Models of / for Teaching Modeling

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Abstract

This paper is based on a number of design studies at Utrecht University in which modeling played an important role. The central question to be discussed is how modeling can be taught in a physics curriculum. Can it be taught in some explicit way, which goes further than the usual implicit way of just letting students take part in some modeling activities? Some examples of a so-called problem posing approach to various ways of modeling are described. It is argued that in the case of theory generating modeling no explicit modeling strategy seems to be available for teaching. However, in the case of theory applying modeling, a system of heuristic rules could be abstracted from reflection on students own modeling experiences, that could serve as a teachable global strategy for further modeling.

Introduction

My first visit to a GIREP conference was in Venice 1973. It was the time just after the famous American and British curriculum development projects in which inquiry learning had been introduced in all kinds of formats. Now its 2006 and again we're at a GIREP conference. And this time I'm even allowed to speak! About the didactics of modeling physics to put it in continental European terms. And thus you may ask, have we made any progress in teaching modeling in these 33 years?

Unfortunately, research has reported that most students still have inadequate ideas about models; e.g., Schwarz and White (2005) wrote: "*There is ample evidence indicating that students may not understand the nature of models or the process of modeling even when they are engaged in creating and revising models*". In spite of all development projects, it seems that models are still largely taught as facts. And that the attention for modeling still has remained largely implicit in much teaching. To my surprise, I even found when looking into a rather recent (1998) Dutch textbook for upper secondary physics education, that the term model was hardly used. Let alone the term modeling.

To my opinion the present focus on modeling is largely due to three main reasons. The first is the recent constructivist attention to conceptions that students bring to the classroom, which is interpreted as an example of the fact that people experience the world in terms of their mental models and modeling. A second is the present emphasis on the role of philosophy in science education, which has resulted in stressing the importance of attention for the nature of scientific knowledge and of scientific models in particular. And thirdly, the present availability of computers that has greatly enhanced the possibilities for creating and testing numerical models, both in science and in science education.

In fact in many proposals for improving teaching, these three aspects come together. As a remedy against students' possible misconceptions, students should better become involved in a modeling process, for which computers provide excellent 'affordances'. As a result of which not only students' learning about models of nature, but also about the nature of such models is supposed to improve. However, this is not at all easy to realize. As Schwarz and White (2005) write: "…*teaching students about the nature of models and the process of modeling has proven to be difficult. Direct efforts at improving modeling knowledge have met with limited success*". So that the main problem still seems to be how this can best be done. Thus we may ask: Can the teaching of models, about models and modeling be functionally integrated so that they strengthen each other? What is an appropriate role for the teacher in such teaching etc? And what can teaching for 'learning to model' if such a thing exists at all mean in practice? Is there something like a general 'modeling competence' and can this then be taught in a more explicit way than by just letting students go through some modeling experiences? These are the questions that I will focus on in the rest of my paper, drawing on our experiences in the Utrecht Centre for Science and Mathematics Education, resulting from a number of design studies in which modeling played an essential role (Vollebregt, 1998, Kortland 2001, Doorman 2005, Westra 2006, Ormel 2007).

But let's first go somewhat deeper into what some other people write about teaching modeling. Schwarz and White developed a teaching approach that should enable "*students to create (computer) models that express their own theories of force and motion, evaluate their models using criteria such as accuracy and plausibility, and engage in discussions about models and the process of modeling"*. Thus, they seem to focus on modeling as a means for the learning of theory and models. And though they teach explicitly about the nature of models, involving *meta-modeling knowledge* as they call it, they do not teach an explicit modeling strategy. Their approach seems to focus on the *theory generating role* of modeling, I would say. Their teaching strategy could be considered as a moderate example of expressive modeling. This refers to a distinction that is often made in the literature, particularly in mathematics education, between expressive and explorative modeling. Ideally, in learning by expressive modeling students have to invent their own models. That is, they are in the first place supposed to express and test their own ideas about the world, but then the problem becomes how to shape those ideas into the concepts to be taught. While in learning by explorative modeling students are in the first place discovering, exploring

and testing a given model, but then the question is how to connect this properly to students' ideas about the world. Or, in other words, do we lead students into the model, or the model into the students.
Hestenes (1987), however, seems to hold a different view. He writes: "*The cognitive process of applying the design principles of a theory to produce a model of some physical object or process is called model development or simply modeling.*" This implies that, in this case, modeling takes place when applying an already known scientific theory (a system of design principles for modeling real objects) to solve new problems. As a consequence, he also formulates a modeling strategy, as a specific problem solving strategy, that, should be taught explicitly to students. Or, in other words, he focuses on the *theory applying role* of modeling.

