 1.5, 2.3 and 3.1). These instances then provided a minor empirical backing for the choice of interaction structure. Although showing that an evaluation could be given in close connection to student input suggested that the students would have understood such an evaluation, this was not tested and therefore remains to be seen. On the other hand, the experiences with the scenario did not invalidate the arguments for the choices of interaction structures given in the scenario. This part of the design therefore remains largely hypothetical, in the sense that arguments for particular interaction structures are based on ideas instead of empirical findings.

8. Embedding in the regular mechanics course

The fourth main theme, embedding in the regular course, concerns the directions and guidance given for the regular course as was written down in the link-manual.

The experiences with the link-manual came from two sources. Firstly, the second teacher reported some experiences in an interview I held with him during the regular course. Secondly, students were interviewed during the regular course in which they were asked whether they recognised elements of the introductory course in the regular course. Furthermore they were asked to solve some textbook problems that were selected to trigger possible use of elements of the introductory course. I will subsequently discuss these two kinds of experiences with the link-manual.

Experiences reported by the teacher

Unfortunately the experiences with the link-manuals after both introductory courses are very limited. The teachers did not use them, which is probably due to the advisory nature of both the link-manual itself and the introduction of the manual during the teacher preparation. Both were largely in the form of suggestions for adaptations of the regular course. This way of presenting left the teachers a lot of room for ignoring it. The second teacher reported some ‘natural’ use of the explanatory scheme for motion that was mainly instigated by himself without use of the link-manual and then recognised by the students. He gave the examples of two falling objects of different mass and a vertically moving pellet shot from a horizontal moving cart (observed using a photograph and a stroboscope), which, he noticed, could be quite naturally explained by him using the concept of influence free motion after which he observed an 'aha-erlebnis' in students. Another idea that the teacher claimed was now better understood was that absence of force not necessarily implies rest. Furthermore he encountered no difficulties in the transition in language from laziness to mass and from influence to force et cetera. He also mentioned the more general perspective on mechanics.

A positive side-effect of the way of working during the course that still lingered in the regular course was that students did stick to a cooperative way of working that emphasised understanding, according to the teacher.

Some time after this interview the second teacher expressed some disappointment about how little spontaneous transfer could be noticed. The fact that he expected spontaneous transfer indicates that something went seriously wrong in my presentation of the link-manual to him. Apparently the whole basis on which this document was built, i.e. the tenet that specific effort has to be made to show and use the connections between introductory and regular course had not been convincing or had not come across. A discussion of my preparation of the teachers took place in section 3 of chapter 4 and also section 3 of this chapter.

Experiences from student interviews

I will first describe the method and design of these interviews and then the results.

Method

During the regular course interviews were held with students to see to what extent the introductory course was useful in discussing (conceptual) mechanics problems. How do students reason with these problems? Do they use elements of the course or recognise them when they are used by the interviewer, like the explanatory scheme for motion? Useful instances of possible application of the introductory course are questions that trigger the usual learning difficulties encountered in mechanics for which this course aimed to provide some means of addressing them. In these interviews students were therefore presented with such questions. When students could discuss these questions with each other and with the interviewer, this was expected to provide information for the research question of this interview of how students reason with these problems and, as part of that question, whether they use elements of the course or recognise them when they are used by the interviewer.

Questions that were used in these interviews were obtained from the well known FCI, mentioned in chapter 2, because use of FCI items has the advantage that the common opinion seems to agree that these questions really concern the classic learning difficulties in mechanics. A meaningful discussion of these questions can therefore be more convincing than a similar discussion of questions I cooked up myself. In the latter case I would have to provide some arguments for that the question triggers some conceptual problem, which can in principle be done, but in practice is less efficient than using what is already available. A discussion of all answer alternatives (instead of merely selecting one from the multiple choice alternatives) could show the reasoning behind the choice and could therefore allow some use of the introductory course to become visible. Pointing out why some alternatives are wrong from the Newtonian perspective is just as interesting and informative as pointing out why one alternative is right. I therefore retained the original multiple choice alternatives, but let students discuss all alternatives. Four interviews were held with the total of eight students that participated in the second trial: two pairs, one group of three students and one single student.

Not all FCI items were relevant for my purposes. For instance many items can hardly be answered with knowledge from the introductory course. The selection of relevant questions happened in the following way: All FCI items were analysed using the conceptual material of the introductory course, each time starting from first principles.

Take for example the first FCI item:

> 1. Two metal balls are the same size, but one weighs twice as much as the other. The balls are dropped from the top of a two story building at the same instant of time. The time it takes the balls to reach the ground below will be:
>
> (A) about half as long for the heavier ball.
>
> (B) about half as long for the lighter ball.
>
> (C) about the same time for both balls.
>
> (D) considerably less for the heavier ball, but not necessarily half as long.
>
> (E) considerably less for the lighter ball, but not necessarily half as long.

To answer this question from first principles using the introductory course would result in a very complex argument like the following:

> The influences working on the ball are gravity and air friction. The air friction on a metal ball is probably negligible compared to gravity. Gravity on the ball is proportional to its heaviness. The deviation from the influence free motion that is generated each time step by gravity is therefore proportional to heaviness/laziness. When we assume that heaviness equals laziness (and equals mass), then the deviation from the influence free motion generated each time step by gravity would be the same for both balls. Since both balls start from the same height from rest, they will in fact both move in the same way. They will therefore reach the ground simultaneously and almost simultaneously when air friction is taken into account. The answer is therefore alternative C.

This question is in theory answerable using the introductory course and therefore one might think that students can be expected to fare slightly better on this question after a successfully designed and executed introductory course, than without such an introduction. However, since the argument for arriving at the answer is very complex this expectation is more likely to shrivel to unnoticeable size.

All FCI items were analysed in this way which resulted in expectations about which questions students would answer better after the introductory course. A more complex argument, as the one seen above, generally indicated that little improvement could be expected. For more simple ones more improvement could be expected. This resulted in a subset of FCI questions that are relevant for this course and that contain the questions 5, 8, 10, 18, 22, 27, 28 and when the optional episode 2.5 is part of the course also questions 6, 24 and 26, see appendix I. These questions were discussed in the interviews. Recurrent guiding questions in the identification of forces that the interviewer posed were related to the two aspects of mechanics: the relation influence – motion and a plausible interaction theory. The former can be expressed as ‘why does the identified force have to be working?’. The latter can be expressed as ‘where does the force come from?’ From the interviews themes were identified around recurrent topics like frequently used arguments, the kinds of non-Newtonian notions that surface or particular successful or unsuccessful ways of addressing these notions.

Results from these interviews

I identified recurrent notions from the interviews that were held and grouped these into themes. Some of these themes I like to discuss here, for they contain some clues how students reason, the kind of arguments they use and how this reasoning might be corrected (that is modified in a more Newtonian way of reasoning) in a way that makes sense to them. Two of these themes concern two typical non-Newtonian notions that were triggered in the students by the questions. In the discussion of these notions two typical arguments were used to identify forces. A seemingly successful way of using elements of the introductory course to address these non-Newtonian notions made use of the graphical construction method.

I will now give an account of these two non-Newtonian notions, the two typical arguments and the way of addressing, illustrated with quite a lot of fragments to give the reader a feel for the way students talked about explaining motions. These examples were selected to illustrate these themes as clearly as possible. Although with four interviews and seven students it is somewhat ridiculous to talk about *typical* examples, the following examples do indicate features common to more than one student.

One non-Newtonian notion that occurred time and again is the Keplerian notion that (larger) speed is accompanied by (larger) force. Take for example a response to FCI item 5 concerning the identification of forces working on a vertically thrown object:

1. I: […]. If you had to choose between these, what would you choose?
2. Ros: Between B and C?
3. I: Yes.
4. Ros: I’d choose B.
5. I: Why?
6. Ros: Because here ehm, let’s say constant, at C it goes constant down, that ball?
7. I: No, It says a constant gravity
8. Ros: But with that gravity they just mean how fast it goes down, don’t they?
9. I: No, with gravity they mean a Newtonian influence, named gravity.
10. Ros: (Then I don’t know what).

Rosa seems to equate gravity with ‘how fast it goes down’ (8).

Another recurrent non-Newtonian notion is the idea of a force having an aftereffect. Take for example the following response to FCI item 27 concerning the speed of a rocket after its engine has been turned off at point c.

1. I: After c there is no influence any longer, is there?
2. Jol: No, I know that. But first, that it will go faster after that by the influence before c.
3. I: Hm hm.

4. Jol: But then it could not.
5. I: I don't understand it completely.
6. Jol: No, because look. Yes. Before point c, than there is an influence. Then after after point c …[audio tape ends]
7. I: Okay. No allright. But your idea would be that it in fact after c, that the influence in a way still works…
8. Jol: Yes.
9. I: … (then) goes somewhat faster. And after that moves constantly. Yes?
10. Jol: Yes.

Jolien specifically mentions that she is aware that the initial influence had ceased (1, 2). However, she still attributes some lingering effect of this influence after it had ceased (6). Jolien assents to my interpretation of this as an aftereffect in (7, 8).

The recurrence of non-Newtonian notions such as these need not be surprising. I did not expect the introductory course, even an improved and well executed one, to make students into Newtonian thinkers. I am therefore not in the least bit concerned that notions such as the two presented surfaced. What is interesting is how these notions are discussed. It is precisely in discussing such notions that the introductory course may show some effect, and it was for this reason (checking whether such an effect can be seen) that these interviews were held.

How were these kinds of problem discussed? Two elements that were frequently used in the discussions by the students (and interviewer) when identifying influences were the arguments from interaction theory ('where does the force come from?') and from the relation force – motion ('why does the identified force have to be working?'). The following examples show how these arguments were used:

The argument from the relation force – motion:

1. Jol: Yes, I think that the gravity remains constant, for the ball is not thrown that high. So, I don't think that gravity increases or decreases.
2. I: Okay. But gravity has to be there, according to you.
3. Jol: Yes.
4. I: Why?
5. Jol: Otherwise it would keep floating.

The influence has to be present because otherwise the motion would be different. The following example shows a more elaborate use of the same argument:

1. Chr: Yeah. (There are of course) motion (…) Something has to have some effect. There has to be some force that has some effect.
2. I: Hm hm. Why is that?
3. Chr: Well, because when you throw the ball upward, it will move upward slower and slower. And after some time it will fall down. It will go increasingly faster downward, so there has to be something that causes that faster and slower.

There has to be something, i.e. an influence, that causes the acceleration. Here again the motion dictates the presence of an influence.

The argument from interaction theory is illustrated in the following response to FCI item 5:

1. I: Okay. We are in doubt about B. ‘A steadily decreasing upward force from the moment it leaves the hand until it reaches its highest point beyond which there is a steadily increasing downward force of gravity as the object gets closer to the earth.’
2. Car: That is wrong, according to me, because it would be (strange) when from that point onwards, is the downward gravity, and that one is there all the time, I say.
3. Mer: The gravity is not continually increasing, is it?

The identification of a non-constant (in fact suddenly appearing) influence is rejected based on knowledge of how gravity roughly works (namely all the time and constant close to the earth’s surface), i.e. a rough interaction theory. Another example of the same type of argument is the following response to FCI item 10 concerning the motion of a ball leaving a circular channel with a gap.

> Jol: Well, I think B because here it [the ball; ASW] is pushed by the channel in that direction, and here the channel is no longer present, so there is no more influence left.

The channel is the influencer. When the channel ends, its influence can no longer work on the ball. Both arguments surface in the following discussion of the same FCI item. Alternative A and C both indicate curved trajectories:

1. I: Yes. Okay. What would you say about this [A or C] response?
2. Ros: Yes, that could be, but it has to be influenced a little bit…
3. Jol: Move the other way.
4. I: Yes, and where would that influence come from?
5. Jol: From the table surface or something.
6. Ros: (…)
7. I: Yes, okay, so but that is not the case here.
8. Ros: No, than it would move straight on.

First the need for an influence is expressed (2) based on the motion. Secondly these alternatives are rejected based on the absence of a feasible source of such an influence (7), which might have been the table surface, but this possibility is not considered likely given the expression ‘or something’ (5) and Rosa’s assent to my rejection of this possibility (8).

So students made use of both the argument from interaction theory and the argument from the relation force - motion. The latter only leads to Newtonian explanations when the relation between force and motion is well understood. For discussing non-Newtonian notions it seemed useful to recall elements from the introductory course amongst which the graphical construction method. The following two examples illustrate the importance of connecting to the introductory course. The first illustrates an unsuccessful way of addressing the non-Newtonian notion of ‘no force implies no motion’, which can be seen as a special case of the ‘(larger) speed is accompanied by (larger) force’ notion. It is my claim that it is unsuccessful because it does not make use of the introductory course. The second example illustrates a way that seems more promising. After these two examples I will turn to how the graphical method may be used in discussing these non-Newtonian notions.

In response to FCI item 18 about comparing the sizes of the forces working on a constantly upward moving elevator:

1. Ros: If there would not be any influence, the elevator would not move upwards, would it?
2. I: Well, according to Newton it would.
3. Ros: But in that case it would move down, wouldn't it?
4. I: No. Look it is true. Look, when the elevator is not moving, let's say it is standing on the ground. If you want it to go up, than you would need a short net influence upwards. Than it would accellerate upwards. When it is at some particular height, so it has been put into motion, and I want it to continue moving with constant speed, then I would need a net influence of zero. There is gravity working, pulling it down all the time. When I compensate that with an equal force from the cable in the other direction, making the net result zero, than it would move here with constant speed according to Newton.
5. Ros: So B.
6. I: So B. But do you find this a convincing story?
7. Jol: Yes.
8. I: Ha ha ha, yes, you are saying yes, but you do not sound very convinced, ha ha ha.
9. Jol: Yes.
10. I: Okay. Rosa isn't.
11. Ros: Yes, it sounds quite logical. Ehm, it looks quite logical and stuff, but I would, one has to have some experience of sorts, when one believes it to be, sounds quite logical.
12. I: Yes, but the whole problem is that one cannot experience this.
13. Ros: No, yes that's why. So you have to believe what is being said.

My explanation (4) was not coming across, which I noticed at that time (8). Jolien who was on the whole much closer in her reasoning to the Newtonian approach disagrees. She claimed she did understand it (7). Rosa cannot relate this explanation to her experience and has to accept it on faith (11, 13), although she said that it sounded logical.

The explanation in the following example from FCI item 5 (vertically thrown object) about the difference between speed and force seems more promising

1. I: […]. So here was an influence from the hand, …
2. Nic: which causes its speed.
3. I: …which causes its speed …
4. Nic: And after a while that influence is not working any longer and then it will go (…).
5. I: Well, this influence is no longer working the moment the pen leaves my hand. Then I no longer influence it.
6. Nic: Yes, but (…)
7. I: Yes, but not according to Newton …
8. Nic: No.
9. Car: No.
10. I: He says: no, I do not need that, for what I assume is that it has received speed. According to me when something has got speed and no influence is working,

it would simply continue. With a constant speed it would continue to fly higher and higher. Well, that is what happens.

11. Car: A kind of influence free motion.

The first example did not really use any elements from the introductory course. The unsuccessful explanation given here by me could have been given by any teacher unaware of the introductory course who would try to remedy this particular notion. The second example did make use of some elements of the introductory course: It recalled the perspective with which these questions are answered, namely the Newtonian one (7, 10), which triggered a recollection of the notion of influence free motion (11).

Another element from the introductory course not used in these examples, uses the tool of graphical constructions to discuss the relation force - motion. Although students did not use the graphical method spontaneously, they were able to understand and be convinced by an account given by me using this method.

Two more observations in connection to these interviews are that: (1) In general can be said that students were very willing to discuss different explanations of motions and could use good arguments (or at least recognise them when they were given) in these discussions. The theoretical orientation of wanting to really understand some motion (most of which were completely irrelevant from a practical point of view) had been properly established. (2) The usefulness of the Newtonian approach as a powerful way of explaining motions that is therefore quite naturally adopted when asked to explain motions has not become established to the intended degree. Given the experiences with the second trial this is not that surprising, but an improved version of the design should result in the clear conclusion that Newton is the winner.

