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 Introduction 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.

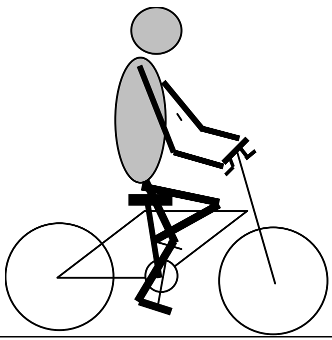
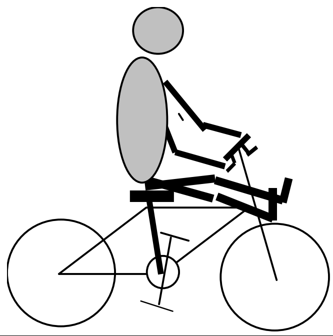
Keeping speed or increasing speed	Gradually moving slower
	
- … - … - …	- … - … - …
Regularity: …	

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).

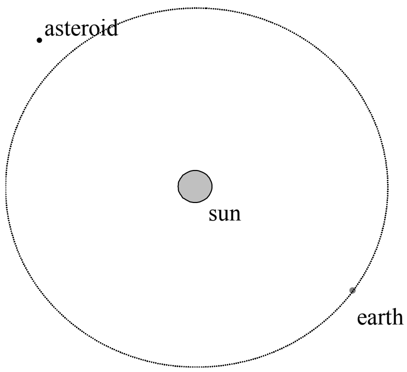
<table>
<tr><td>Motion of the asteroid: …</td><td>Influence free motion of the asteroid:…</td></tr>
<tr><td>
</td><td>asteroid</td></tr>
<tr><td>Working is:
- …
- …</td><td>No influence is working on the asteroid.</td></tr>
<tr><td colspan="2">Regularities:
….
….</td></tr>
<tr><td colspan="2">Relation influence – motion:
…</td></tr>
</table>

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.

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[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.

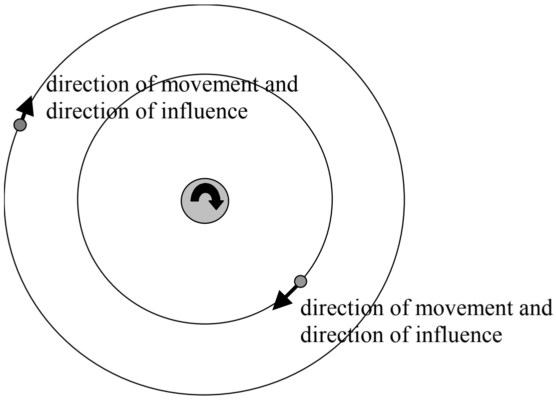


Figure 7: Direction of turning of sun about her axis and planets around the sun.

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).

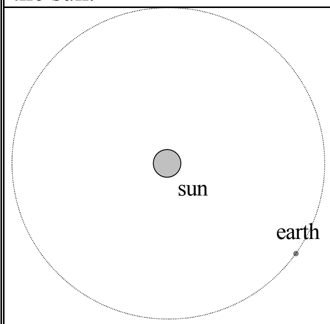
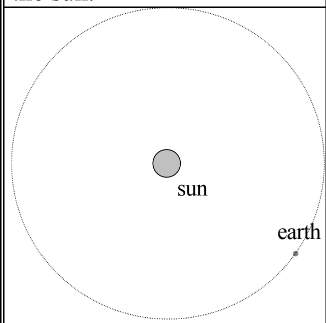
<table>
<tr><th colspan="2">Kepler</th><th colspan="2">Newton</th></tr>
<tr><td>Motion to be explained:
Earth making turns around the sun.</td><td>Influence free motion: …
rest</td><td>Motion to be explained:
Earth making turns around the sun.</td><td>Influence free motion:
straight, with constant speed</td></tr>
<tr><td>
</td><td>some drawing indicating rest</td><td>
</td><td>some drawing indicating straight motion, with constant speed</td></tr>
<tr><td>Working is:
- drag from sun (in direction of motion)</td><td>Working is no influence</td><td>Working is:
- attraction from sun (in direction of sun)</td><td>Working is no influence</td></tr>
<tr><td colspan="2">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.</td><td colspan="2">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.</td></tr>
<tr><td colspan="2">Relation influence - motion:
The larger the influence on an object, the larger the deviation from the influence free motion.</td><td colspan="2">Relation influence - motion: ….
The larger the influence on an object, the larger the deviation from the influence free motion.</td></tr>
</table>

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.