These two approaches are of course not in contradiction but complementary. Both have their role to play in a curriculum that aims to teach physics by modeling. Thinking of such a curriculum, it seems also useful to make yet another distinction between four 'ways of modeling' that in some sense seem to build on each other. And in as far as the latter is true, you could maybe even speak of 'levels' of modeling. Modeling should start, I think, where students are at the beginning, i.e. with common sense. When they enter the classroom, we can say that students already possess many relevant reasoning skills. I.e., starting from a for them familiar context and from a for them relevant practical purpose, in general they are able to reason about and to appropriately reduce that context, to make relevant representations, to frame and test relevant expectations and to draw relevant conclusions. It is precisely this common sense level of modeling that we may and need to draw on in developing more scientific ways of modeling in teaching. Learning to model then boils down to something like: learning to use and extend the common sense modeling skills to new, possibly rather complex situations to be described/explained with new scientific conceptual models, possibly involving new modeling strategies and techniques. It seems obvious that such a learning goal cannot be reached in one stroke, but that it requires permanent attention in a long-term teaching trajectory. I cannot delineate this trajectory here in any detail, but will restrict myself to describing examples of teaching the other three ways of modeling, that can be seen as successive stations along the road. So I will discuss examples of descriptive, causal and dynamical modeling respectively.

Symbolizing and descriptive modeling

A first step on the road of learning to make scientific representations of our physical experience is to learn to describe that experience in terms of scientific symbols, and mathematical relations and graphs. Doorman (2005) studied this in a mathematics lesson series on symbolizing and modeling motion. '*From trace graphs to instantaneous change*' as he called it. It was meant to be done from an expressive perspective, or as ‘guided reinvention’ as he calls it in line with the views of Freudenthal, the late Dutch mathematics educator. However, in designing expressive teaching activities it is always difficult to find the right subtle balance between providing appropriate guidance and giving appropriate construction freedom. If the freedom is too large, this may result in so much diversity in students’ expressions that the teacher is no longer able to productively deal with them. And if the guidance is too strict, then students are no longer expressing their views, but mainly trying to discover what the teacher or the textbook might mean. I will not go into any details but only mention that Doorman did let students make extensive use of trace graphs, discrete displacements, bar graphs, and continuous graphs, in looking for patterns to describe and predict rather familiar one-dimensional motion situations. The required models were not taught directly in their final form, but gradually emerged during the learning process, to a large extent as a result of students’ own modeling activities. They looked for patterns and regularities, and for appropriate ways to depict them, using some specially developed software. We can interpret the successive ways of description as a range of successive intermediate models. A new model is first developed as a model OF a situation, to become itself subsequently a model FOR further conceptual modeling. Given a clear purpose, students’ reasoning was meant to start from concrete experience and to remain to be rooted in it during this process of meaning making and tool construction. Thus it was tried with some success to avoid some usual learning difficulties with graphing and kinematics. From the fact that no quality difference in students discourse appeared to be noticeable from classes that had or had not already been taught a regular ‘direct’ kinematics course, it may be concluded that such a gradual modeling approach has something important to add regarding understanding.