Conclusion from these interviews

In reasoning about explanations of motion elements from the introductory course can be used productively: arguments for identifying influences from relation influence – motion and from interaction theory are already used by students, the graphical construction method is not used by them, but can be recognised and understood and can be convincing, recalling Newtonian (or Keplerian) perspectives immediately trigger a proper mindset of theoretical explanations and bring to mind specific details of their theories.

Reflecting on the usefulness of the graphical method I think that such constructions are really needed to address the difficult topic of conflict between the argument from motion and the argument from interaction theory. Usually with the kind of (FCI) problems that were used, wrong answer alternatives can be dismissed because the depicted motion calls for some influence, mostly in the direction of motion, based on the argument from motion that can not be there because of the argument from interaction. For this reasoning to be convincing one should see how the influence that *can* be identified (e.g. only gravity) can account for the complete motion (e.g. vertical toss). The reason many students identify some upward force is that they very strongly feel the need for one because of the argument from motion. Countering this argument only with the argument that the force of the throw cannot be working after the throw many students find insufficient. For this second argument to be convincing quite an elaborate Newtonian interaction theory is already required. An alternative approach would be to use the first argument and show how the same motion can be accounted for without identifying the non-Newtonian force. This approach uses the graphical construction method.

Further research

What this section has shown so far is that making use of the introductory course in the regular course is important and needs to be carefully developed. The preliminary attempts made here suggest some promising ways in which this topic can be further developed, but much more thought and trial is required to arrive at a proper approach for the regular course (e.g. written down in a link-manual) that optimally uses the introductory course to productively discuss the usual mechanics problems. Looking back the amount of work (and time) involved in this aspect of my research had been underestimated.

9. Concluding remarks

In this chapter the results of my design have been presented on a detailed level. The method for data collection, analysis and presentation was described in section 2. Here was seen that the scenario and the analysis questions guided a way through the plethora of collected data of which only a small fraction could be displayed in this chapter.

In section 3 the results of the teacher preparation were presented. The picture that arose there was that given the restrictions in time the teacher was prepared as best as I could manage, although the idea of using interaction structures as a tool for the teacher in designing a practical implementation of the already designed content was not fully accepted.

The sections 4, 5 and 6 contained the detailed results of main theme 1, 2 and 3 respectively. The first main theme, the how and why of explaining motions, resulted in some empirical backing for the ideas for triggering and explicating both the general explanatory scheme and the explanatory scheme for motion. The asteroid problem and the general explanatory scheme as stepping-stone might also perform their intended functions and students were seen to develop some sense of theoretical orientation. Other important goals were not achieved: Students did not see the explanatory scheme for motion as a special case of the general explanatory scheme and they did not realise that for a complete explanation of motion further specification of the elements of the explanatory scheme would be necessary. These failures here, as well as in the other themes, were mainly attributed to deviations in the execution. Apart from the few scenario improvements that had been suggested in the course of section 4, this test did not provide empirical grounds for changing the design of main theme 1 in a major way.

The second main theme, the extension of knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining planetary motion, resulted in disappointing recognition of the main thread and poor understanding of the mechanics content by the students. Students did manage to use the criteria of empirical adequacy and plausibility for choosing between models. Both Keplerian and Newtonian models remained feasible alternatives.

The third main theme, evaluation of models and *types* of model in the light of achieving broader applicability, resulted in the observation that criteria to determine which type of model explains best could be used and were used, but should be made more explicit, especially ‘broad applicability’. Furthermore, cumulative effects of earlier failures in main theme 1 and 2 made the appreciation of Newtonian models rather weak.

In all main themes little could be said about the choice for the used interaction structures.

The fourth main theme, embedding in the regular course, was approached differently than the other main themes. It was investigated to a far less extent than the earlier main themes and merits further research. However, some preliminary findings that I came across include that in reasoning about explanations of motion elements from the introductory course could be used productively. Arguments for identifying influences from the relation influence – motion and from interaction theory were used by students themselves, the graphical construction method was not used by them, but could be recognised and understood and provided for convincing reasoning.

Chapter 7

Reflection

1. Introduction

In this chapter I will look back on the starting points of this research in light of the results. The starting points were the educational goals, my problem analysis, approach to overcome the identified problem in learning mechanics and my view on teaching/learning. In section 2 will be discussed to what extent the educational goals have been reached and whether they can be reached. The evaluation of the other three starting points in section 3 amounts to a discussion of the idea of using the explanatory scheme in a problem posing way. In that section I will reflect on this idea and describe two main problems I encountered in putting this idea into practice. In section 4 I will argue that these problems can not be easily solved by applying advice from the research literature, but that this literature may trigger some useful further thought about possible directions in which solutions may be found. Finally, in section 5, I will present some ideas for addressing the main problems in the design. These ideas are naturally not worked out in great extent and will require further research to prove (un)workable.

2. Are the goals met?

The three main educational goals of the introductory course were (see chapter 3 section 1) that students (1) come to know how mechanics works, (2) develop some appreciation for its power and range and (3) acquire a vocabulary with which the usual learning difficulties can be discussed. Of course this did not mean that students should understand mechanics after only an introductory course. With ‘knowing how mechanics works’ was meant some insight in the broad picture of the project of doing mechanics, that is knowing *that* the central concepts of influence or force, laziness or inertia, influence law or force law, et cetera are related and account for motion, and have some sense of *how* they are related and account for motion.

The second goal of appreciation for the power and range of mechanics meant having some sense that Newtonian mechanics is (1) quite good in predicting and explaining motion, (2) quite plausibly and (3) in a quite general way. In here the three criteria of empirical adequacy, plausibility and broad applicability can be recognised. The vocabulary useful for addressing learning difficulties would then consist of the mentioned main concepts of mechanics like influence, influence free motion, laziness et cetera and their more widely used counterparts in regular mechanics.

To what extent have these goals been reached? And can they be reached? I will subsequently discuss these questions for each of the three goals.

Know how mechanics works

To what extent the goals of each episode have been reached was described in detail in chapter 6. There was seen that students had difficulty distinguishing influence from parameters in an influence law. Furthermore they had difficulty relating influence, laziness and deviation from the influence free motion in the intended way, that is, in accordance with the rule deviation = influence/laziness. Instead they related influence and laziness to the more readily observable effects on the motion in the explored computer models, which I called an operational understanding (see chapter 6, section 5.3).

Looking more closely to what students were meant to do to construct the concepts of laziness and influence, one can find a possible explanation for this difficulty. Students were expected to get some sense of what laziness is by a single example, namely varying the laziness of a planet moving around the sun in a computer model. Furthermore the notion of laziness could very easily be confused with the earlier explored effect of influence on the planet (also using a single example), since both concepts had similar results in changing the motion of the investigated planet in the computer model. Although at the time this seemed to me quite doable for students, I now think that establishing the main concepts in mechanics like laziness or influence in relation to each other is more difficult than expected.

One possible approach to overcome this difficulty is that one could reconsider the introduction of the various concepts in an introductory course. Omitting laziness, for instance, would considerably reduce the number of relations between the concepts. The concept laziness was needed in this introductory course for making the Keplerian type of model a feasible alternative to the Newtonian type of model when modelling more than one planet. Can this be achieved without introducing the concept of laziness (in an introductory course), but such that there remains a sufficient basis for evaluating the relative merits of Keplerian and Newtonian models as applied to the motions of the planets? Further research may shed more light on if, and how, this is possible.

The results of thirteen 65’ lessons (approximately seventeen 50’ lessons, about the same amount of time spent in a regular course on Newton’s laws) may seem somewhat meagre. Even when one takes into account that the introductory course also aims at other goals and is still in the experimental phase. It can be expected to be shortened after some streamlining. This first goal is largely addressed in the first two main themes which took nine 65’ lessons. Some minor adjustments like skipping the detailed and optional graphical construction method and cutting some corners would still result in about six 65’ lessons (about eight 50’ lessons). This is still a considerable amount of time to spend on only an introduction. Far from suggesting that such an introduction is better omitted, this further indicates the difficulty in arriving at the regular educational goals for mechanics that, as was mentioned in chapter 2, are not met in traditional education. The point I am making here is that knowing what mechanics is about as an educational goal of any regular course (preceded or not by the designed introductory course) may be more difficult to achieve and more time consuming than even people who are aware of the learning difficulties in mechanics anticipate. My assumption has been all the time that the regular educational goals for mechanics are attainable in principle, given some properly designed and executed course. This does not mean, however, that these goals must be attainable in roughly the same amount of time as is normally spent on mechanics in traditional education (which results in not attaining these goals).

Appreciation of power and range

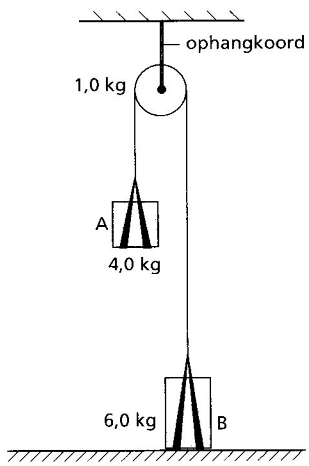
Appreciation of the power and range of (Newtonian) mechanics was lacking although students were seen to implicitly apply the epistemic virtues. This leads me to believe that when these criteria are made explicit and used as such, students would be able to give some argued reasons for preferring Newtonian mechanics, which would amount to some appreciation. This goal builds on the previous one, since knowing that Newtonian mechanics is empirically adequate and broadly applicable without some sense of how the main concepts are related and therefore without knowing what Newtonian mechanics *is*, is not much of an appreciation[1].

Vocabulary

The vocabulary in which to address the usual learning difficulties would have to use notions like influence(law) and laziness (or their more widely used counterparts), which had not become sufficiently clear for this purpose. Students' weak grasp of such concepts makes a convincing discussion of these problems very difficult. In chapter 6 also some encouraging aspects were found in a preliminary attempt at discussing several triggered learning difficulties during the regular course (see chapter 6, section 8). Students made use of two specific arguments, the argument from interaction theory, which can be expressed as an answer to the question 'where does the force come from?', and the argument from the relation force – motion, which can be expressed as an answer to the question 'why does the identified force have to be working?' Both questions need to be answered in almost all mechanics problems, but are seldom explicitly asked. When these basic arguments can be combined with a sufficient understanding of the main concepts, one has obtained a useful approach for addressing most of the mechanics problems.

Many problems neglect the interaction theory aspect. Take for example the kind of reasoning expected in the following question, obtained from a much used physics textbook for the fourth grade (16 year old students):

> See Figure 3.30. The mass of the cords is negligible in comparison to the mass of the blocks A and B.
>
> a. Redraw this figure and add to your drawing the forces working on A and those working on B.
>
> b. Which block needs to be considered first in order to calculate all these forces?
>
> c. Now calculate these forces.



[1] Finding Newtonian mechanics more plausible already implies some understanding of its main concepts. Plausibility differs in this respect from the other two criteria.

The causal chain of events in this example is that various ‘influencers’ work on the object in question by applying some force. (How they do this is part of the interaction theory aspect). These various forces add up to one net force. This net force causes a deviation from the influence free motion and therefore accounts for the observed or predicted motion of the object (the relation force - motion). In this example and many others this chain of events is assumed to be clear. Students are then asked to reverse this reasoning by determining some force from the motion of the object, which in this case is rather easy, namely rest, but in many cases is motion with constant velocity. Since two of the forces adding up to the net force are clear from grounds of interaction theory (gravity and the force in the rope), another force that is also part of the net force, the normal force from the ground, can be calculated. The question where that other force comes from (interaction theory) is not addressed and of course one does not have to, strictly speaking. However, not addressing it assumes a lot of trust in and familiarity with the whole line of reasoning. I think using the two mentioned questions when discussing mechanics problems can make a lot of the steps in this kind of reasoning explicit and thereby clarify some confusion.

3. Are the starting points still useful in meeting the goals?

Apart from the educational goals mentioned in the previous section there were three more starting points in this research: My problem analysis, approach to overcome the identified problem in learning mechanics and my view on teaching/learning. These starting points amounted to the ideas (1) that common sense and Newtonian mechanics have an explanatory scheme in common and (2) that this commonality could be used in teaching/learning mechanics in a problem posing way. In this section I will reflect on especially the second idea and describe two main problems I encountered in putting it into practice.

Putting it into practice involved that the explanatory scheme, after being triggered and explicated, was to guide students in a process of further specification of the scheme leading to a first encounter with the main Newtonian concepts like influence or force, laziness or inertia, and heaviness or heavy mass, and their relation to motion. Furthermore the difference between common sense and Newtonian ways of explaining motion was attributed to various ways in which one can specify the explanatory scheme, reflecting one’s aims and interests for such an explanation. Within those specifications that are more theoretically oriented, like those of Kepler and Newton, the epistemic virtues of empirical adequacy, broad applicability and plausibility become more important[2]. They can function as criteria for comparing and weighing alternative theories and can thereby also help guiding the teaching/learning process. The guidance provided by the explanatory scheme and epistemic virtues would consist of giving students some perspective on what they are doing and why, and thereby aid in making the approach problem posing.

[2] There are also other epistemic virtues, see e.g. (Quine, 1966), but these three played a part in my design.

There are no reasons to doubt the notion that common sense and Newtonian mechanics have an explanatory scheme in common, which will therefore not be further discussed. This aspect of the problem analysis is still valid. The suspicion that this commonality could be used in teaching/learning mechanics in a problem posing way, thereby reaching certain educational goals, however, raises some questions. To what extent can the goals be reached? And can the design be said to be sufficiently problem posing? The first question has already been addressed in the previous section. In answering the second question let us revisit the didactical structure of the design, for it makes explicit the succession and interplay of activities and motives and shows therefore its problem posing character on a structural level. After that I will reflect on how this didactical structure was implemented in the teaching/learning activities, which shows the design's problem posing character on a more detailed level.

Didactical structure

The didactical structure of the design is depicted in Figure 1 in chapter 5. The course started with a broad orientation on motions that are worth predicting or explaining. This orientation concerned both learning about mechanics (the left column in Figure 1) and learning about explaining (the right column). I have found no indications to doubt that the asteroid problem is a good example in this respect.

This orientation resulted in the notion that this could be an important and interesting theme worth knowing more about. This notion then functioned as a motive for starting with exploring explanation in general and explanation of motions in particular. Students were seen to make use of the explanatory scheme, but this use was not explicated, so that students remained unaware of this use. This did therefore not sufficiently lead to the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of this underlying scheme. Although students did develop a theoretical orientation to the extent that they understood the goal of explaining motions to be to arrive at some theory of motion, had some impression (however vague) of what such a theory might be, and were somewhat challenged by it, they did not come to realise that for a complete explanation of motion further specification of the elements of the explanatory scheme would be necessary. This crucial motive for engaging in learning most of the mechanics content in the next step was lacking.

The main thread in learning the mechanics content was that it was organised as a step by step specification of the underlying explanatory scheme for motion into two specific schemes (Keplerian and Newtonian) in the context of developing and testing models of the motion of heavenly bodies. This thread was not recognised at the start of this part of the course (as a motive), and was not picked up during the subsequent unfolding of the course either. Since the course design made the explication of the explanatory scheme an essential prerequisite for learning the mechanics content, this problem of explicating the scheme is one of the main problems in the design.

In chapter 6 the failure in explicating the explanatory scheme for motion was mainly attributed to the deviations in the execution of the scenario. There were no empirical findings that suggested major changes in the design of the first main theme. However, in this chapter I would like to further qualify this conclusion by suggesting some other ways in which the design may be improved than those already mentioned in chapter 6, triggered by research literature I became aware of after identifying problems in my design, see section 5 in this chapter.

Although learning results of the mechanics content proved to be unsatisfactory, the extensive exploration of the Keplerian and Newtonian specifications of the explanatory scheme did result in raising the motive of evaluating the fruitfulness of the specific schemes and models, which prepared for a reflection on criteria to determine which schemes and models explain best. In the reflection the intended criteria for choosing between types of model did surface, but were not made explicit. Therefore, the criteria could not be seen to function in motivating a plan for further validation of the specified schemes, namely the application of Keplerian and Newtonian schemes to motions on earth. After this the cumulative effects of the previous shortcomings makes claims about the rest of the (didactical structure of the) design speculative.