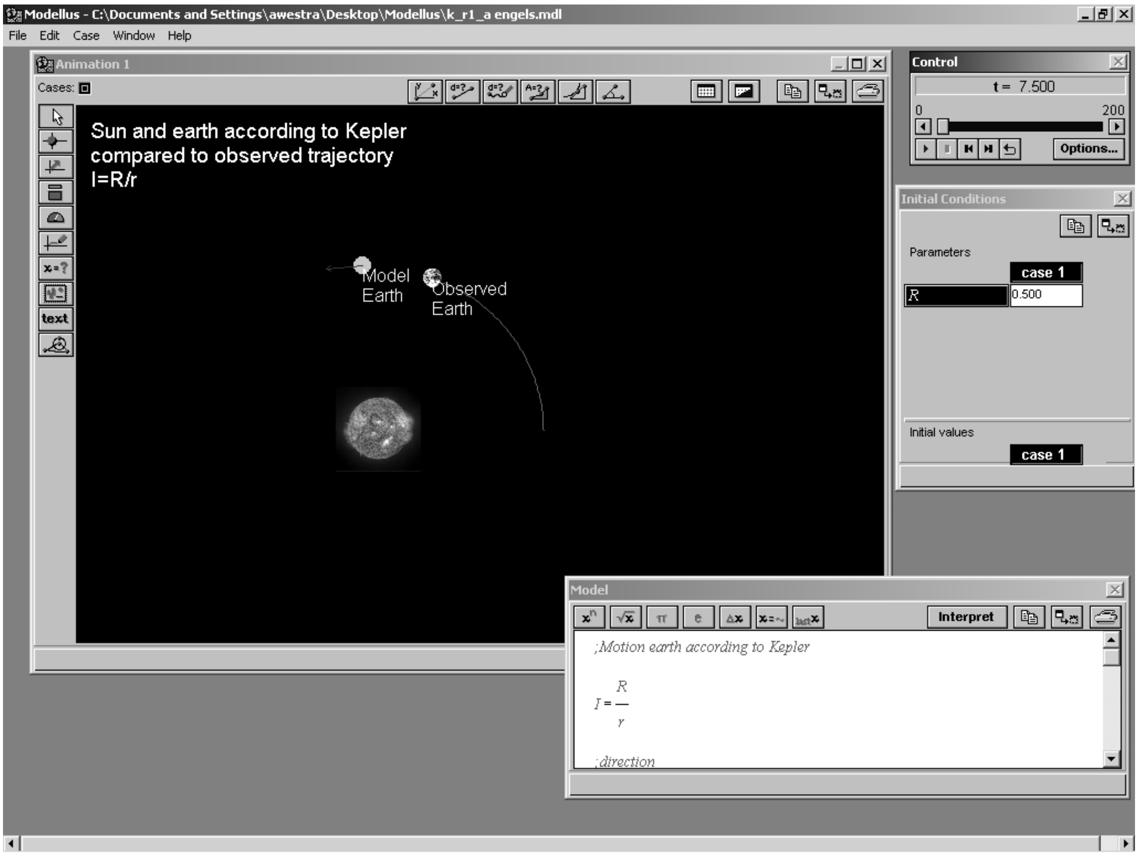


Figure 9: Modellus model of the motion of the earth around the sun demonstrating the matching problem.

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).

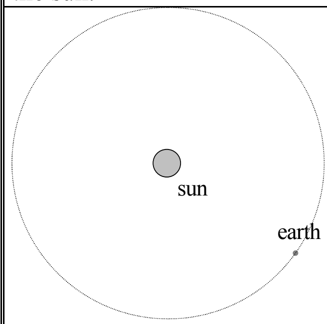
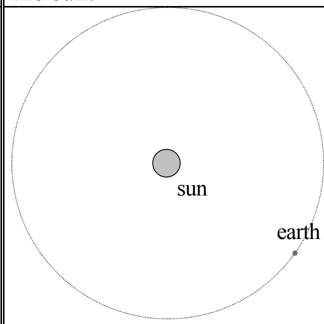
Kepler		**Newton**	
Motion to be explained: Earth making turns around the sun.	Influence free motion: … *rest*	Motion to be explained: Earth making turns around the sun.	Influence free motion: *straight, with constant speed*
	*some drawing indicating rest*		*some drawing indicating straight motion, with 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.