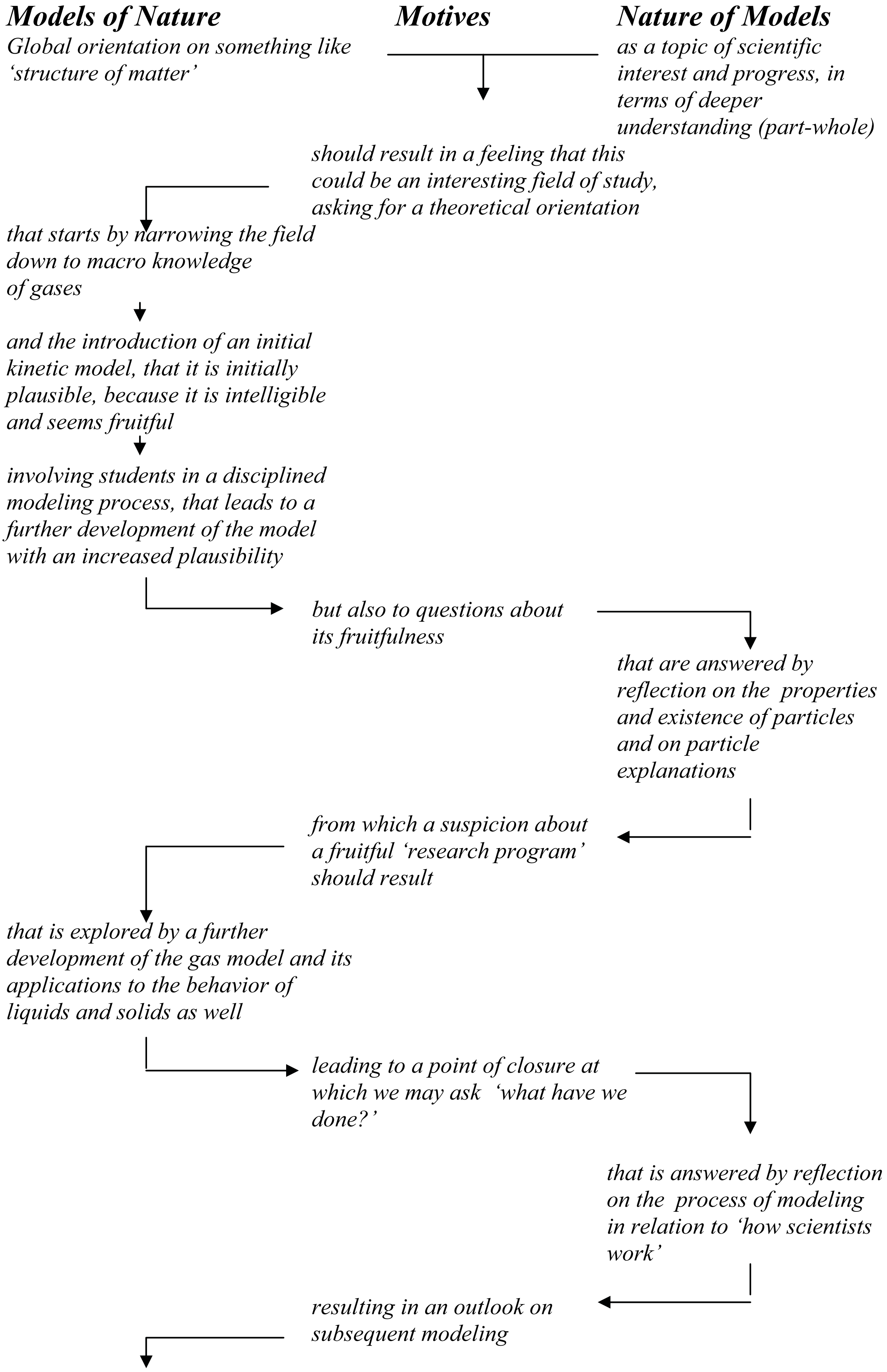
Causal modeling

However, the modeling process becomes more difficult when the modeling purpose becomes more theoretical, e.g., when we move to the teaching of causal explanations, as, e.g., when introducing an initial particle model. Vollebregt (1998) and Klaassen designed a lesson series for that purpose from, what we call, a *problem posing perspective.* A problem posing approach aims to promote that students have *content related* motives for their learning activities, at any time during a learning process. Or, in other words, ideally they always should be aware of the content related point of what they are doing. That this is not at all a self evident requirement was adequately expressed by Gunstone (1992) when he wrote: “*This problem of students not knowing the purpose(s) of what they are doing, even when they have been told, is perfectly familiar to any of us who have spent time teaching*.” Students often carry out learning activities according to their number (*I dunno, I never really thought about* *it....just doing it... its 8.5...just got to do different numbers*) as being told by the teacher, without knowing what learning road they are walking on and what the respective activities are supposed to contribute to that goal. Just as teachers usually do not worry enough about making this road clear to their students. We think this to be rather unfortunate for a successful learning process.