For the sake of completeness I will risk a few speculative remarks about the final steps in the didactical structure. The intended reason for exploring motions on earth was that application of the criterion of broad applicability might help in the evaluation of the two alternative types of model. This was not understood. This made surfacing of the next motive, which is the closing question “which schemes and models explain best?” and its answer in the final evaluation of which schemes and models explain best and which elements of this scheme are still unknown very difficult. With a shaky grasp of what mechanics is all about and lacking *explicit* criteria for choosing between different types of model an appreciation of the Newtonian scheme by students can no longer be expected.

In conclusion: The main (structural) problem is the unsatisfactory explication of the explanatory scheme, and thus the failure to provide a proper motive for engaging in learning most of the mechanics content. The other motives in the didactical structure seem to function more or less as intended, although this claim for the final steps is rather speculative. On this structural level the design can be said to be sufficiently problem posing, except for the mentioned problem.

Implementing the didactical structure in the activities

Although on the structural level the design seems to be quite alright, apart from the mentioned problem, on a more detailed level the design still falls short in implementing this structure in the activities within the episodes. The intended motives were not sufficiently incorporated in the design of the successive activities. In retrospect one can see this already in the description of the design. The reason that some activities could not become ‘alive’ in the sense of forming a driving force behind students’ learning is that many a time such reasons were meant to be told by the teacher, instead of arising more naturally from students themselves. Although it was at these times intended that the teacher would only have to make some reason explicit based on student input that was triggered in some preceding activity, or recalling such motives in an introduction of the current activity, these kind of evaluations and introductions would be better designed if they involved more student activity.

To name but one example, in episode 2.5 about the precise relation between influence and motion, students were meant to develop some trust in the difficult graphical construction technique by exercising it in a couple of assignments (see chapter 5 section 4.5). They were seen to get lost in the details and had no idea what they were doing at that time (see chapter 6 section 5.5). The designed questions did not provide students with a motive for engaging in the activities that was recognisable and ‘driving’ enough. There was a motive in the design, but this was intended to be expressed in the introduction of these questions by the teacher, which involved students only to the extent that they had to listen to some exposition[3]. It would be preferable when such important aspects as raising a motive would involve more student activity than only listening. It is therefore understandable that they were rather lost in this case.

My primary intention was to design a course bottom-up, meaning starting from common sense and continually using what students bring in (see also chapter 3, section 4.1 where my view on teaching/learning was described). However, in retrospect much of the design turned out to be too much top-down, in the sense of emphasising teacher input, such as in the mentioned example. The activities exhibited too much of a kind of ‘transfer’ perspective on teaching/learning, and too little of the intended educational constructivist perspective. As a result the designed activities did not guarantee that student input would matter[4], which I consider an important ingredient of a more constructivist educational design. So the design being too much top-down is in contrast with the intention of making student input matter, as well as attributing to not rightly implementing motives.

4. Some aid from the literature?

The main problems in the design that were described in section 3 lay in explicating the explanatory scheme and implementing the didactical structure in the activities in a bottom-up way. Furthermore there were the earlier mentioned problems in the execution of the design, which were related to difficulties in the design itself and difficulties in the teacher preparation.

In this section I aim to show that these problems can not be easily solved by applying advice from the research literature, but that this literature may trigger some useful further thought about possible directions in which solutions may be found. This may also make the difficulties themselves somewhat clearer.

4.1. Explicating the explanatory scheme

The difficulty in explicating the explanatory scheme may lie in that it makes explicit a high level of causal thinking. It could be the case that this causal thinking in itself may be more difficult than anticipated. Making it explicit would then also prove to be more difficult than expected. What has the research have to say about the difficulty of causal

[3] When the teacher succeeds in recognisably using a lot of student input from the previous questions in such an exposition, this will to some degree make students involved, I expect.

[4] Having sufficient student interaction (a rough measure would be that students talk more than the teacher) is one basic requirement of a more constructivist design. Making that input matter by using it in a recognisable and meaningful way is another.

thinking? An overview of relevant research in understanding of causality in children and adults, both from the field of research in developmental psychology and the field of science education research is given by Grotzer (2003).

In Grotzer's meta-study she distinguishes four dimensions of causal complexity in models, namely mechanism, interaction pattern, probability and agency. For instance agency, where we locate the source or locus of a cause, ranges from a central and direct agent to highly emergent causality, with various levels in between. The research she discusses is organised around this taxonomy, so that most of the mentioned studies address the development along one dimension from this taxonomy, or focus on one level within one dimension.

The main body of the paper goes into what research has to say about each of the elements of her taxonomy. One section is headed, for example, 'what does the research tell us about children's ability to consider that agents do not always have direct and immediate influence over effects'. Other sections address the other elements of her taxonomy.

If it were the case that the explanatory scheme involves mainly the more complex forms along each dimension of the taxonomy, this kind of research would suggest that trying to use the explanatory scheme as I have been using it is very ambitious. The explanatory scheme itself does not easily fit into the taxonomy, but it does contain rather difficult elements that need to be explicated in relation to each other. These elements, like distinguishing between influences, causal factors and regularities, can (arguably) be placed high in Grotzer's taxonomy for the dimensions 'mechanism' and 'interaction pattern'.

All the research Grotzer mentions seems to be mainly concerned with breaking down causal thinking in various elements (like the ones used in the taxonomy), describing the (development of) understanding of children of one or more of these causal elements and identifying problematic areas in this understanding. It is mainly descriptive. In contrast, in my research I tried to *use* causal thinking instrumentally in teaching/learning mechanics. The explanatory scheme not only describes causal thinking, but was meant to become a tool for students. Since it mainly concerned description, the research Grotzer mentioned gave no clues as to how elements of causal thinking could become tools in teaching/learning some scientific topic. She suggests that "broadening students' causal repertoire within the context of a given science concept will increase the likelihood that they will develop deep understanding of the concept", but how this should be done for a particular science concept remains unanswered.

Grotzer's work did lead to appreciating the importance of making the explanatory scheme as simple as possible, by succinctly expressing its bare essence. The explanatory scheme can for instance be expressed as 'whenever there is a deviation from how something would move of itself, you search for some cause for that'. This basic causal notion does not seem that difficult in terms of Grotzer's taxonomy. This may help in facilitating the scheme's explication.

4.2. Making the design more bottom-up

The second main problem in the design was how to make the design more bottom-up. Also for addressing this difficulty practically no guidance can be found in the literature. Let us take for example the advice given by Leach and Scott for designing science teaching sequences (Leach & Scott, 2002). This is one of the few articles that actually tries to give some general guidelines for designing teaching sequences.

Their generalised approach to inform the design of teaching sequences is:

1. identify the school science knowledge to be taught;
2. consider how this area of science is conceptualised in the everyday social language of students;
3. identify the learning demand by appraising the nature of any differences between 1 and 2;
4. develop a teaching sequence, as redefined earlier, to address each aspect of the learning demand.

Further advice is given in how a teaching sequence can be conceptualised from a social constructivist perspective. Leach and Scott distinguish three features: staging the scientific theory, supporting student internalisation and handing-over responsibility to the students. These are not successive phases, but overlap each other.

In staging the scientific story the topic is made available in an interactive ‘performance’ guided by the teacher and involving various activities. The unfolding of the scientific point of view needs to take students’ existing understanding into account and be convincing so that the scientific story appears intelligible and plausible to the students. This staging also needs to find a balance between presenting information (focussing on the authoritative function) and allowing opportunities for exploration of ideas (focussing on the dialogic function). In supporting student internalisation, Leach and Scott emphasise the continuous monitoring of, and responding to, students’ understanding, for which student input is required and needs to be harvested through for instance whole class questioning and discussion. In handing-over responsibility to the students, they start applying the new ideas, where the support and assistance of the teacher is gradually diminished. This way of conceptualising teaching sequences emphasises “the way in which the teacher works with students to ‘talk into existence’ (Ogborn *et al*., 1996) the scientific story” (Leach & Scott, 2002, p. 124).

The need to find a proper balance between presenting information and allowing opportunities for exploration of ideas seems to say something about the problem of making the design more bottom-up. At least Leach and Scott identify a similar problem, but apart from expressing that one needs to find such a balance, they do not indicate how this can be done. Furthermore, this distinction in only these two functions seems somewhat thin. Making the design more bottom-up would involve more than only choosing between presenting information or allowing exploration of ideas.

The general advice Leach and Scott give does not help either. Without much trouble I can fit my design in this perspective. I adhere to a similar view on teaching/learning as Leach and Scott and have followed (unintentionally) the given advice for designing a teaching/learning sequence. My identification of the learning demand in particular is extensively spelled out in my problem analysis of the learning difficulties in mechanics (see chapter 2 and 3). Also much attention was paid to the way in which the teacher works with students, which was made explicit in my scenario (chapter 5). This general advice does not provide much guidance when it comes down to the actual nitty-gritty of designing activities in some teaching/learning sequence.

5. Possible solutions and further research

In this section I will present two ideas that may prove useful for addressing the two main problems in the design as well as the problems in the execution of the design. The first idea is to educationalise a practice. The second idea is to devise proper interaction structures. I will present both ideas subsequently and discuss how I think that they might help in solving the encountered problems. Finally, in section 5.3, I will speculate whether perhaps the idea of using an explanatory scheme may be applied to, and useful for, other topics or subjects.

5.1. Educationalising practices

The idea of educationalising practices surfaced in the Centre for Science and Mathematics Education in Utrecht (Bulte et al., 2002), (Bulte, Westbroek, Rens, & Pilot, 2004). I will give a very brief outline of this idea here, assuming the reader is familiar with activity theory. A more extensive presentation of this idea can be found in the mentioned papers by Bulte et al. The basic idea of educationalising a practice, where the term ‘practice’ is used similarly as it is in (neo)Vygotskian activity theory, is that a professional practice that is by its nature purposeful for those who participate in it may be adapted for use in school in such a way that students can also recognise and appreciate its purpose. Within such an adapted or ‘educationalised’ practice students could then learn the things we would like them to learn in a meaningful way[5]. The adaptation would consist of making a coherent and recognisable part of the practise fit the boundaries set by a school environment, so that goal and characteristic procedure remain or become sufficiently clear to students[6]. An important aspect of educationalising a practice is letting students and teacher adopt recognisable roles that are derived from the practice and that are used consistently.

Relation with problem posing

The relation with a problem posing approach lies in the fact that sometimes a characteristic procedure can be identified within a professional practice that, when properly adapted to an educational setting, could guide the teaching/learning process by suggesting directions in which to continue. This guidance can occur because steps in the

[5] For a discussion of the concept ‘meaningful’ I refer to Westbroek (2005), who identifies three characteristics, namely *context* (or *practice* in the sense used here), *need to know* and *making student input matter*.

[6] A ‘sufficiently clear’ characteristic procedure can still be pretty vague, as long as it can function in suggesting to students directions for a next step in the teaching/learning process. The procedure itself can become more clear along the way, which can be an educational goal in itself.

direction suggested by the procedure can be made to correspond to the extension of knowledge that the course(designer) intends. The procedure furthermore guides the reflection on what is done by raising the question about the status of completion of the procedure. Students can therefore know by means of the characteristic procedure at all times where they are and where they are going. They also have to want to go where they are going. Therefore, the goal to what the characteristic procedure or the practice as a whole leads must be appreciated. The choice for a practice (to be educationalised) should take into account whether students can recognise and appreciate the nature and relevance of the goal this practice is aiming at. A suitable practice makes it clear for students what it is, it is trying to accomplish, which should be something considered worthwhile. The procedure within such a practice should characterise the practice (therefore 'characteristic procedure') in the sense of fulfilling an important function within the practice, but has not necessarily to completely cover the whole practice. For instance the characteristic procedure for testing water quality (Westbroek, 2005) characterises the professional practice of testing and judging water quality, but the latter involves *all* aspects of this professional practice including the report of findings, acquisition of new assignments, et cetera.

Could this idea apply to my work?

Since mechanics is a rather theoretical topic, educationalising a professional practice is more difficult than it would be for practical topics. A practice from which a characteristic procedure may be obtained could be the academic practice of 'constructing theoretical knowledge'. Within this practice people are researching, investigating, explaining, understanding and predicting phenomena. A well known distinction in this practice is to separate the context of discovery from the context of justification[7]. I will organise my discussion of how the idea of educationalising practices could apply to my work around the two mentioned contexts.

There are no procedures for discovery in the sense of mechanical, repetitive, step by step guidelines for discovering things. If there were, we could all learn them and start discovering things. However, we can take the underlying idea of a characteristic procedure to be to divide the process in for students understandable steps, that will lead in a for students recognisable way to the particular goal the characteristic procedure aims for. In the case of the work of Westbroek, this division lead to a characteristic procedure for judging water quality, which was a quite practical, mechanical, procedural course of action. In my case I could apply the underlying idea to the academic practice of constructing theoretical knowledge by dividing the main question of 'how does explanation of motion work?' into the sub questions 'how does something move by itself?' and 'what influences are working in this situation?' This division can be expected to guide the teaching/learning process in a for students recognisable way, since it uses the basic notion that 'an influence causes a deviation of the way something would move by itself'.

[7] This distinction has been attributed to Reichenbach and Popper and was later much criticised, for instance by Kuhn (1962). The philosophical ins and outs of this distinction need not concern us here.

In the context of justification some guidelines can be identified like epistemic virtues. This central role of epistemic virtues was also identified by Leach and Scott as an important element of the scientific practice:

> Thus the *scientific* social language, the scientific way of talking and thinking, is that which has been developed within the scientific community. It is based on the use of specific concepts such as energy, mass and entropy, it involves the development of models which provide a simplified account of phenomena in the natural world, and it is characterized by certain key epistemological features such as the development of theories which can be generally applied to different phenomena and situations. However, it is not the case that 'anything goes' in the generation of scientific knowledge, as this knowledge should, in principle, be consistent with empirical evidence about the material world. Scientists are not in a position to create their social language in isolation from empirical data. (Leach & Scott, 2003)

The epistemic virtue of general applicability is explicitly mentioned. The last remark about consistency with empirical evidence can be read as indicating the epistemic virtue of empirical adequacy. So criteria or epistemic virtues like broad applicability, empirical adequacy and plausibility play an important role in the academic practices. They also exist rudimentary in students, but need to be made more explicit in order to function in guiding the teaching/learning process, as was seen in chapter 6 section 6.

Perhaps a characteristic procedure for my design could be found in the use of criteria for valuing explanations. Explicitly using such a procedure almost guarantees that the criteria themselves become more explicit. A rough outline of the educationalised academic practice of constructing theoretical knowledge would then consist of (1) dividing the main question 'how does explaining motions work' into sub questions, (2) answering these sub questions, and (3) evaluating the answers using the epistemic virtues, where (1) and (2) comprise the context of discovery and (3) the context of justification. In this way it could become clear to students that they need to justify some choice between alternative theories. They will find themselves in a 'context of justification', with a felt need for some tool to help them choose (and value the outcome of such a choice).

Another aspect of the academic practice that may become useful in educationalising it is the academic drive of curiosity. Although students cannot be expected to have a clear notion about what academics do, they *can* be expected to know and appreciate what drives academics, namely curiosity, the desire to deeply understand how things work. This will not guide the teaching/learning process in a particular direction, but may serve in bringing the practice more alive.

How can this idea help me?

Trying to adopt this idea is useful, for it may suggest ways of addressing the identified problems in explicating the explanatory scheme and implementing the didactical structure in the activities.

Development of the use of the practice of constructing theoretical knowledge could improve the theoretical orientation (see e.g. chapter 2, section 3.1), which could help in explicating the explanatory scheme, for it would further clarify its purpose. The question how this can be done effectively is still not answered satisfactorily. In my design the theoretical orientation was tried to be developed by means of focussing and enlarging aspects of the common practice of explaining, that all people do all the time, to use it for a particular goal, namely explaining motion in such an exact way that important motions (of for instance an asteroid moving towards earth) can be predicted with precision. In chapter 6 was seen that this can be said to have happened to some extent, but there is certainly room for improvement. Further research may shed some light on this.

Filling in consistent and recognisable roles for students and teacher would affect the kind of interaction between them (which would then have to be in accordance with their respective roles). The role perspective could help to guide the interaction, making it clearer for the teacher what kind of interaction is required. See also the next section on interaction structures. Adopting this ‘role perspective’ while further implementing the didactical structure in the activities may give ideas for more bottom-up activities. In addition it may help in avoiding the pitfall of too much top-down activities. The use of this role-perspective is rather speculative. I do not know yet which roles may be appropriate.