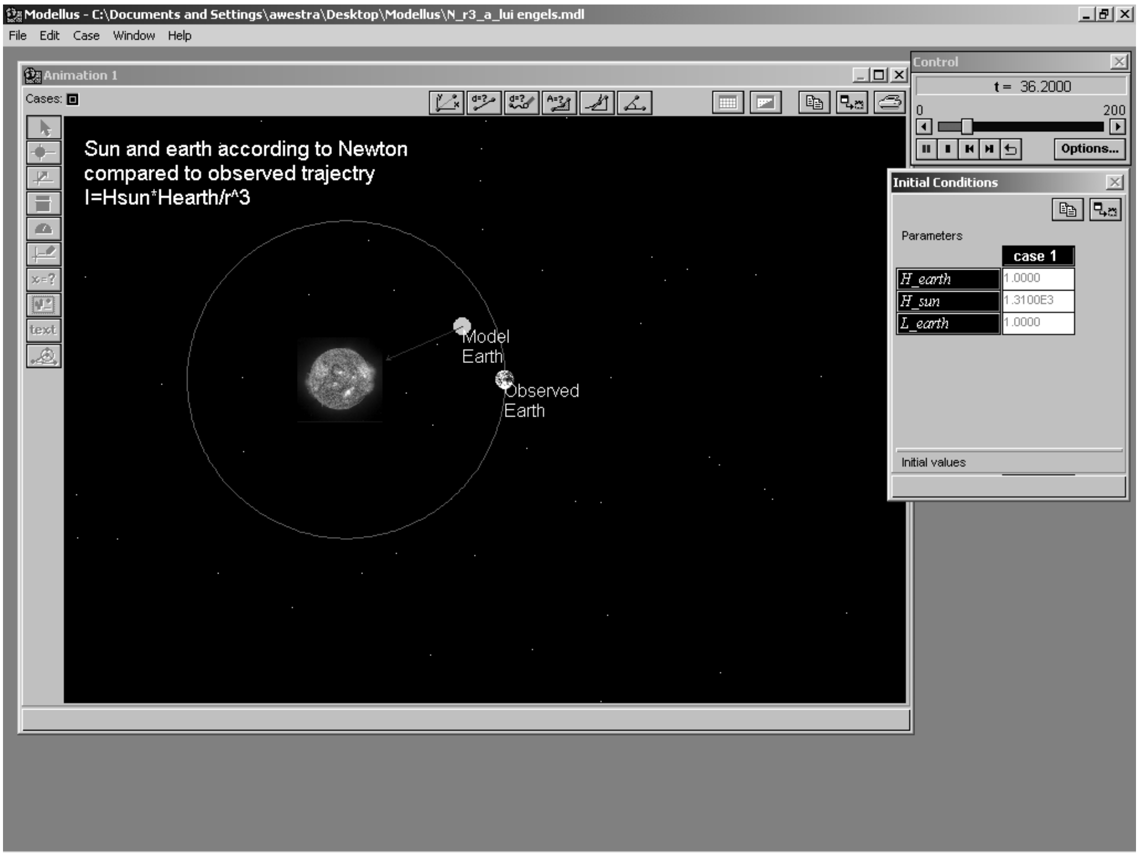


Figure 11: Newtonian motion model of the motion of the earth around the sun including laziness as a parameter.

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.)

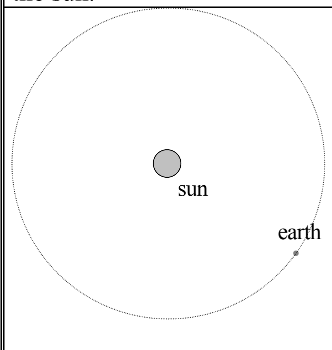
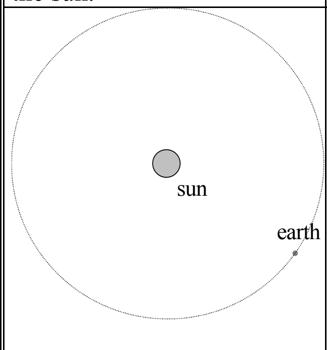
<table>
<tr><th colspan="2">Kepler</th><th colspan="2">Newton</th></tr>
<tr><td>Motion to be explained:
Earth making turns around the sun.</td><td>Influence free motion: …
rest</td><td>Motion to be explained:
Earth making turns around the sun.</td><td>Influence free motion:
straight, with constant speed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

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.