The didactical structure that is based on Vollebregt's work can be depicted in three columns: *Models of nature, Nature of models* and *Motives*. So, the structure depicts in fact two coupled teaching-learning processes in which students are supposed to learn about a particular model of nature, and about the nature of that model in a functionally integrated way. I.e., both learning processes are intertwined and driven by motives that may be made to emerge naturally. The arrows indicate the designed story line that the teaching process is supposed to follow. This teaching process should thus more or less be experienced as a coherent activity with a clear direction and purpose and not as a series of independent activities. The final structure shows some interesting points that are of more general importance, I think. First, it appears to be crucial to give ample attention to an orientation period, from which the purpose of the lesson sequence should clearly emerge, i.e. a global motive. In this case, this purpose, the explanation of macroscopic behavior of matter, involves in particular the development of a theoretical 'state of mind', i.e. the willingness to understand the (macroscopic) rules of nature at a deeper level. Together with the common sense clue (or advance organizer) that we often feel that we understand the working of something (machines, a human body) when we know how this working results from the functioning of its parts. Then, the global motive is narrowed down and a particular knowledge need is formulated (a first local motive). In the study of Vollebregt this concerned the behavior of gases and the explanation of the gas laws.

A second point to note is the introduction of the *germ* of a particle model (imagine that a gas behaves like a bunch of small bouncing balls). At this point we made the choice not to go for expressive modeling, i.e. to let students make their own particle model, but to go for the further exploration of a teacher-introduced model. The reason is the following. From the literature we knew that others had followed the expressive path. They asked students to design their own particle model. This resulted, quite naturally, in almost all students starting with particles as just 'tiny pieces', i.e. small pieces of matter that still have all the macroscopic properties. However, this meant that somewhere during the teaching process, teachers had to tell students, without a clear reason, that their model was not adequate and that scientists used a quite different particle model, which was then introduced.

Figure 1



Models of Nature ***Motives*** ***Nature of Models***

Global orientation on something like 'structure of matter'

as a topic of scientific interest and progress, in terms of deeper understanding (part-whole)

should result in a feeling that this could be an interesting field of study, asking for a theoretical orientation

that starts by narrowing the field down to macro knowledge of gases

and the introduction of an initial kinetic model, that it is initially plausible, because it is intelligible and seems fruitful

involving students in a disciplined modeling process, that leads to a further development of the model with an increased plausibility

but also to questions about its fruitfulness

that are answered by reflection on the properties and existence of particles and on particle explanations

from which a suspicion about a fruitful 'research program' should result

that is explored by a further development of the gas model and its applications to the behavior of liquids and solids as well

leading to a point of closure at which we may ask 'what have we done?'

that is answered by reflection on the process of modeling in relation to 'how scientists work'

resulting in an outlook on subsequent modeling

Instead, as already said, we introduced an analogy from the start, *to put students* directly *on the right track*. And to let them follow and explore the consequences of that track and develop gradually more confidence in it. First by connecting variables as volume and pressure to space to move in and collisions. Then, the coupling of temperature to speed got ample attention. And although the teaching process should still give many opportunities for students to express their ideas, this is now done within the borders of an explorative trajectory. This means that the students are not so much invited to express their ideas about the world, but to express their ideas about and to reason with the suggestions and proposals introduced by the teacher.