5.2. Using interaction structures

The second idea that may contribute in solving the problems in the design and the execution of the design is designing appropriate interaction structures. This is of course no new idea. I already tried to make use of interaction structures in the second trial. In this section I will revisit this idea and reflect a little on how it might be improved.

The idea of using interaction structures in the preparation of the teacher was described in chapter 4 section 3.3. Its main use there lay in addressing problems encountered in the first trial, namely the importance of proper introductions and evaluations, the attention to student input, getting the ideas and purposes of the scenario across, and instilling a sense of ownership. In chapter 6 section 3 it was seen that this idea did not function as intended, which was attributed to the fact that the second teacher was not made appreciative of the problems from the first trial. These were not his problems. So he did not perceive implementing a possible solution in the form of using interaction structures as important enough to merit a lot of time and effort.

5.2.1. Interaction structures to make the design more bottom-up

Using interaction structures could not only be helpful in preparing the teacher, but also in making the design more bottom-up. The kind of interaction and the design being bottom-up or top-down are strongly related, since a bottom-up design should start from common ground and continually use student input. Such a design should therefore allow for sufficient student input to surface sufficiently clearly, which places demands on the kind of interaction that should take place.

The kind of interaction structures that were used in the design emphasised mainly the evaluation phase, which was strongly teacher oriented (see this chapter section 3). In the two interaction structures that were used the most, 'taking stock' and especially 'concluding', the main conclusion was meant to be explicated by the teacher in the evaluation phase. Although this explication should use as much as possible earlier student input, the description of these two interaction structures focussed on the teacher side of the interaction. This did therefore not contribute to the design being bottom-up. An improved description of interaction structures (paying more attention to the student side of the interaction) or even entirely different interaction structures may become helpful in this respect.

Of course student input as such does not guarantee the teaching/learning process to become more problem posing. On the other hand without making student input matter, it is hard to imagine students experiencing any real felt motives for a process which is apparently indifferent to their input, nor is it possible for a teacher to explicate motives which students can recognise as their own. Student input is important as feedback to the teacher on how their learning progresses. When students realise that this kind of feedback is actually used by the teacher to adjust her teaching, this will further stimulate their involvement[8].

Again, even *recognisably using* student input is not enough to guarantee the teaching/learning process to become more problem posing. It should be used in such a way that the designed main thread of successive episodes linked by successive motives is recognised by the students as describing the process of what actually goes on in their head when they engage in the topic. For this, introductions and evaluations are meant to establish a link between the activities students are about to engage in (on one level) and the encompassing motive for the episode (on another level). Here the content perspective and the interaction perspective meet. From the interaction perspective 'making student input matter' and 'emphasising proper introductions and evaluations' can be said to be necessary but not sufficient conditions for making a sequence problem posing. The content perspective is needed to inform what a 'proper' introduction and evaluation would be, i.e. what would make the episode problem posing.

5.2.2. Interaction structures to improve the teacher preparation

The introductory course required particularly much of the teacher. The teacher needed to harvest sufficient student input on the difficult topics of explaining in general and explaining motion in particular and extract from that input the explanatory schemes, without adding too much or too little. This careful balancing between own input and making student input matter is very difficult. This difficulty in executing the course lies in the design itself and in preparing the teacher for this design. Interaction structures may be useful in addressing both aspects.

[8] I am aware that the kind of interaction in a class, here described isolated and connected to a single episode (short term) has implications for the class culture (long term), which in turn helps or hinders the kind of interaction that can take place. See for an interesting discussion of interaction and class culture the work of Genseberger (Genseberger, 1997), which draws heavily on Habermas' notion of communicative action.

The first aspect was already mentioned in section 5.2.1. If the course were designed more from an interaction perspective, using improved interaction structures that pay attention to both teacher and student side of the interaction, this would help the teacher preparation. Also adopting roles from an ‘educationalised’ professional practice (see section 5.1) can clarify what is expected from a teacher in order to make the design work. I will first elaborate on improving interaction structures and then address the second aspect, how interaction structures can become useful for preparing the teacher.

Improving interaction structures

The used interaction structures emphasise the various subsequent aspects of the teacher side of the interaction. Although this implicitly suggests the student side, for instance a ‘clarification’ by the teacher suggests an unclear student response, making these explicit would better capture the interaction and remove the suggestion that it is mainly the teacher who is doing the talking. Furthermore, placing more emphasis on the student side may result in useful thinking about what input and reactions are actually expected from students.

For a teacher who already has a problem posing mindset the process of filling in an interaction structure for some episode naturally raises the right kind of questions (see chapter 4 section 3.3). What answers do I expect from students? How am I going to respond to these answers? Why respond in that way? How does this serve the educational goal for this activity? How can I evaluate the activity in such a way that does justice to what the students have said? Does this evaluation properly prepare for the next episode? et cetera. For such a teacher these interaction structures can be very helpful. For a teacher without such a mindset the used interaction structures as such do not necessarily start such a person in a problem posing direction. Even improved interaction structures would not change the mindset of such a teacher. For this, in addition to improved interaction structures themselves, a different way of using such structures would be required.

Using interaction structures for preparing the teacher

The potential value of interaction structures lies in their ability to enable the right kind of discussion between teacher and developer. What the developer considers important in the interaction in some episode can be made concrete by the way an appropriate interaction structure is selected and filled in. Perhaps a first episode can be filled in as an example by the researcher, thereby verbalising all considerations involved. This orientates the teacher towards those aspects of the interaction that are considered to be important (by the designer). She can then try filling in one or more herself, which can be discussed in a way that emphasises the important aspects of the interaction. From the teacher’s point of view I expect interaction structures to be quite easily understandable, for they resemble well known teaching formats. Filling in interaction structures would for teachers boil down to a quite normal way of lesson planning. It would be a rather more elaborate lesson planning that emphasises different aspects, but similar enough to what they are used to. Starting from this normal use of teaching formats teacher and designer can, by discussing the filled in interaction structures, get closer and closer in a mutual appraisal of the desired kind of interaction.

Such a discussion may be further facilitated by slightly generalising the recurrent pattern of introduction, main question and answer phase, and evaluation in light of the context. This pattern was first described in the context of interaction structures (chapter 4), but can be seen to recur on several levels. It can be seen in the introductory and regular course as a whole, where the introductory course functions as setting the context for the regular course, in which then one or more main questions are answered. The regular course should then end in an evaluation in light of the context set by the introductory course. Within this overall structure of introductory and regular course smaller repetitions of the same pattern can be found, which are 'nested' within the larger structure. Within more complex episodes one can sometimes describe the context setting or evaluation of a complex episode in terms of a nested sub-episode.

Apart from making thinking about and discussing interaction structures easier by describing them as recurrences of the same pattern, a further use of stretching this perspective beyond the original episode application is that it forces one to think about exactly what the 'main question' of a topic is and how this should be introduced and evaluated (in light of this introduction). These questions can be asked and answered on every level and in this case I am inclined to say that 'can implies ought'.

The problem remains how a teacher can be made sensitive to the kind of problems interaction structures aim to help to solve. The second teacher can perhaps be made sensitive for the difficulties in the execution of the second trial by the experiences with the first teacher from the first trial[9]. Somehow material from the first trial may be used to show the difficulties in properly introducing and evaluating the main questions in the subsequent episodes, and the detrimental effects when these fall short, in a for the teacher recognisable way. How this can be done is an open question that needs to be addressed in further research.

5.3. Other explanatory schemes?

The basic strategy that was followed and resulted in the idea to investigate the possible use of the explanatory scheme for motion in teaching/learning mechanics was that on a underlying structural level there are similarities between common sense and scientific reasoning. The specific similarity in the case of motion was expressed as the explanatory scheme for motion, and this was seen to be a special case of a basic structure in causal explaining in general, expressed in the general explanatory scheme.

One could explore this idea further and look for more similarities on a basic level in common sense and scientific reasoning. Klaassen (2003) suggests that such similarities may lead to identifying constituting elements of understanding the world. (The following citations are from the mentioned paper.) These elements "express constraints on the application of such basic concepts as those of cause, state, kind, substance and object" and could therefore be relevant in teaching/learning topics in which such concepts are used, that is almost all topics. In chapter 3 it was seen how the general explanatory scheme constrains 'state', 'change' and 'cause'. Another example of a constituting element constraining the concept of 'substance' would be the basic scheme

[9] Of course it would be preferable if the same teacher could participate in all trials.

with which both common sense and scientists (chemists in this case) classify substances: Part of what makes something a substance of a certain kind is that it behaves in a certain way in certain circumstances. What kinds of behaviour and what circumstances are considered relevant depends on one's explanatory aims and interests.

Identifying and making explicit such constitutive elements is difficult, although they may seem obvious once they are formulated. "It takes the greatest minds to articulate the constitutive elements clearly and sharply". Finding such elements is therefore a job for the great philosophers. "It is up to [... the] educationalists to explore whether and how they can be made educationally productive."

This research project was a first attempt at exploring the educational use of one example of a constitutive element. Within this wider perspective it would be premature to abandon this strategy because of the relative lack of success. It is not yet decided whether this strategy can be made to work for the topic of mechanics. That question is still open, I think. Whether the strategy as a whole will prove useful is a very wide question that will not be decided by applying it to one or two examples.

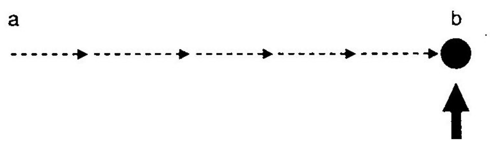
Appendix

FCI items used in the interviews for main theme 4

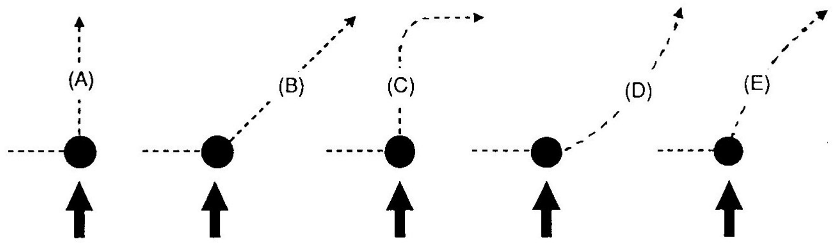
5. A boy throws a steel ball straight up. Disregarding any effects of air resistance, the force(s) acting on the ball until it returns to the ground is (are):

   (A) its weight vertically downward along with a steadily decreasing upward force.
   (B) a steadily decreasing upward force from the moment it leaves the hand until it reaches its highest point beyond which there is a steadily increasing downward force of gravity as the object gets closer to the earth.
   (C) a constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point, after which there is only the constant downward force of gravity.
   (D) a constant downward force of gravity only.
   (E) none of the above, the ball falls back down to the earth simply because that is its natural action.

* **Use the statement and diagram below to answer the next four questions:**
* **The diagram depicts a hockey puck sliding, with a constant velocity, from point "a"to point "b" along a frictionless horizontal surface. When the puck reaches point "b", it receives an instantaneous horizontal "kick" in the direction of the heavy print arrow.**



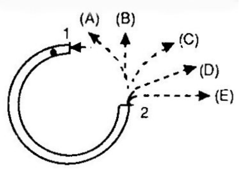
6. Along which of the paths below will the hockey puck move after receiving the "kick" ?



8. Along the frictionless path you have chosen, how does the speed of the puck vary after receiving the "kick"?

   (A) No change.
   (B) Continuously increasing.
   (C) Continuously decreasing.
   (D) Increasing for a while, and decreasing thereafter.
   (E) Constant for a while, and decreasing thereafter.

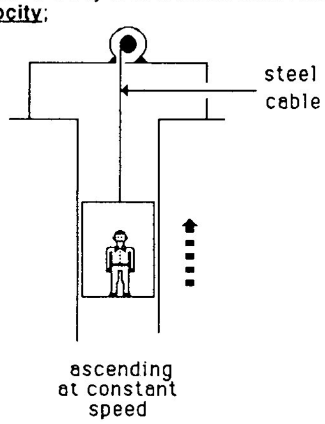
10. The accompanying diagram depicts a semicircular channel that has been securely attached, in a horizontal plane, to a table top. A ball enters the channel at "1" and exits at "2". Which of the path representations would most nearly correspond to the path of the ball as it exits the channel at "2" and rolls across the table top.



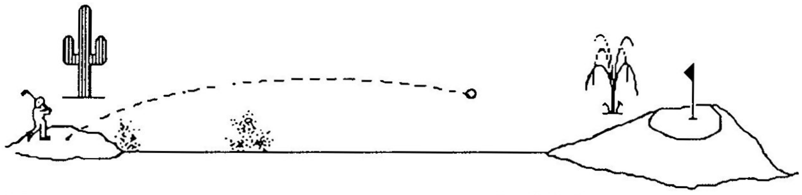
* **When responding to the following question, assume that any frictional forces due to air resistance are so small that they can be ignored.**

18. An elevator, as illustrated, is being lifted up an elevator shaft by a steel cable. When the elevator is moving up the shaft at a constant velocity;

   (A) the upward force on the elevator by the cable is greater than the downward force of gravity.
   (B) the amount of upward force on the elevator by the cables equal to that of the downward force of gravity
   (C) the upward force on the elevator by the cable is less than the down ward force of gravity.
   (D) it goes up because the cable is being shortened, not because of the force being exerted on the elevator by the cable.
   (E) the upward force on the elevator by the cable is greater than the downward force due to the combined effects of air pressure and the force of gravity.



22. A golf ball driven down a fairway is observed to travel through the air with a trajectory (flight path) similar to that in the depiction below.

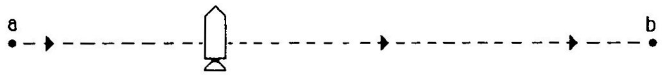


Which following force(s) is(are) acting on the golf ball during its entire flight?

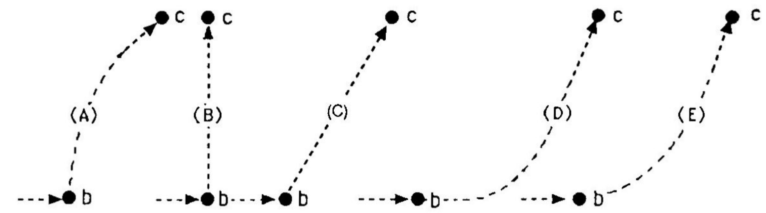
1. the force of gravity
2. the force of the "hit"
3. the force of air resistance

(A) 1 only
(B) 1 and 2
(C) 1, 2, and 3
(D) 1 and 3
(E) 2 and 3

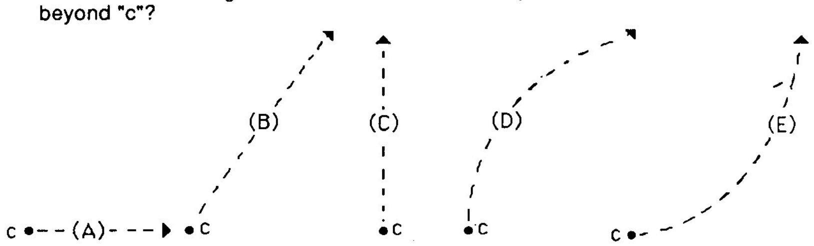
* **When answering the next four questions, refer to the following statement and diagram.**
* **A rocket, drifting sideways in outer space from position "a" to position "b". is subject to no outside forces. At "b", the rocket's engine starts to produce a constant thrust at right angles to line "ab". The engine turns off again as the rocket reaches some point "c".**



24. Which path below best represents the path of the rocket between "b" and "c"?



26. At "c" the rocket's engine is turned off. Which of the paths below will the rocket follow beyond "c"?



27. Beyond "c", the speed of the rocket is;

(A) constant.
(B) continuously increasing.
(C) continuously decreasing.
(D) increasing for a while and constant thereafter.
(E) constant for a while and decreasing thereafter.

