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?'

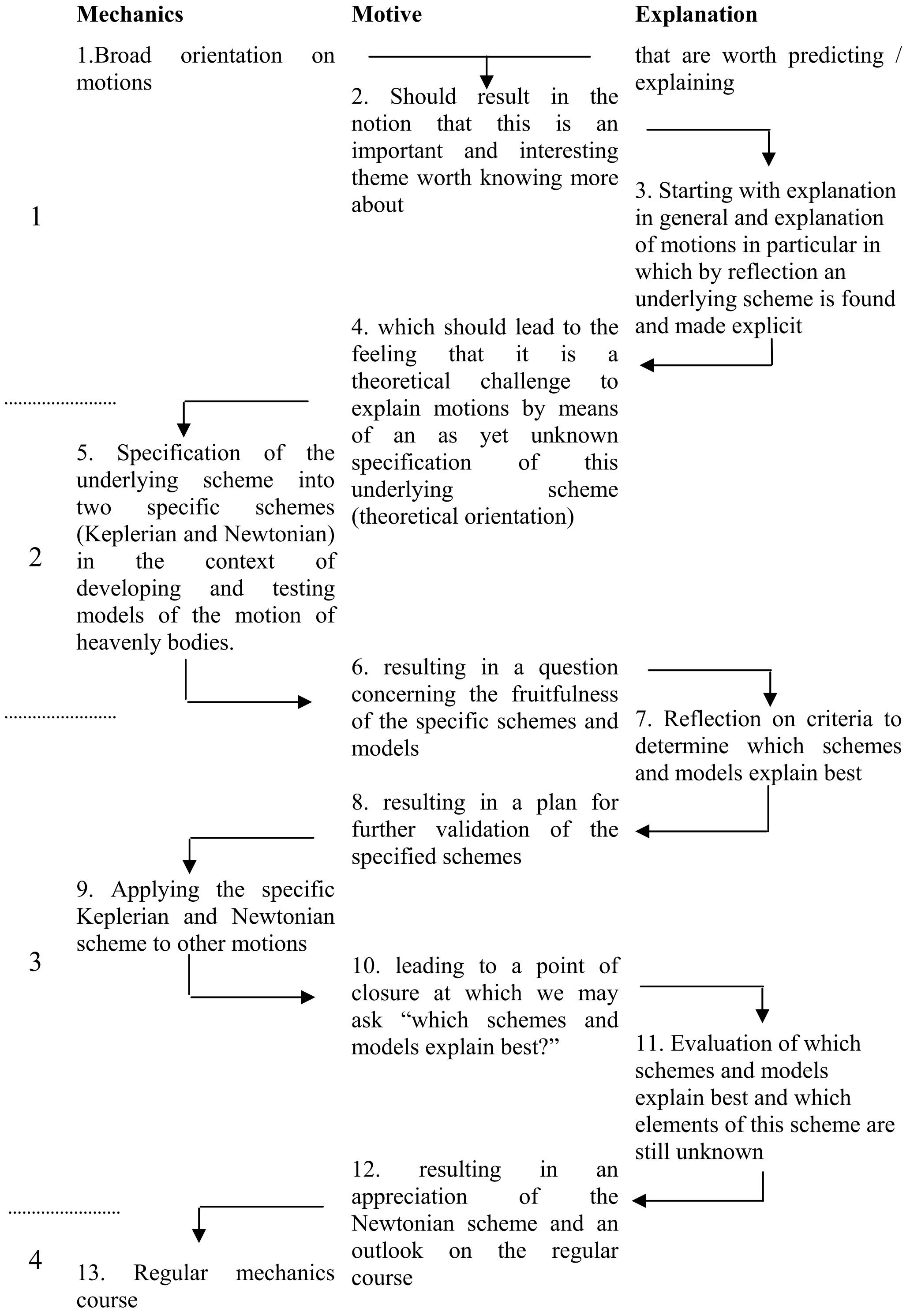
This design question is investigated using the method of a 'design experiment', which involves a cyclic process of designing, testing and revising a prototype. In order to make the didactical quality of the prototype object of study, detailed qualitative data of the actual teaching/learning process needs 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

2. Should result in the notion that this is an important and interesting theme worth knowing more about

that are worth predicting / explaining

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.