Starting from a just-like-bouncing-balls analogy had another fruitful consequence. Students first accepted the challenge to explain the behavior of gases with this model. However, after some lessons this quite understandably led to the question: what's the use of all this thinking and reasoning if this analogy does not make sense. If a gas does not really consist of small 'balls'. Thus providing a clear motive to discuss what it means for this ball-model to 'be realistic', i.e. to be simple, considered fruitful, consistent, empirically adequate, etc. And that a particle-model means that we try to explain macroscopic change by means of motion of unchangeable small balls. This leads to questions like: if they really exist why can't they be seen, and how can they keep moving, etc., which lead to further exploration. In fact, in this case, the need for developing metamodelling knowledge is functionally integrated in the teaching process, and not an additional extra, as e.g. in the case of Schwarz and White. Thus, in a careful designed lesson sequence, teacher and students appeared to be able to go a long way in developing and testing an introductory particle model, as well as in reflecting on the nature of that model. The sequence was rounded of with reflecting on the question in what way the final model was in line with what the global motive required, i.e. explaining matter at a deeper level. To underline the value of what was achieved it was indicated that the final model was more or less the same as proposed by Clausius in 1857. Clausius, however, also proposed that some of his particles consisted of clusters of other particles, which we now call atoms and molecules, which provides an outlook for the next step in particle modeling.

In Vollebregt's teaching sequence, we thought it appropriate that students themselves actually had to take part in a modeling process, but at that time, this was considered to be a *means*, i.e. an adequate constructivist-inspired teaching strategy, and not yet a *goal* in itself, i.e., learning to model. Nevertheless, the rounding off session also meant to reflect on the process of modeling, i.e. it was meant to make them realize that this process was more or less comparable to what scientists do. On second thought however, I think that we have to say that this part was an incorrect rounding off. Something that we did feel already then, however without being able to give this uneasy feeling a clear name. And not only because it didn't function properly in practice, as students didn't really see the point of it. In retrospect, I think that the problem is that we mixed up two different things. I.e. making a product, a model, and the process of making that product, modeling. In making a model it is natural to ask questions about the quality of that model, thus to reflect on its characteristics. Does it do what it is supposed to do. I.e., in a problem posing approach the making of a model and reflecting on the nature of that model can be functionally coupled. In this theoretical case, this meant that the model itself was developed in functional alternation with (rather basic) reflections on epistemological and ontological aspects of the model. However, a problem posing reflection on the general nature of the modeling *process* asks for a separate motive. And thus also for a separate orientation in order to prevent that this reflection cannot really make sense to students. In our structure these aspects are not yet properly accounted for.