28. A large box is being pushed across the floor at a **constant speed** of 4.0 m/s. What can you conclude about the forces acting on the box

(A) If the force applied to the box is doubled, the constant speed of the box will increase to 8.0 m/s.
(B) The amount of force applied to move the box at a constant speed must be more than its weight.
(C) The amount of force applied to move the box at a constant speed must be equal to the amount of the frictional forces that resist its motion.
(D) The amount of force applied to move the box at a constant speed must be more than the amount of the frictional forces that resist its motion.
(E) There is a force being applied to the box to make it move but the external forces such as friction are not "real" forces they just resist motion.

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Summary

In this thesis a research project is described that took place from 2000 until 2004 in the Centre for Science and Mathematics Education in Utrecht. It involves a didactical research into the teaching and learning of an introduction to mechanics for fourth grade pre-university level students (Dutch: 4 VWO). Many people consider mechanics as an important part of physics, well worth teaching and learning, but also as a topic in which many difficulties in learning and understanding surface. The aims of the research are to contribute to a further understanding of these difficulties and to point in the direction of possible solutions.

In **chapter 2** my research is positioned in the field of relevant other research. This other research is presented and critically discussed, focusing on educational goals, problem analysis, approach and method & results.

In addition to the common goal of understanding mechanics, three additional goals are identified in 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 is characterised by its focus on history, development and inquiry) and finally mechanics as raising the motivation of students for physics. In my view, these additional goals are indeed important aspects that perhaps can be connected to mechanics. They seem mostly fit for academically inclined minds, however, and some modesty in one's expectations about the extent to which these goals can be reached is in order.

Three types of analyses of the problems in mechanics education are 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 are criticised on grounds of their neglect of solving the interpretation problem. Whether one wants to change, restructure, confront or build on students' beliefs, it is important to first know what these beliefs are. In my opinion, this is in many cases not properly established. An alternative interpretation of students' beliefs is given in terms of a basic *scheme* for explaining motion. It involves an assumption for an influence free motion coupled to interaction theory from which it follows which influences are at work in a given situation. The influences are to account for deviations from the assumed influence free motion. This scheme can be seen to underlie both everyday and Newtonian explanations of motion and might therefore become useful in teaching and learning mechanics. The problem analysis in terms of a lack of attention to process is considered valid. An important point is still found to be lacking, however, namely how it 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 are presented and discussed.

- 'Making productive use of epistemological resources' correctly brings out the importance of students' appreciation of the epistemic virtue of generalizability. But it fails to address the important question why one model can be considered more general than another.

- ‘Overcoming misconceptions’ has lost a lot of its relevance after the severe criticism of the problem analysis on which this approach is based.
- ‘Providing adequate attention to process in teaching’ seems a valid approach given its aims. Apart from a similar objection as in the epistemological approach, the description of the approach is unclear about the way it is concretely implemented.
- ‘Building on useful intuitive notions by means of bridging’ does not mention nor solve the interpretation problem. Interpreted from the perspective of the explanatory scheme, very little happens with students’ concept of force in this approach.
- ‘Restructuring potentially useful intuitive notions’ mentions but does not solve the interpretation problem. It teaches one important aspect of the concept of force, namely interaction, but not other aspects. And some questions remain, most notably in what way students’ concept of force changes.

The emphasis in the discussion of the Method & Results of the approaches is on those that claim success, notably the Hestenes – Wells approach. By means of a discussion of what the FCI and MB tests actually measure, it is shown that what students learn in this approach is how to solve standard textbook problems, but not what the relation is between common sense and Newtonian mechanics.

The discussion of the relevant literature therefore shows that there is still some work to do concerning an understanding of the learning difficulties in mechanics, and concerning ways to remedy the difficulties and thereby to improve education in the direction of one’s educational goals.

In **chapter 3** the theoretical and methodological backgrounds of the design of an introductory course in mechanics are addressed. First of all, I present my goals for mechanics:

1. students come to know how mechanics works;
2. students develop some appreciation of the power and range of mechanics;
3. students are provided a vocabulary with which the usual learning difficulties can be discussed.

Subsequently, the explanatory scheme underlying both common sense and Newtonian mechanics is extensively discussed. It is argued that this scheme is a special case of causal explanation in general. Our ordinary picture of causation is one of things remaining in the same state unless interfered with by external causes. Causes effectuate changes of state. In giving a causal explanation, what we typically want to know is what to add to one state to make the change to another state intelligible. In order to achieve this, we appeal to more or less strict regularities (usually of an ‘other things being equal’ type) that cover the case. What we select as ‘the’ cause of some change, furthermore, is some feature chosen from the totality of causal factors which particularly interests us. Relations such as these, between the concepts of change, cause, regularity and interest, comprise a basic structure in causal explanation in general. I refer to this structure as the *general explanatory scheme*. It can also be seen at work in explanation of motion, and shapes the explanatory scheme of motion. What gets explained in an explanation of motion are changes of *state of motion*, and forces effectuate such changes. An assumption for the influence free motion comes down to saying what is to count as a state of motion. This assumption needs to be checked by interaction theory. If in a given situation an object's motion deviates from the assumed influence free motion, this deviation must be attributable, via interaction theory, to influences exerted by other objects. This explanatory scheme for motion also allows for a variety of specific explanations of motion, each with a different assumption for the influence free motion, where the variety to some degree reflects the variety of explanatory interests we may happen to have.

In this way the explanatory scheme of motion is provided with a solid backbone. It is then argued that two conditions need to be fulfilled if the explanatory scheme is to productively function in mechanics education: (1) Students' use of the scheme needs to be triggered and explicated and (2) Newton's use of the scheme needs to be made explicit. Subsequently a pilot study is presented, which aims to explore the feasibility of meeting the first condition. The promising results of this pilot have given rise to the main research question: 'How can the idea of a common explanatory scheme for motion in common sense and Newtonian mechanics be made productive in teaching/learning mechanics?'

This design question is investigated using the method of a 'design experiment', which involves a cyclic process of designing, testing and revising a prototype. In order to make the didactical quality of the prototype object of study, detailed qualitative data of the actual teaching/learning process needs to be collected and compared with an equally detailed description and justification of the expected teaching/learning process in a scenario.

Theoretical guidelines for the design are expressed in my view on teaching and learning, which can be called educational constructivist. In addition I adhere to a *problem posing* approach to education, which aims at having students at all times see the point of what they are doing, thereby making the teaching/learning process make more sense to them. The work of Vollebregt (1998) has served as an important source of inspiration, both in suggesting several main themes in my design and in providing for the idea of a 'didactical structure' as a functional description of the main steps in teaching/learning some topic.

The main themes in my design are:

1. The *why* and *how* of introducing the topic. The explanatory scheme for motion plays a role in the 'how'.
2. Extending students' knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining motion.
3. Reflection on the knowledge developed so far and the method of working. This consists of an evaluation of models and *types* of model in the light of achieving broader applicability.
4. Preparation of and embedding in the regular course.

The didactical structure in Figure 1 shows how these four main themes are implemented in the second (and within my research last) version of the design. The numbers on the left of this figure indicate the four main themes. Below I further elaborate the structure.

	Mechanics	**Motive**	**Explanation**
1	1.Broad orientation on motions		that are worth predicting / explaining
		2. Should result in the notion that this is an important and interesting theme worth knowing more about	
			3. Starting with explanation in general and explanation of motions in particular in which by reflection an underlying scheme is found and made explicit
		4. which should lead to the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of this underlying scheme (theoretical orientation)	
2	5. Specification of the underlying scheme into two specific schemes (Keplerian and Newtonian) in the context of developing and testing models of the motion of heavenly bodies.		
		6. resulting in a question concerning the fruitfulness of the specific schemes and models	
			7. Reflection on criteria to determine which schemes and models explain best
		8. resulting in a plan for further validation of the specified schemes	
3	9. Applying the specific Keplerian and Newtonian scheme to other motions		
		10. leading to a point of closure at which we may ask "which schemes and models explain best?"	
			11. Evaluation of which schemes and models explain best and which elements of this scheme are still unknown
		12. resulting in an appreciation of the Newtonian scheme and an outlook on the regular course	
4	13. Regular mechanics course		

Figure 1: Didactical structure of the second design of the introductory course

First main theme

The function of the first main theme is to address the questions '*why* study the topic of explaining motions?' and '*how* are motions explained?'. This should result, firstly, in the motive that this is an important and interesting theme worth knowing more about, related to the why-question (step 2 in figure 1). Secondly, this should result in the feeling that it is a theoretical challenge to explain motions by means of an as yet unknown specification of a causal explanatory scheme, related to the how-question (step 4).

In order to raise the why-question, the example of an asteroid moving towards earth is used as a prototype of a situation in which an explanation or prediction of motion is clearly desirable and not so easy to obtain. The first point appeals to a certain importance, the second point to an intellectual challenge. While maintaining the theoretical orientation, the 'how-question' is then answered in terms of the explanatory scheme for motion (step 3). It is introduced by using the general explanatory scheme, describing all causal explanation, as a stepping-stone. The general structure in causal explanations is introduced by letting students reflect on some simple explanations is terms of a comparison. Two situations are pictorially compared, one in which the event to be explained occurs and a reference situation in which it does not. The features lacking from the reference situation, furthermore, are to be easily identifiable as causing the event, and this identification is to be reinforced by familiar background knowledge that causes of that kind are bound to be followed by an event of the kind to be explained (other things being equal). In this way it is tried to make the abstract general explanatory scheme as concrete and recognisable as possible for students. The explanatory scheme for motion is then introduced as a special case of the more general scheme. Again, two situations are pictorially compared. One in which an object is moving under an easily recognisable influence, and a reference situation in which the object is moving without that influence. This is to introduce the basic idea of 'the influence as the cause of the difference between the two motions'. In more complicated situations, students are expected to be less sure or to disagree about the influences that might be at work (i.e. about interaction theory) or about the way an object would move of its own accord in the absence of all influences (i.e. about the influence free motion). The insecurities or disagreements are to introduce the basic idea as just a *scheme*. Students are expected to realize that it needs to be further specified, without yet knowing how to do this in more difficult situations such as the motion of the asteroid. To find this out sets the agenda for the bulk of the course in main theme 2.

Second main theme

Kepler's and Newton's theories of planetary motion are introduced as alternative ways to detail the explanatory scheme (step 5). Their respective assumptions for the influence free motion are given (rest versus uniform rectilinear), as well as their respective interaction theories (a whirling influence due to the rotation of the sun versus an attractive gravitational influence). The interaction theories are at first presented qualitatively, and subsequently several alternative ways to quantify the qualitative relations are discussed. The qualitative statement 'the farther away, the smaller the influence' can for instance be implemented by assuming that the influence varies as the inverse of the distance, or by assuming that that it varies as the inverse square of the distance, and so on. In this way a set of parameterised influence laws comes forward, both in Kepler's and in Newton's scheme. The Keplerian influence laws have the rotation speed of the sun and the power of the inverse distance as parameters; the Newtonian ones the heaviness of the sun and the planet as well as the power of the inverse distance.

Students are then introduced to a modelling environment on a computer in which the motions of two objects are displayed: of an observed planet and of a model planet that moves according to some specification of the explanatory scheme, e.g., Kepler's assumption for the influence free motion in combination with a specific Keplerian influence law. One constraint on the appropriateness of the specification in accounting for the motion of the planet is expected to be intuitively clear to students: the two motions should match. In other words, the specification should be empirically adequate. The task for students, therefore, becomes to (virtually) solve the problem of matching theory with observation, by manipulating parameters and seeing the effect of the manipulations. This is expected to be a worthwhile task for the students, even if they do not know the ins and outs of how the computer determines the motion of the model planet.

Then the concept of laziness or inertia is addressed in order to deal with situations in which two or more objects are subject to an influence (e.g., two or more planets). The idea is that the deviation (from the assumed influence free motion) not only depends on the influence, but also on the object itself. This leads to the rule 'deviation = influence / laziness'. Both Kepler and Newton believed that 'the amount of matter' is a measure for the laziness.

Optionally, the precise relation between influence and motion is further investigated by means of graphical time-step by time-step construction. The quickest and brightest students can in this way gain deeper insight in how the motion of an object can be determined (and is determined by the computer program) from given influences and an assumption for the influence free motion.

The question how fruitful the Keplerian and Newtonian types of model are is expected to pop up occasionally in the process of investigating Keplerian and Newtonian models throughout the second main theme, and to become stronger along the way (step 6). This seems a natural response to continuously investigating alternatives, especially when both alternatives seem feasible. Since within both types of model more or less empirically adequate solutions to the matching problem can be found, the question which type of model is better remains unanswered and is unanswerable on the basis of just this one criterion. The criterion of empirical adequacy is effective to rule out specific models, but not a *type* of model.

Third main theme

The function of the third main theme is to reflect on criteria to determine which type of model explains best (step 7). Subsequent application (step 9) and evaluation (step 11) of these criteria should result in an appreciation of Newtonian models and an outlook on the regular course (step 12). The second main theme is supposed to have resulted in a (slowly strengthening) question about the fruitfulness of the two types of model (step 6). Reflection on the accomplishments of the first main themes (step 7) should lead to the conclusion that this question cannot be answered solely on the basis of the criteria of empirical adequacy and plausibility. Some students are by now expected to come up with the additional criterion of broad applicability, or otherwise the teacher can introduce it, as part of a possible and intuitively clear way of shedding further light on this question. This additional criterion is to function as a guiding strategy for further investigation of the value of the two types of model (step 8).

In the light of the additional criterion of broad applicability students are to see the application of Keplerian and Newtonian models to a situation on earth (step 9) as an additional way to estimate the value of these types of model (step 10). In this process they are expected to prefer Newton to Kepler. Wider applicability is one reason for appreciation of the Newtonian specification of the explanatory scheme, i.e. Newtonian mechanics (step 12). This appreciation can be further strengthened by solving the initial asteroid problem with a (Newtonian) model.

Fourth main theme

The possibility to explain all kinds of motions with the Newtonian specification of the explanatory scheme is an important element in understanding all change in a mechanicistic sense. (Another element is some knowledge about particle models.) A mechanicistic view is presented to provide further appreciation for the power and range of mechanics. This appreciation marks the transition to the regular course (step 13), in which the Newtonian specification of the explanatory scheme is further applied using new influences and influence laws. A preview of the regular course is given at the end of the introductory course (step 12).

The didactical structure depicted in Figure 1, and explained above, is arrived at by testing and evaluating an earlier design. In **chapter 4** the development from the first design of the introductory course to the second design is described. The first design showed considerable shortcomings when it was put to the test, even though it was fairly convincingly justified in theory. Chapter 4 therefore illustrates the method of developmental research, in showing how it helped in understanding many of the shortcomings in retrospect and how it helped generating ideas for improving the design. For this both the empirical test and the scenario are needed.

A second topic addressed in chapter 4 is teacher preparation. The problem encountered in preparing the teacher is that a problem posing approach requires a way of teaching that, on the one hand, allows a lot of student input and, on the other, guides students in keeping track of the main thread. Attention to these two points seems to be a blind spot in much traditional education. This problem is discussed and illustrated with some experiences from the first trial. An important factor in addressing this problem is to make the teacher have a sense of ownership concerning the implementation of the design in such a way that the intended goals and functions can be met. In order to achieve this, it is suggested to let the teacher think of appropriate *interaction structures* for each of the activities. That is, to let the teacher think of ways to structure the interaction with students such that they feel that their input matters, and of ways to introduce and evaluate each activity such that it helps students to keep track of the main line. The teacher's planned implementation can then be discussed with the designer in view of its suitability for realizing the goals and functions of the activities.

In **chapter 5** the second design is described on two different levels of detail. After a quite general level of description in chapter 4, the design is described on the intermediate level of episodes and on the detailed level of activities within each episode. An 'episode' is a sequence of connected activities related to a particular goal. 'Activities' are, for example, reading a text, answering some questions or discussing an outcome with a fellow student. An episode forms a coherent unit in the sense that it requires the introduction of a central question, a middle part in which this question is addressed, and finally an evaluation of the answers that are found or further questions that are raised. Its duration ranges from 30 - 80 minutes. For each episode its function is briefly recapitulated, a justification of the content and interaction structure in the light of the function is given, and the expected unfolding of the three parts of each episode is given (introduction, search for answers, evaluation). Descriptions on this level of detail are needed, because the process of testing makes use of the detailed level when the actual teaching/learning process is followed and compared with the intended teaching/learning process. This comparison is guided by the formulation of several analysis questions in relation to each episode. Answering these analysis questions on the intermediate level uses the detailed level and provides the basis for broader conclusions on the level of main themes and introductory course itself.