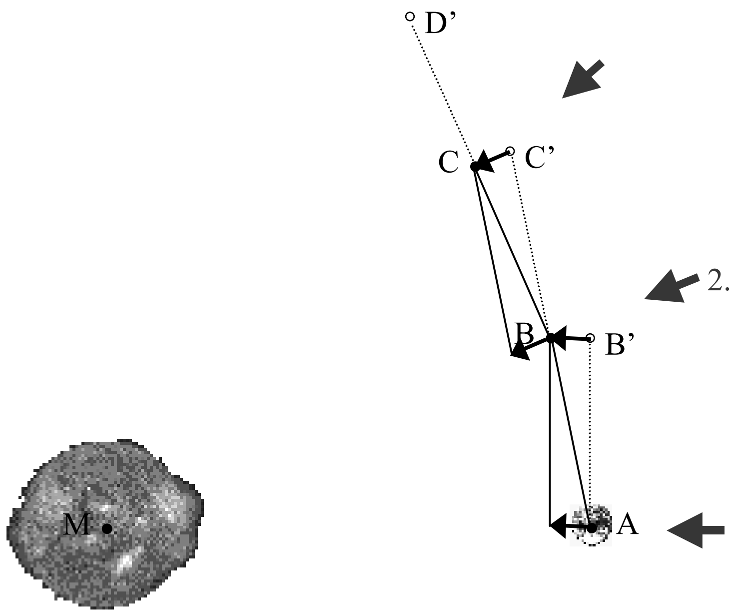


Figure 13: Two subsequent influences

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.

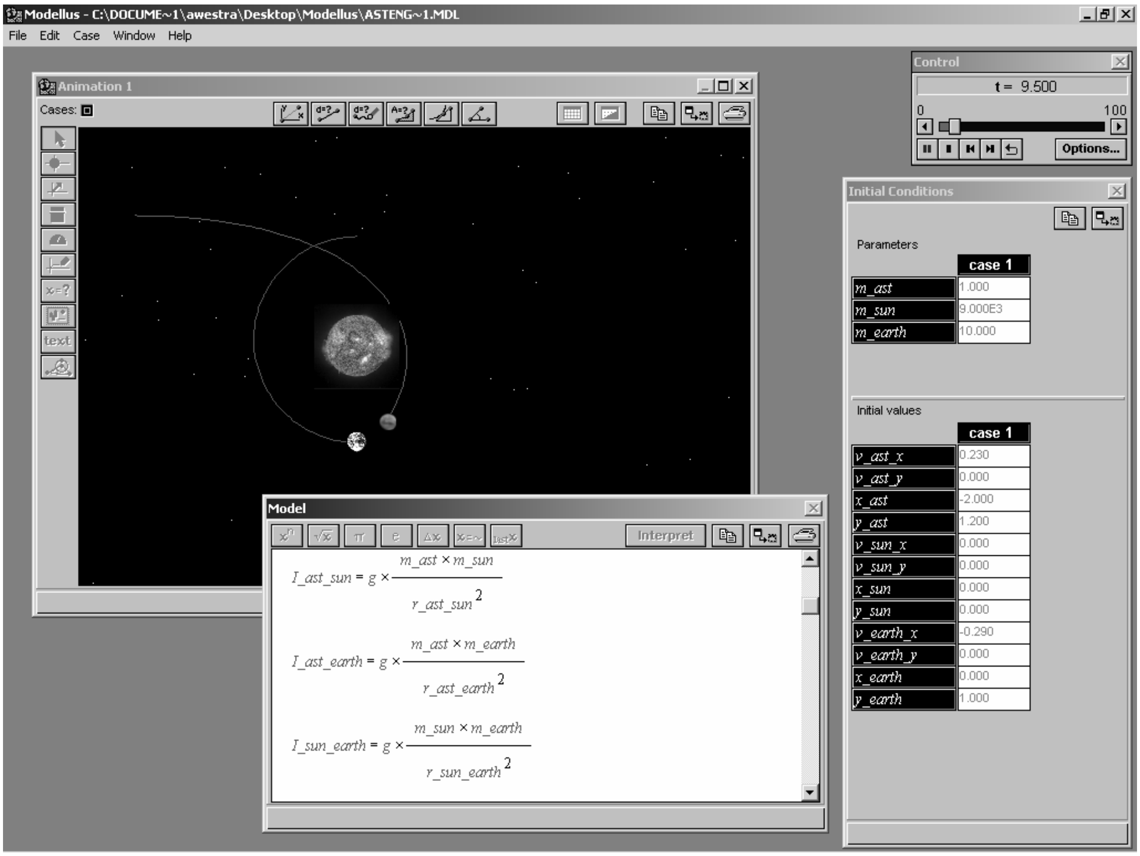


Figure 14: Newtonian motion model of the motion of an asteroid moving towards earth.

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.