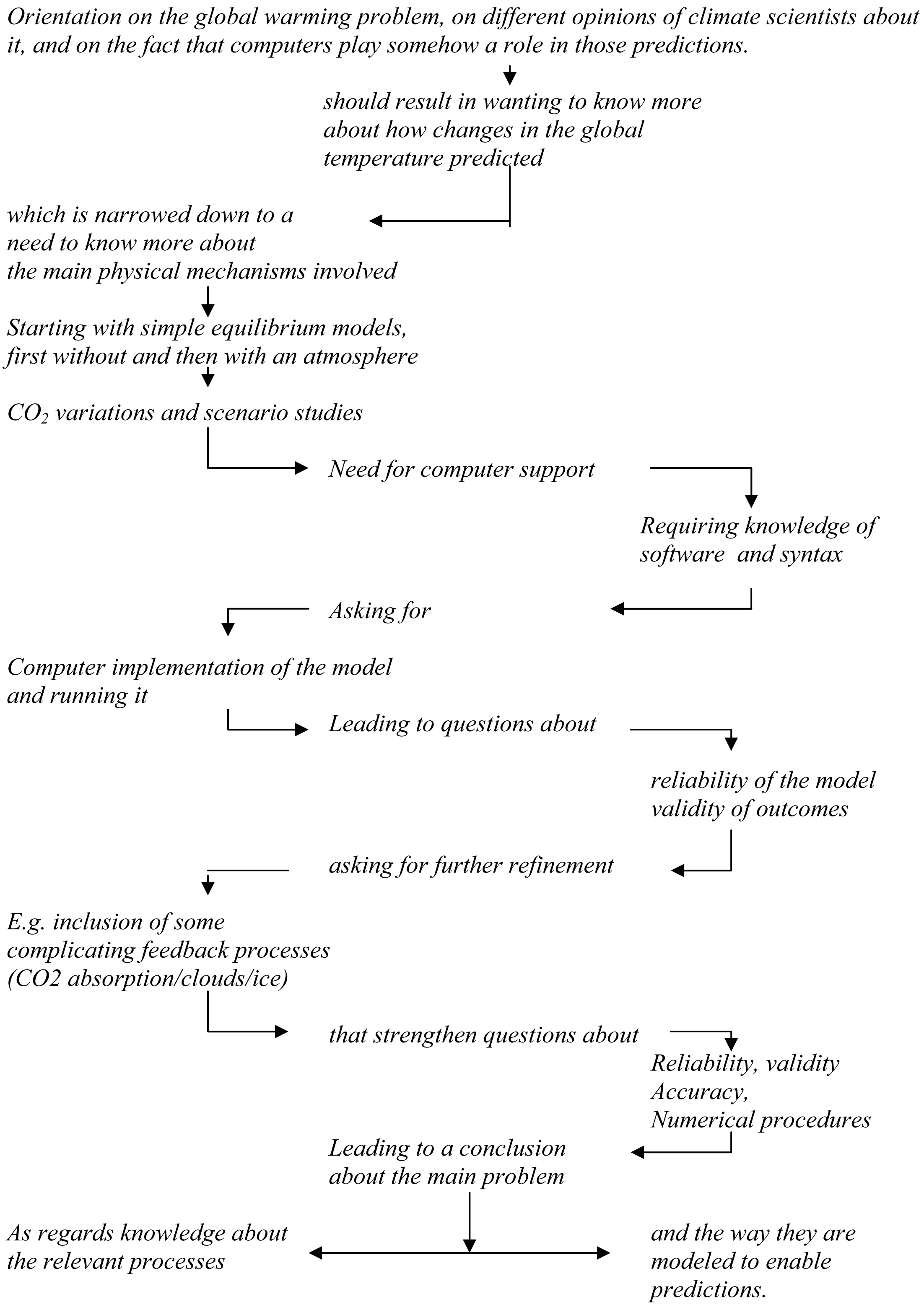
Now one could ask about the purpose of such a process of reflection. Is it just to give some more insight into how science works or is it also because it could students in some explicit sense ‘teach to model’. In fact, modeling at this theoretical level, largely consists of framing creative adequate conceptual hypotheses and test them by means of disciplined critical logical reasoning in view of the evidence available. It seems fruitful to make students aware of this nature that may contribute to developing a critical ‘scientific attitude’, but it is doubtful whether this will lead to something what you might call ‘learning new transferable modeling skills’. So, we may conclude that in theory generating modeling, i.e., in the context of discovery to put it in philosophical terms, no explicit teachable modeling strategy seems to be possible, apart from dealing with epistemic virtues. These may be considered as the boundary conditions for the modeling process. When properly integrated in the teaching-learning process, such virtues have a natural role to play. We found this also in another study (Westra, 2006) in which students had to model the orbit of planets using either Newton’s or Kepler’s theory. Students found it rather self evident, once being put on the right track, to use epistemic values as plausibility, empirical adequacy, consistency, generality as criteria for trying to decide between such rival theoretical possibilities.

Dynamical modeling

However, our conclusions on the explicit teaching of modeling may differ when we deal with theory applying modeling, as already indicated, as, e.g., in the case of dynamical modeling.

Figure 2

Models of temperature change Motives Nature of such models



Orientation on the global warming problem, on different opinions of climate scientists about it, and on the fact that computers play somehow a role in those predictions.

should result in wanting to know more about how changes in the global temperature predicted

which is narrowed down to a need to know more about the main physical mechanisms involved

Starting with simple equilibrium models, first without and then with an atmosphere

CO_2 variations and scenario studies

Need for computer support

Requiring knowledge of software and syntax

Asking for

Computer implementation of the model and running it

Leading to questions about

reliability of the model validity of outcomes

asking for further refinement

E.g. inclusion of some complicating feedback processes (CO2 absorption/clouds/ice)

that strengthen questions about

Reliability, validity
Accuracy,
Numerical procedures

Leading to a conclusion about the main problem

As regards knowledge about the relevant processes

and the way they are modeled to enable predictions.