In **chapter 6**, the results are presented of putting to the test the second design of the didactical structure. In the description of the method for data collection, analysis and presentation, it is seen that the scenario and the analysis questions guide a way through the plethora of collected data of which only a small fraction is presented. In order to compare the expected teaching/learning process with the actual teaching/learning process, the latter is recorded by means of notes of observations, video and audio recording, photocopies of students' written materials, and student interviews after the course. This data is analysed with the help of the scenario, analysis questions and so called lesson reports (rough summaries of collected data per lesson). My answers to the analysis questions are read by a second researcher who has access to the lesson reports and who goes through the process of selecting and interpreting relevant data from the lesson reports in order to arrive at answers to a subset of analysis questions. The interpretations and answers are discussed until agreement is reached (in rare cases the agreement is that there are several possibilities).

The results of the preparation of the teacher for the second trial are also presented in this chapter. Given the restrictions in time the teacher was prepared in the best way I could. Nevertheless, the teacher did not accept the idea of using interaction structures as a tool for the practical implementation of the already designed content. This was not just unwillingness on the part of the teacher. Due to circumstances, he was not able to spend the required time and energy. One consequence is that hardly any conclusions can be drawn with respect to the appropriateness of interaction structures. Another unfortunate consequence is that the teacher's actual implementation deviated to such an extent from what was intended, that it became very difficult to separate failures due to deviations in the implementation from failures in the didactical structure. I my evaluation I was forced to use al lot of counterfactual reasoning of the kind 'if this and that had be done, it might have been the case that …'. Obviously, this has considerably reduced the empirical support of the answers to my research questions concerning the quality of the didactical structure. Below I summarize the conclusions that I think can nevertheless, though with some care, be drawn.

Concerning the first main theme, the how and why of explaining motions, some empirical backing is obtained for the possibility of triggering and explicating both the general explanatory scheme and the explanatory scheme for motion (step 3 in figure 1). The asteroid problem (step 1 and 2) and the general explanatory scheme as stepping-stone (step 3) might also perform their intended functions and students are seen to develop some sense of theoretical orientation (step 4). An important goal is not achieved, however. Students do recognise the various elements of the explanatory scheme for motion, and they do appreciate to some extent that these elements need to be further specified, but they do *not* recognise that such specifications promise to combine to an explanation of motion. In this sense, the explanatory scheme does *not* come forward as a guideline to get a further grip on how to explain motion (step 4). Therefore the motive for the second main theme is lacking. This failure points at an error in the didactical structure.

Consequently, the second main theme, the extension of knowledge by detailing the explanatory scheme to arrive at empirically adequate models for explaining planetary motion, results in a disappointing recognition of the main thread (step 5). Furthermore, it seems that too many factors determining a motion are introduced too close together. This makes it hard for students to clearly separate e.g. the respective roles that the dynamically relevant parameters in influence laws and the concept of laziness play in an explanation of motion (step 5). Students do manage to use the criteria of empirical adequacy and plausibility for choosing between models. Both Keplerian and Newtonian models remain feasible alternatives and the question concerning the fruitfulness of the specific schemes and models does emerge (step 6).

The third main theme, evaluation of models and *types* of model in the light of achieving broader applicability, results in the observation that students do use the relevant criteria to determine which type of model explains best. More attention should have been paid to making the criteria explicit, however, especially 'broad applicability' (step 7). That would have made clearer the reason for applying the models to other motions (step 8 and 9). Furthermore, cumulative effects of earlier failures in the first two main themes makes the evaluation of the models very difficult (step 10 and 11) and the appreciation of Newtonian models (step 12) rather weak.

The fourth main theme, embedding in the regular course (step 13), is investigated to a far less extent than the earlier main themes and merits further research. However, some preliminary findings include that in reasoning about explanations of motion elements from the introductory course can be used productively. Arguments for identifying influences from the relation influence – motion and from interaction theory are used by students themselves. The graphical construction method is not used by them, but can be recognised and understood and provides for convincing reasoning.

Chapter 7 starts with an evaluation of the three main educational goals of the introductory course. With respect to the first goal of gaining insight in how mechanics works, it is seen that students have difficulty distinguishing influence from parameters in an influence law. Furthermore they have difficulty correctly relating influence, laziness and deviation. Establishing these main concepts in relation to each other may be more difficult to achieve and more time consuming than anticipated. A possible simplification could be to omit an early introduction of the concept of laziness. With respect to the second goal of appreciation of the power and range of (Newtonian) mechanics, it can be said that it is not achieved. Nevertheless, students are seen to implicitly apply the relevant epistemic virtues. This leads me to believe that when these criteria are made explicit and used as such, students will be able to give some argued reasons for preferring Newtonian mechanics, which will amount to some appreciation. In my research hardly any attempts are made to reach the third goal, the provision of a vocabulary in which to address the usual learning difficulties. Some encouraging aspects were found in a preliminary attempt at discussing several triggered learning difficulties during the regular course. This issue deserves a more comprehensive study.

This research started with the ideas (1) that common sense and Newtonian mechanics have an explanatory scheme in common and (2) that this commonality can be used in teaching/learning mechanics in a problem posing way. I have no reason to doubt the first idea, in view of the solid theoretical underpinning I have provided for it. I also do not doubt the second idea, even though I clearly fell short of implementing it. The reasons for this failure are, I think, twofold. First, no proper way has as yet be found to make the explanatory scheme 'come alive' as familiar, somewhat elusive and yet as providing a useful and promising guideline. This relates to the failure to provide a proper motive (step 4 in figure 1) for engaging in learning most of the mechanics content. The second main problem that is encountered is that on a more detailed level the design still falls short in implementing the didactical structure in the activities within the episodes. The intended motives are not sufficiently incorporated in the design of the successive activities. Much of the design turns out to be too much top-down, in the sense of emphasising teacher input and exhibits too much of a 'transfer' perspective on teaching/learning, and too little of the intended educational constructivist perspective. This problem is particularly felt in step 5 (figure 1) and accounts for the poor results in this part of the design.

With respect to the first problem, a useful suggestion may be to not conceptually overload the explanatory scheme. No more seems to be needed than the basic idea that 'whenever there is a deviation from how something would move of its own accord, you search for some cause for that'. Perhaps it is also possible to more directly expand this basic idea to a proto-version of a graphical construction method, with the implication that an assumption about the influence free motion (of-its-own-accord motion) and assumptions about influences promise to combine to an explanation of a motion.

Two ideas may be helpful in addressing especially the second problem: educationalising practices and using interaction structures. The basic idea of educationalising a practice is that a professional practice that is by its nature purposeful for those who participate in it may be adapted for use in school in such a way that students can also recognise and appreciate its purpose. Within such an adapted or 'educationalised' practice students can then learn the things we would like them to learn in a meaningful way, which would fit nicely in a problem posing approach. In the case of mechanics the underlying idea can be applied to the academic practice of constructing theoretical knowledge by dividing the main question of ‘how does explanation of motion work?’ into the sub questions ‘how does something move of its own accord?’ and ‘what influences are working in this situation?’. This division can be expected to guide the teaching/learning process in a for students recognisable way, since it uses the basic notion that ‘an influence causes a deviation of the way something would move of its own accord’. A rough outline of the educationalised academic practice of constructing theoretical knowledge will then consist of (1) dividing the main question ‘how does explaining motions work’ into sub-questions, (2) answering these sub-questions, and (3) evaluating the answers in the light of relevant epistemic virtues such as those of empirical adequacy and broad application.

Using interaction structures not only can be helpful in preparing the teacher, but also in making the design more bottom-up. The kind of interaction and the design being bottom-up or top-down are strongly related. An improved description of interaction structures (paying more attention to the student side of the interaction) or even entirely different interaction structures may become helpful in this respect. This can prove helpful in the difficult process of carefully balancing between teacher input and making student input matter. The main potential value of interaction structures lies in their ability to enable the right kind of discussion between teacher and designer, making the teacher preparation more effective.

Chapter 7 concludes with the speculation that the used strategy of using similarities between common sense and scientific reasoning on a underlying structural level in teaching/learning a topic may be useful for other topics than mechanics.

Samenvatting

In dit proefschrift wordt een onderzoek beschreven dat van 2000 tot 2004 in het Centrum voor Didactiek van Wiskunde en Natuurwetenschappen aan de Universiteit Utrecht plaatsvond. Het behelst een didactisch onderzoek naar het leren en onderwijzen van een introductie in de mechanica voor leerlingen in 4 VWO. Velen zien mechanica als een belangrijk onderdeel van de natuurkunde, dat het zeer zeker waard is te onderwijzen en te leren, maar ook als een onderwerp waarin veel leer- en begripsproblemen voorkomen. Het doel van dit onderzoek is bij te dragen aan een dieper begrip van deze problemen en richtingen voor mogelijke oplossingen ervan aan te wijzen.

In **hoofdstuk 2** wordt mijn onderzoek in het relevante onderzoeksveld geplaatst. Relevante onderzoeksliteratuur wordt gepresenteerd en kritisch besproken, waarbij met name gekeken wordt naar educatieve doelen, probleem analyses, oplossingsbenaderingen en methode & resultaten besprekingen.

Naast het gemeenschappelijke doel van het begrijpen van mechanica worden in enkele invloedrijke curriculumvernieuwingsprojecten uit de laatste 40 jaar drie additionele doelen geïdentificeerd: Mechanica als een voorbeeld van 'natuurwetenschap op zijn best', mechanica als een voorbeeld van een humanistische onderneming (gekarakteriseerd door de nadruk op geschiedenis, ontwikkeling en onderzoek) en als laatste mechanica als middel om de motivatie van leerlingen voor natuurkunde te verhogen. Naar mijn mening zijn deze additionele doelen inderdaad belangrijk en kunnen ze misschien gekoppeld worden aan mechanica. Ze lijken wel vooral geschikt voor de meer academisch georiënteerde geesten, en enige bescheidenheid in de verwachtingen over de mate waarin deze doelen gerealiseerd kunnen worden is raadzaam.

Er worden drie soorten analyse van de problemen in mechanica onderscheiden: (1) verwaarlozing van intuïtieve mechanica, waarbij sommigen deze intuïtieve mechanica als potentiële hulp bij het leren zien en anderen als potentieel obstakel, (2) verwaarlozing van epistemologische opvattingen en (3) het ontbreken van aandacht voor het *proces* bij het onderwijzen. De kritiek op de eerste twee soorten is dat ze nalaten het interpretatieprobleem op te lossen. Of men nu de ideeën van leerlingen wil veranderen, herstructureren, confronteren of erop wil bouwen, men moet eerst weten wat die ideeën zijn. Naar mijn mening wordt dit in veel gevallen niet goed nagegaan.

Een alternatieve interpretatie van de ideeën van leerlingen wordt gegeven in termen van een basaal *schema* voor het verklaren van beweging. Dit schema behelst een aanname voor een invloedloze beweging, gekoppeld aan interactietheorie waaruit volgt welke invloeden er in een gegeven situatie zijn. De invloeden moeten dan afwijkingen van de invloedloze beweging verklaren. Dit schema kan herkent worden in zowel Newtoniaanse als alledaagse verklaringen van beweging en kan daarom wellicht nuttig gebruikt worden in het onderwijzen en leren van mechanica.

De probleemanalyse die het probleem vooral in het ontbreken van aandacht voor het proces zag, wordt als geldig gezien. Hierin ontbreekt alleen nog een belangrijk aspect, namelijk hoe het leerlingen duidelijk gemaakt kan worden waarom expliciete aandacht voor het proces epistemologische waarden als algemeenheid, exactheid, voorspellend vermogen et cetera uit zou drukken.

Er worden vijf benaderingen voor het overwinnen van de geïdentificeerde problemen in mechanicaonderwijs gepresenteerd en bediscussieerd:

- ‘Productief gebruik maken van epistemologische bronnen’ laat goed het belang zien van de waardering van leerlingen voor de epistemologische waarde ‘algemeenheid’. Het kaart echter niet de belangrijke vraag aan waarom het ene model als algemener dan het andere gezien kan worden.
- ‘Het overwinnen van misconcepties’ heeft veel van zijn relevantie verloren na de serieuze kritiek op de probleemanalyse waarop deze benadering is gebaseerd.
- ‘Adequate aandacht schenken aan het proces bij het onderwijzen’ lijkt een geldige benadering, gegeven haar doelstellingen. Behalve een soortgelijk bezwaar als bij de epistemologische benadering, wordt in de beschrijving van deze benadering ook niet duidelijk hoe hij nu concreet wordt geïmplementeerd.
- ‘Het bouwen op bruikbare intuïtieve ideeën middels overbrugging’ vermeld het interpretatieprobleem niet en lost dit ook niet op. Vanuit het perspectief van het verklaringsschema bekeken gebeurt er erg weinig met het krachtconcept van leerlingen in deze benadering.
- ‘Het herstructureren van potentieel nuttige intuïtieve ideeën’ noemt het interpretatieprobleem wel, maar lost het niet op. Het onderwijst een belangrijk aspect van het krachtconcept, namelijk interactie, maar geen andere aspecten. Ook blijven sommige vragen onbeantwoord, met name op welke manier het krachtconcept van leerlingen verandert.

Nadruk in de bespreking van de methode & resultaten van de verschillende benaderingen ligt op diegene, die beweren succesvol te zijn, met name de Hestenes – Wells benadering. Door een discussie van wat de FCI test en de MB test nu werkelijk meten, wordt getoond dat wat leerlingen in deze benadering vooral leren hoe ze standaard leerboek opgaven moeten maken, maar niet wat de relatie tussen alledaagse en Newtoniaanse mechanica is.

De bespreking van de relevante literatuur laat daarom zien dat er nog steeds werk te doen is in het begrijpen van leerproblemen in mechanica, in het vinden van manieren om iets aan die moeilijkheden te doen, en in het op die manier verbeteren van het onderwijs in de richting van de gestelde educatieve doelen.

In **hoofdstuk 3** worden de theoretische en methodologische achtergronden van het ontwerp van een introductiecursus in mechanica besproken. Eerst presenteer ik mijn doelen voor mechanica:

1. leerlingen leren hoe mechanica werkt;
2. leerlingen ontwikkelen enige waardering voor de kracht en reikwijdte van mechanica;

3. leerlingen krijgen een vocabulaire aangeboden waarmee de gebruikelijke leerproblemen besproken kunnen worden.

Daarna wordt het verklaringsschema wat zowel in alledaagse als Newtoniaanse mechanica herkend kan worden uitgebreid besproken. Er wordt beargumenteerd dat dit schema een speciaal geval is van causaal verklaren in het algemeen. Onze gewone voorstelling van causaliteit is dat dingen in dezelfde toestand blijven totdat een externe oorzaak ze beïnvloedt. Oorzaken zorgen voor toestandsveranderingen. Als we een causale verklaring geven, willen we met name weten wat we moeten toevoegen aan de ene toetstand om de overgang naar de andere toestand begrijpelijk te maken. Om dit voor elkaar te krijgen doen we een beroep op meer of minder strikte regelmatigheden (meestal van het ceteris paribus type), die op het geval van toepassing zijn. Wat we als 'de' oorzaak van een of andere verandering kiezen is één van de vele causale factoren, namelijk degene die we interessant vinden. Dit soort relaties tussen de concepten verandering, oorzaak, regelmatigheid en interesse vormen een basale structuur van causaal verklaren in het algemeen. Ik noem deze structuur het *algemene verklaringsschema*. Het kan ook herkend worden in verklaringen van beweging en geeft vorm aan het verklaringsschema voor beweging.

Wat verklaard wordt bij een verklaring van beweging zijn veranderingen in de *bewegingstoestand*, tot stand gebracht door krachten. Een aanname voor een invloedloze beweging komt neer op het vaststellen van wat als een bewegingstoestand gerekend kan worden. Deze aanname moet passen bij de interactietheorie. Als in een bepaalde situatie een voorwerp anders beweegt dan de aangenomen invloedloze beweging, dan moet deze afwijking toegeschreven kunnen worden, via interactietheorie, aan invloeden die door andere objecten worden uitgeoefend op het voorwerp in kwestie. Dit verklaringsschema voor beweging staat een variëteit van verschillende specifieke verklaringen van beweging met verschillende aannames voor de invloedloze beweging toe, waarbij de variëteit enigszins de variëteit in verklaringsdoelstellingen die mensen kunnen hebben weerspiegelt.

Op deze manier wordt het verklaringsschema voor beweging van een stevige fundering voorzien. Er wordt dan beargumenteerd dat er twee voorwaarden moeten worden vervuld, wil het verklaringsschema productief kunnen worden in mechanica onderwijs: (1) Het gebruik dat leerlingen maken van het verklaringsschema moet opgeroepen en expliciet gemaakt worden en (2) het gebruik dat Newton ervan maakt moet expliciet gemaakt worden. Daarna wordt een vooronderzoek gepresenteerd, wat tot doel heeft de werkbaarheid van de eerste voorwaarde te verkennen. De veelbelovende resultaten van dit vooronderzoek leidden tot de onderzoeksvraag: 'Hoe kan het idee van een gemeenschappelijk verklaringsschema voor beweging in alledaagse en Newtoniaanse mechanica productief gebruikt worden in het onderwijzen/leren van mechanica?'

Deze ontwerpvraag werd onderzocht via een 'ontwerpexperiment' methode, die bestaat uit een cyclisch proces van ontwerpen, testen en bijstellen van een prototype. Om de didactische kwaliteit van het prototype tot onderzoeksobject te maken moeten gedetailleerde kwalitatieve gegevens van het werkelijke onderwijsleerproces verzameld worden en worden vergeleken met een even gedetailleerde beschrijving en rechtvaardiging van het verwachte onderwijsleerproces in een scenario.

Theoretische aanwijzingen voor het ontwerp worden in mijn visie op onderwijzen en leren uitgedrukt. Deze visie kan educatief constructivistisch genoemd worden. Daarnaast volg ik een *probleemstellende* benadering van onderwijs, die tot doel heeft dat leerlingen voortdurend het nut inzien van wat ze doen, waardoor het onderwijsleerproces als zinniger en begrijpelijker ervaren wordt. Het werk van Vollebregt (1998) diende als een belangrijke inspiratiebron, zowel door verschillende hoofdthema's in mijn ontwerp voor te stellen als ook het gebruik en nut van het idee van een 'didactische structuur', een functionele beschrijving van de belangrijkste stappen in het leren/onderwijzen van een onderwerp, te illustreren.

De hoofdthema's in mijn ontwerp zijn:

1. Het *hoe* en *waarom* van het introduceren van het onderwerp. Het verklaringsschema voor beweging speelt een rol in het 'hoe'.
2. De kennis van leerlingen uitbreiden door de details van het verklaringsschema in te vullen en zo te komen tot empirisch adequate modellen voor het verklaren van beweging.
3. Een reflectie op de ontwikkelde kennis en de gebruikte werkmethode. Dit bestaat uit een evaluatie van modellen en model*soorten* in het licht van het bereiken van grotere toepasbaarheid.
4. Voorbereiding van en inpassen in de reguliere cursus.

De didactische structuur in Figuur 1 laat zien hoe deze vier hoofdthema's in de tweede (en in mijn onderzoek laatste) versie van het ontwerp zijn verwerkt. De cijfers links in de figuur geven de vier hoofdthema's aan. Hieronder zal ik de structuur verder toelichten.

Eerste hoofdthema

De functie van het eerste hoofdthema is om de vragen '*waarom* zou je het verklaren van beweging bestuderen?' en '*hoe* worden bewegingen verklaard?' aan te kaarten. Dit zou ten eerste moeten leiden tot de beweegreden dat dit een belangrijk en interessant onderwerp is, wat het waard is om meer over te weten, wat samenhangt met de waarom-vraag (stap 2 in figuur 1). Ten tweede zou dit moeten leiden tot het gevoel dat het een theoretische uitdaging is om bewegingen te verklaren met behulp van een vooralsnog onbekende invulling van het causale verklaringsschema, wat samenhangt met de hoe-vraag (stap 4).

Om de waarom-vraag op te roepen wordt het voorbeeld van een asteroïde die naar de aarde beweegt gebruikt als een prototype van een situatie waarin een verklaring of voorspelling van een beweging duidelijk wenselijk is en niet zo gemakkelijk is. Het eerste punt geeft het belang aan, het tweede punt een intellectuele uitdaging. De hoe-vraag wordt dan beantwoord met gebruikmaking van het verklaringsschema voor beweging (stap 3), terwijl ook de theoretische oriëntatie gehandhaafd zou moeten blijven. Het schema wordt geïntroduceerd door gebruik te maken van het algemene verklaringsschema als opstapje.

	Mechanica	**Beweegreden**	**Verklaren**
	1. Brede oriëntatie op bewegingen		die het waard zijn voorspeld/verklaard te worden
		2. moet leiden tot het idee dat dit een belangrijk en interessant onderwerp is, waar je meer over wilt weten	
1			3. Beginnen met verklaren in het algemeen en het verklaren van bewegingen in het bijzonder, waarin door reflectie een onderliggend schema gevonden en expliciet gemaakt wordt
		4. wat moet leiden tot het gevoel dat het een theoretische uitdaging is bewegingen door middel van een nog onbekende specificatie van dit onderliggende schema te verklaren (theoretische oriëntatie)	
2	5. Specificatie van het onderliggende schema in twee specifieke schema's (Kepleriaans en Newton-iaans) in de context van het ontwikkelen en testen van modellen voor de beweging van hemel-lichamen.		
		6. leidt tot een vraag naar wat de specifieke schema's en modellen opleveren	
			7. Reflectie op criteria om te bepalen welke schema's en modellen het best verklaren
		8. leidt tot een plan voor de verdere fundering van de ingevulde schema's	
3	9. Toepassen van de ingevulde Kepleriaanse en Newtoniaanse schema's op andere bewegingen		
		10. leidt tot een afronding waarin we ons kunnen afvragen "welke schema's en welke modellen verklaren het best?"	
			11. Evaluatie van welke schema's en modellen het best verklaren en welke elementen in dit schema nog onbekend zijn
		12. leidt tot een waardering van het Newtoniaanse schema en een uitkijk op de reguliere cursus	
4	13. Reguliere mechanica cursus		

Figuur 1: Didactische structuur van het tweede ontwerp van de introductiecursus

De algemene structuur in causale verklaringen wordt geïntroduceerd door leerlingen op eenvoudige verklaringen te laten reflecteren in termen van een vergelijking. Twee situaties, een waarin de te verklaren gebeurtenis voorkomt en een reverentiesituatie waarin dat niet zo is, worden met behulp van plaatjes vergeleken. De eigenschappen die niet in de referentiesituatie te vinden zijn, zouden gemakkelijk als de oorzaak van de gebeurtenis aangewezen moeten kunnen worden. Dit aanwijzen zou versterkt moeten worden door bekende achtergrondkennis die zegt dat oorzaken van deze soort altijd gevolgd worden door een soort gebeurtenis zoals degene die verklaard moet worden (als alle andere dingen hetzelfde blijven). Op deze manier wordt getracht het abstracte algemene verklaringsschema zo concreet en herkenbaar mogelijk te maken voor leerlingen. Het verklaringsschema voor beweging wordt dan geïntroduceerd als een speciaal geval van het meer algemene verklaringsschema. Opnieuw worden twee situaties met behulp van plaatjes met elkaar vergeleken. In de ene situatie beweegt een voorwerp als gevolg van een gemakkelijk herkenbare invloed en in de andere referentiesituatie beweegt het voorwerp zonder die invloed. Hiermee wordt het basale idee geïntroduceerd dat 'de invloed de oorzaak is van het verschil tussen de twee bewegingen'. In ingewikkelder situaties zijn leerlingen naar verwachting onzekerder of het oneens met elkaar over welke invloeden er werkzaam zouden zijn (dus over de interactietheorie) of over hoe een voorwerp uit zichzelf, in de afwezigheid van invloeden, zal bewegen (dus over de invloedloze beweging). De onzekerheden of meningsverschillen dienen om het basale idee als alleen maar een *schema* te introduceren. Er wordt van leerlingen verwacht dat ze zich realiseren dat het schema verder ingevuld moet worden, zonder dat ze weten hoe dit concreet gedaan moet worden in ingewikkelder gevallen zoals de beweging van de asteroïde. Dit gaan uitzoeken vormt de agenda voor het leeuwendeel van de cursus in hoofdthema 2.

Tweede hoofdthema

De theorieën van Kepler en Newton over planeetbeweging worden geïntroduceerd als alternatieve manieren om het verklaringsschema voor beweging in te vullen (stap 5). Hun aannames voor de invloedloze beweging worden gegeven (resp. rust en eenparig rechtlijnige beweging), evenals hun interactietheorieën (resp. een voortslepende invloed als gevolg van de rotatie van de zon om zijn as en een aantrekkende invloed als gevolg van gravitatie). De interactietheorieën worden eerst kwalitatief beschreven, waarna verschillende alternatieve manieren om de kwalitatieve relaties te kwantificeren besproken worden. De kwalitatieve uitspraak 'hoe verder weg, hoe kleiner de invloed' kan bijvoorbeeld gekwantificeerd worden door aan te nemen dat de invloed omgekeerd evenredig is met de afstand, omgekeerd evenredig is met het kwadraat van de afstand, et cetera. Op deze manier komen enkele geparametriseerde invloedswetten naar voren, zowel in het Kepleriaanse als in het Newtoniaanse schema. De Kepleriaanse invloedswetten hebben de rotatiesnelheid van de zon en de macht van de inverse afstand als parameter, de Newtoniaanse parameters zijn de zwaarte van de zon en de planeet en ook de macht van de inverse afstand.

Leerlingen maken dan kennis met een modelleeromgeving op een computer waarin de bewegingen van twee voorwerpen worden weergegeven: een waargenomen planeet en een modelplaneet die beweegt volgens de invulling van het verklaringsschema, bijvoorbeeld Kepler's aanname voor de invloedloze beweging in combinatie met een bepaalde Kepleriaanse invloedswet. Een randvoorwaarde voor de geldigheid van de specifieke invulling voor het verklaren van de beweging van de planeet is naar verwachting intuïtief duidelijk voor leerlingen: de twee bewegingen moeten samenvallen. Of, in andere woorden, de invulling van het verklaringsschema voor beweging moet empirisch adequaat zijn. De opdracht voor leerlingen wordt dan om (virtueel) het probleem op te lossen om theorie met waarneming te laten samenvallen, door de parameters in het model te veranderen en te zien wat het effect hiervan is. Dit is naar verwachting een zinvolle taak voor leerlingen, ook al weten ze niet de details van hoe de computer de beweging van de modelplaneet bepaald.

Vervolgens wordt het concept luiheid of inertie aangekaart om hiermee situaties waarin twee of meer voorwerpen onderhevig zijn aan een invloed (bijvoorbeeld twee of meer planeten) te kunnen modelleren. Het idee is dat de afwijking van de aangenomen invloedloze beweging niet alleen afhangt van de invloed, maar ook van het voorwerp zelf. Dit leidt tot de regel 'afwijking = invloed / luiheid'. Zowel Kepler als Newton geloofde dat 'de hoeveelheid materie' een maat is voor de luiheid.

Naar keuze kan de precieze relatie tussen invloed en beweging verder onderzocht worden door grafische (tijds)stap voor stap constructies. De snelste en slimste leerlingen kunnen op deze manier dieper inzicht krijgen in hoe de beweging van een voorwerp bepaald kan worden (en bepaald wordt door het computer programma) uit gegeven invloeden en een aanname voor de invloedloze beweging.

De vraag wat de Kepleriaanse en Newtoniaanse soorten model opleveren steekt naar verwachting af en toe de kop op tijdens het onderzoeken van en werken met Kepleriaanse en Newtoniaanse modellen gedurende het tweede hoofdthema, en wordt naar verwachting langzaam steeds sterker (stap 6). Dit lijkt een natuurlijke reactie op het voortdurend onderzoeken van alternatieven, vooral wanneer beide alternatieven het goed schijnen te doen. Aangezien binnen beide soorten model min of meer empirisch adequate oplossingen voor het samenvallen van theorie met waarneming gevonden kunnen worden, blijft de vraag welk model het meeste oplevert onbeantwoord. Deze vraag is ook onbeantwoordbaar met alleen het criterium van empirische adequaatheid. Met dit criterium kan wel een specifiek model afgekeurd worden, maar niet een *soort* model.

Derde hoofdthema

De functie van het derde hoofdthema is te reflecteren op criteria om te bepalen welk soort model het beste beweging verklaart (stap 7). Toepassing (stap 9) en evaluatie (stap 11) van deze criteria zouden moeten leiden tot een waardering van Newtoniaanse modellen en een uitkijk op de reguliere cursus (stap 12). Het tweede hoofdthema zou geleid moeten hebben tot een (geleidelijk sterker wordende) vraag naar welke soort model het meeste oplevert (stap 6). Reflectie op wat er in de eerste hoofdthema's bereikt is (stap 7) zou moeten leiden tot de conclusie dat deze vraag niet alleen met de criteria van empirische adequaatheid en plausibiliteit beantwoord kan worden. Naar verwachting zouden enkele leerlingen tegen deze tijd op het additionele criterium van brede toepasbaarheid kunnen komen. Anders kan de docent het introduceren als een mogelijke en intuïtief duidelijke manier om meer licht op deze vraag te laten schijnen. Dit additionele criterium zou moeten dienen als een richting gevende strategie voor het verdere onderzoek naar de waarde van de twee soorten model (stap 8). In het licht van het nieuwe criterium zouden leerlingen de toepassing van Kepleriaanse en Newtoniaanse modellen op situaties op aarde (stap 9) moeten zien als een aanvullende manier om de waarde van de twee soorten model in te schatten (stap 10). In dit proces zullen ze naar verwachting een voorkeur voor Newton ontwikkelen. Ruimere toepasbaarheid is een reden om een Newtoniaanse invulling van het verklaringsschema, dat wil zeggen Newtoniaanse mechanica, te waarderen (stap 12). Deze waardering kan nog verder versterkt worden door het beginprobleem met de asteroïde op te lossen met een Newtoniaans model.

Vierde hoofdthema

De mogelijkheid alle soorten bewegingen te verklaren met een Newtoniaanse invulling van het verklaringsschema is een belangrijk element voor het begrijpen van alle veranderingen op een mechanicistische manier. (Een ander element is enige kennis hebben van deeltjesmodellen.) Een mechanicistische visie wordt hier gepresenteerd om meer waardering voor de kracht en reikwijdte van mechanica op te roepen. Deze waardering markeert de overgang naar de reguliere mechanicacursus (stap 13), waarin de Newtoniaanse invulling van het verklaringsschema verder wordt toegepast met nieuwe invloeden en invloedswetten. Aan het eind van de introductiecursus wordt een vooruitblik op de reguliere cursus gegeven (stap 12).

De didactische structuur zoals weergegeven in Figuur 1 en hierboven toegelicht kwam tot stand door het testen en evalueren van een eerder ontwerp. In **hoofdstuk 4** wordt de ontwikkeling van het eerste ontwerp van de introductiecursus naar het tweede ontwerp beschreven. Het eerste ontwerp vertoonde aanzienlijke tekortkomingen toen het getest werd, ook al was het theoretisch redelijk overtuigend gerechtvaardigd. Hoofdstuk 4 illustreert daarmee de methode van ontwikkelingsonderzoek door te laten zien hoe zij hielp, terugkijkend, veel tekortkomingen te begrijpen en hoe zij hielp ideeën voor verbetering van het ontwerp te genereren. Hiervoor waren zowel de empirische test als het scenario nodig.

Een tweede onderwerp wat in hoofdstuk 4 aan de orde komt is de voorbereiding van de docent. Het probleem dat opkwam bij de docentvoorbereiding was dat een probleemstellende benadering een manier van onderwijzen vraagt, die, aan de ene kant, veel ruimte laat voor leerling-inbreng en, aan de andere kant, leerlingen stuurt in het vasthouden van de grote lijn. Aandacht voor deze twee punten lijkt een blinde plek in veel traditioneel onderwijs te zijn. Dit probleem wordt besproken en geïllustreerd met enkele ervaringen uit de eerste testronde. Een belangrijke factor bij het omgaan met dit probleem is de docent eigenaar maken van de implementatie van het ontwerp op een zodanige manier dat de doelen en functies van het ontwerp vervuld kunnen worden. Om dit voor elkaar te krijgen wordt voorgesteld de docent geschikte *interactiestructuren* voor alle activiteiten te laten bedenken. Dat wil zeggen dat de docent nadenkt over manieren om de interactie met de leerlingen te structureren op zo'n manier dat zij voelen dat hun inbreng ertoe doet, en dat iedere activiteit zo wordt geïntroduceerd en geëvalueerd dat leerlingen de grote lijn kunnen vasthouden. De bedachte implementatie van de docent kan dan besproken worden met de ontwerper in het licht van de geschiktheid voor het realiseren van de doelen en functies van de verschillende activiteiten.

In **hoofdstuk 5** wordt het tweede ontwerp op twee verschillende detailniveaus besproken. Na een vrij algemeen beschrijvingsniveau in hoofdstuk 4 wordt het ontwerp hier beschreven op het tussenniveau van episodes en op het gedetailleerde niveau van activiteiten binnenin episodes. Een ‘episode’ is een reeks samenhangende activiteiten die betrekking hebben op een bepaald doel. ‘Activiteiten’ zijn, bijvoorbeeld, een tekst lezen, vragen maken of antwoorden met een medeleerling bespreken. Een episode vormt een samenhangende eenheid. Het bevat een introductie van een centraal staande vraag, een deel in het midden waarin die vraag wordt aangekaart, en een evaluatie van de gevonden antwoorden of nieuwe vragen die zijn opgekomen. Een episode duurt zo tussen de 30 tot 80 minuten. In de beschrijving wordt voor iedere episode de functie kort samengevat, een rechtvaardiging van de inhoud en interactiestructuur in het licht van de functie gegeven, en wordt de verwachte afwikkeling van de drie delen van iedere episode (introductie, zoektocht naar antwoorden, evaluatie) gegeven. Beschrijvingen op dit detailniveau zijn nodig omdat het testen gebruik maakt van het gedetailleerde niveau als het werkelijke onderwijsleerproces wordt vergeleken met het bedoelde onderwijsleerproces. Deze vergelijking wordt gestuurd door de formulering van verschillende analysevragen bij iedere episode. Het beantwoorden van deze analysevragen op het tussenniveau maakt gebruik van het gedetailleerde niveau en vormt de basis voor algemenere conclusies op het niveau van hoofdthema’s en introductiecursus als geheel.

In **hoofdstuk 6** worden de resultaten gepresenteerd van het testen van het tweede ontwerp van de didactische structuur. In de beschrijving van de methode voor het verzamelen van gegevens en de analyse en presentatie ervan zien we dat het scenario en de analysevragen een weg door de veelheid van gegevens (waarvan hier maar een klein deel weergegeven wordt) wijzen. Om het verwachte onderwijsleerproces te vergelijken met het werkelijke onderwijsleerproces, wordt het laatste vastgelegd met observatienotities, video- en audio-opnamen, fotokopieën van wat leerlingen opschrijven, en leerlingeninterviews na de cursus. Deze gegevens worden geanalyseerd met behulp van het scenario, analysevragen en zogenaamde lesverslagen (ruwe samenvattingen van de verzamelde gegevens per les). Mijn antwoorden op de analysevragen worden gelezen door een tweede onderzoeker, die toegang heeft tot de lesverslagen en die ook het proces van het selecteren en interpreteren van relevante gegevens van de lesverslagen doorloopt om zo tot antwoorden op een deelverzameling van de analysevragen te komen. De interpretaties en antwoorden worden besproken totdat overeenstemming is bereikt (in uitzonderlijke gevallen is de overeenstemming dat er verschillende mogelijkheden zijn).

De resultaten van de docentvoorbereiding voor de tweede testronde worden ook in dit hoofdstuk gepresenteerd. Gegeven de tijdsbeperkingen heb ik de docent zo goed als ik kon voorbereid. Toch accepteerde de docent het idee om interactiestructuren als gereedschap voor de praktische invulling van de al ontworpen inhoud te gebruiken niet. Dit was geen tegendraadsheid van de docent. Door omstandigheden kon hij hier niet de gewenste tijd en energie in steken. Een van de gevolgen is dat er bijna geen conclusies getrokken kunnen worden over de geschiktheid van de keuzes voor interactiestructuren.

Een ander ongelukkig gevolg is dat de werkelijke uitvoering van het ontwerp zo sterk afweek van wat bedoeld was, dat het erg moeilijk is om fouten als gevolg van afwijkingen in de uitvoering te scheiden van fouten in de didactische structuur. In mijn evaluatie was ik dan ook gedwongen veel redeneringen van het type ‘als dit en dat gedaan was, dan zou zus en zo gebeurd kunnen zijn’ te gebruiken. Dit heeft natuurlijk de empirische ondersteuning van antwoorden op mijn onderzoeksvragen naar de kwaliteit van de didactische structuur doen afnemen. Hieronder vat ik de conclusies samen die naar mijn mening toch, hoewel met enige voorzichtigheid, getrokken kunnen worden.

Wat betreft het eerste hoofdthema, het hoe en waarom van het verklaren van bewegingen, is enige empirische ondersteuning gevonden voor de mogelijkheid om zowel het algemene verklaringsschema als het verklaringsschema voor beweging op te roepen en expliciet te maken (stap 3 in Figuur 1). Het asteroïdenprobleem (stap 1 en 2) en het algemene verklaringsschema als opstapje (stap 3) kunnen ook hun bedoelde functies vervullen en de ontwikkeling van enige theoretische oriëntatie werd bij leerlingen waargenomen (stap 4). Een ander belangrijk doel is echter niet bereikt. Leerlingen herkennen de verschillende elementen van het verklaringsschema voor beweging en ze zien enigszins in dat deze elementen verder ingevuld moeten worden, maar ze herkennen *niet* dat zulke invullingen tot potentiële verklaringen van beweging combineren. Op deze manier vormt het verklaringsschema geen gids voor leerlingen om meer grip te krijgen op hoe beweging verklaard wordt (stap 4). Daardoor ontbreekt de beweegreden voor het tweede hoofdthema. Deze tekortkoming wijst naar een fout in de didactische structuur.

Als een gevolg hiervan resulteert het tweede hoofdthema, de kennis uitbreiden door de details van het verklaringsschema in te vullen en zo te komen tot empirisch adequate modellen voor het verklaren van beweging, in een teleurstellende herkenning van de hoofdlijn (stap 5). Daarnaast lijkt het erop dat te veel verschillende factoren die de beweging bepalen te dicht op elkaar geïntroduceerd worden. Dit maakt het moeilijk voor leerlingen om bijvoorbeeld de verschillende rollen die de dynamisch relevante parameters in invloedswetten en het concept luiheid spelen in een verklaring van beweging helder te onderscheiden. Leerlingen kunnen wel de criteria empirische adequaatheid en plausibiliteit gebruiken wanneer ze kiezen tussen modellen. Zowel Kepleriaanse als Newtoniaanse modellen blijven geschikte alternatieven en de vraag naar de geschiktheid van de schema’s en modellen komt inderdaad op (stap 6).

Over het derde hoofdthema, een evaluatie van modellen en model*soorten* in het licht van het bereiken van grotere toepasbaarheid, kan gezegd worden dat leerlingen de relevante criteria gebruiken om te bepalen welke modelsoort het beste verklaard. Wel zou er meer aandacht geschonken moeten worden aan het expliciet maken van die criteria, vooral ‘brede toepasbaarheid’ (stap 7). Hierdoor zou de reden voor het toepassen van modellen op andere bewegingen (stap 8 en 9) duidelijker kunnen geworden. Verder maken cumulatieve effecten van eerdere fouten in de eerste twee hoofdthema’s de evaluatie van modellen erg moeilijk (stap 10 en 11) en de waardering van Newtoniaanse modellen (stap 12) vrij zwak.

Het vierde hoofdthema, het inpassen in de reguliere cursus (stap 13), is veel minder uitvoerig onderzocht dan de eerdere hoofdthema's en verdient verder onderzoek. Enkele voorlopige bevindingen zijn dat in het redeneren over verklaringen van beweging elementen van de introductiecursus nuttig gebruikt kunnen worden. Leerlingen gebruiken zelf argumenten voor het identificeren van invloeden gebaseerd op de relatie invloed – beweging en op interactietheorie. De grafische constructiemethode wordt niet door leerlingen zelf gebruikt, maar wordt wel herkend en begrepen en levert voor leerlingen overtuigende argumenten voor de identificatie (aanwezigheid, grootte en richting) van invloeden.

Hoofdstuk 7 begint met een evaluatie van de drie onderwijsdoelen van de introductiecursus. Wat betreft het eerste doel om inzicht te krijgen in hoe mechanica werkt, blijken leerlingen moeite te hebben invloed van parameters in invloedswetten te onderscheiden. Daarnaast hebben ze moeite op een correcte manier invloed, luiheid en afwijking met elkaar in verband te brengen. Deze centrale concepten in relatie tot elkaar op de kaart zetten kan wel eens moeilijker zijn en meer tijd kosten dan voorzien. Een mogelijke versimpeling zou het weglaten van een vroege introductie van het concept luiheid kunnen zijn. Over het tweede doel om waardering voor de kracht en reikwijdte van (Newtoniaanse) mechanica op te roepen kan gezegd worden dat het niet bereikt is. Toch gebruiken leerlingen impliciet wel de relevante criteria. Daarom geloof ik wel dat als die criteria zelf en hun gebruik ervan expliciet gemaakt worden, leerlingen enkele beargumenteerde redenen kunnen geven waarom Newtoniaanse mechanica te verkiezen is, wat neerkomt op enige waardering.

In mijn onderzoek werd bijna niet getracht om het derde doel, het aanbieden van een vocabulaire waarmee de gebruikelijke leerproblemen besproken kunnen worden, te bereiken. Enkele bemoedigende aanwijzingen werden gevonden in een eerste poging om enkele opgeroepen begripsproblemen te bespreken tijdens de reguliere cursus. Deze zaak verdient een grondiger en meer omvattende studie.

Dit onderzoek begon met de ideeën (1) dat alledaagse en Newtoniaanse mechanica een verklaringsschema gemeen hebben en (2) dat deze gemeenschappelijkheid gebruikt kan worden in het onderwijzen en leren van mechanica op een probleemstellende manier. Ik heb geen redenen om aan het eerste idee te twijfelen, gezien de solide theoretische onderbouwing die ik ervoor heb gegeven. Ik twijfel ook niet aan het tweede idee, ook al schoot ik duidelijk tekort in de toepassing ervan. Er zijn, denk ik, twee redenen voor deze tekortkoming. Ten eerste is er tot nu toe nog geen manier gevonden om het verklaringsschema te laten leven als iets bekends, enigszins ongrijpbaars, maar toch als een nuttige en veelbelovende gids voor leerlingen. Dit hangt samen met de structurele tekortkoming om een goede beweegreden voor het leren van de bulk van de mechanica inhoud te geven (stap 4 in Figuur 1). Ten tweede schiet op het detailniveau het ontwerp nog tekort in het implementeren van de didactische structuur in de activiteiten binnenin de episodes. De bedoelde beweegredenen zijn nog niet voldoende in het ontwerp van de opeenvolgende activiteiten ingebakken. Veel van het ontwerp blijkt teveel 'top-down', in de zin van het benadrukken van docentinbreng, en vertoont te veel een 'overdrachtsperspectief' op onderwijzen en leren in plaats van het bedoelde educatief constructivistische perspectief. Dit probleem laat zich vooral voelen in stap 5 (Figuur 1) en verklaart mede de slechte resultaten van dat deel van het ontwerp.

Wat betreft het eerste probleem zou een nuttige suggestie kunnen zijn het verklaringsschema niet conceptueel te overladen. Er lijkt niet meer nodig te zijn dan de basale notie dat 'telkens als er een afwijking is van hoe iets uit zichzelf zou bewegen, je dan zoekt naar een oorzaak daarvoor'. Misschien is het ook mogelijk dit idee directer te vertalen in een proto-versie van een grafische constructiemethode, met de implicatie dat een aanname voor de invloedloze beweging (hoe iets uit zichzelf beweegt) en aannames voor invloeden gezamenlijk lijken te gaan leiden tot een verklaring van beweging.

Twee ideeën zijn wellicht nuttig in het omgaan met vooral het tweede probleem: het educationaliseren van handelingspraktijken en gebruik maken van interactiestructuren. De grondgedachte van het educationaliseren van handelingspraktijken is dat een professionele handelingspraktijk, die van nature betekenisvol is voor hen die eraan deelnemen, op een zodanige manier aangepast zou kunnen worden voor gebruik in school dat leerlingen ook haar nut kunnen herkennen en waarderen. Binnen zo'n aangepaste of 'geëducationaliseerde' handelingspraktijk kunnen leerlingen dan die dingen leren die we ze willen leren op een betekenisvolle manier, wat mooi aansluit bij de probleemstellende benadering. In het geval van mechanica kan de grondgedachte worden toegepast op de academische handelingspraktijk van het construeren van theoretische kennis, door de hoofdvraag 'hoe werkt verklaring van beweging?' op te delen in de subvragen 'hoe beweegt iets uit zichzelf?' en 'welke invloeden werken er in deze situatie?'. Dit onderscheid stuurt het onderwijsleerproces naar verwachting op een voor leerlingen herkenbare manier, omdat het gebruik maakt van de basale gedachte dat 'een invloed een afwijking veroorzaakt van hoe iets uit zichzelf beweegt'. Een ruwe schets van de geëducationaliseerde academische handelingspraktijk van het construeren van theoretische kennis zal dan bestaan uit (1) het opdelen van de hoofdvraag 'hoe werkt verklaren van beweging?' in subvragen, (2) het beantwoorden van deze subvragen, en (3) het evalueren van de antwoorden in het licht van relevante criteria, zoals empirische adequaatheid en brede toepasbaarheid.

Gebruik maken van interactiestructuren kan niet alleen nuttig zijn bij het voorbereiden van de docent, maar ook bij het meer 'bottom-up' maken van het ontwerp. De aard van de interactie en of het ontwerp bottom-up is of meer top-down hangen nauw samen. Een verbeterde beschrijving van interactiestructuren (die meer aandacht schenkt aan de leerlingkant van de interactie) of zelfs volkomen andere interactiestructuren kunnen nuttig zijn in dit opzicht. Dit kan behulpzaam blijken in het moeilijke ontwerpproces van voorzichtig balanceren tussen docentinbreng aan de ene kant en ervoor zorgen dat leerling-inbreng er echt toe doet aan de andere kant. Het grootste potentiële nut van interactiestructuren ligt in hun mogelijkheid om een goede soort discussie tussen docent en ontwerper mogelijk te maken en daardoor de docentvoorbereiding effectiever te maken.

Hoofdstuk 7 sluit af met de speculatie dat de gehanteerde strategie van het gebruikmaken van overeenkomsten op een structureel niveau tussen alledaagse en wetenschappelijke manieren van redeneren voor het onderwijzen/leren van een onderwerp nuttig zou kunnen zijn voor andere onderwerpen dan mechanica.

Curriculum Vitae

Axel Westra was born on March 15, 1971 in Amsterdam. In 1989 he got his pre-university degree (Athenaeum) at the Farel College in Amersfoort. After this he studied technical physics at Twente University, which he completed in 1994 with a major in chemical physics, resulting in the Dutch equivalent of a master's degree in physics.

In 1998 he finished teacher training at Utrecht University and subsequently taught physics at the Rotterdams Montessori Lyceum in Rotterdam and the College Blaucapel in Utrecht, both for one year. From 2000 until 2004 he worked on the PhD project at the Centre for Science and Mathematics Education (CD-β) in Utrecht that resulted in this dissertation.

From 2005 he is teaching general sciences (Dutch: ANW) at RSG Broklede in Breukelen, which he is still doing at the moment of writing (2006).

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