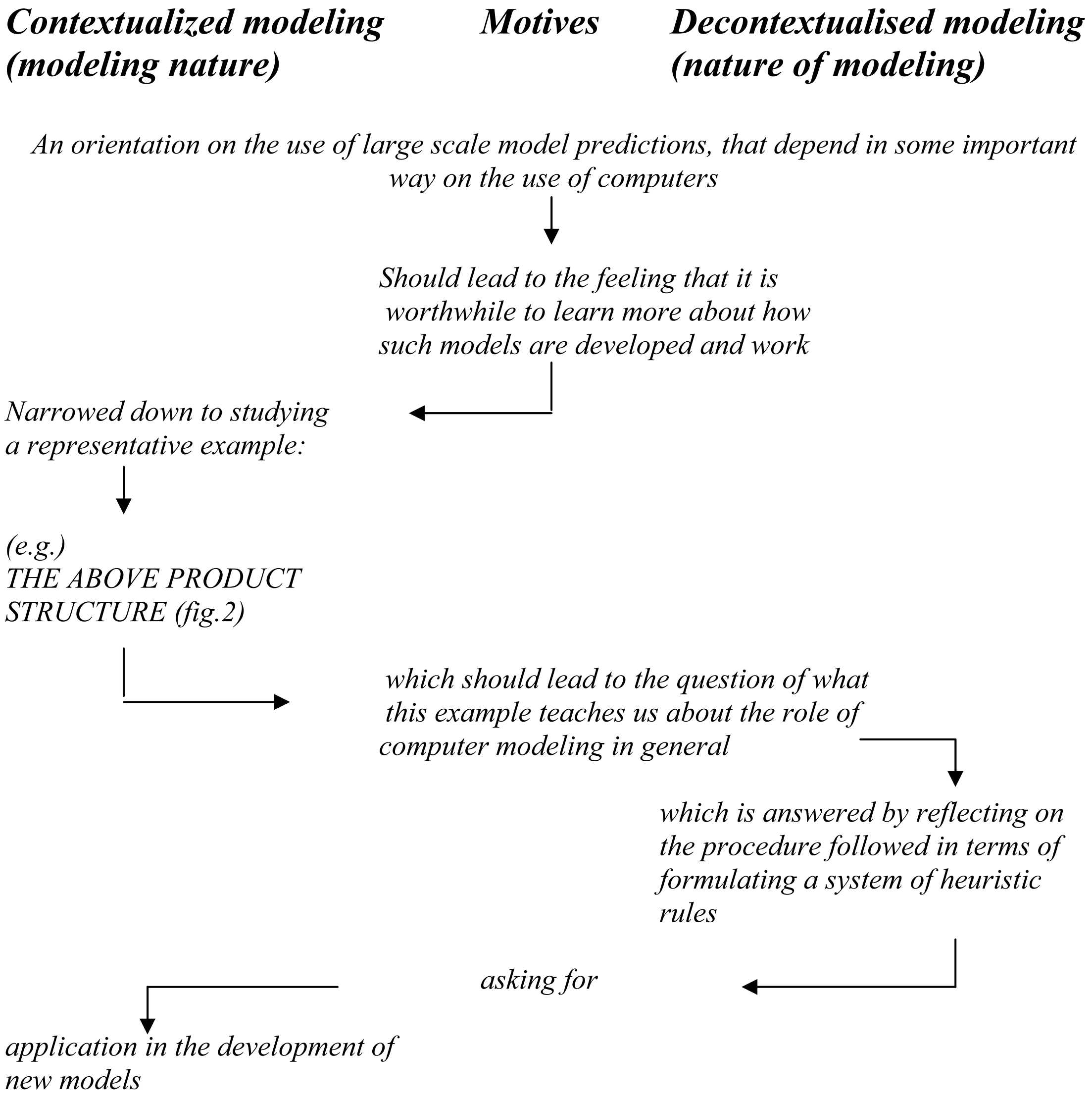
Before going into this issue, let me first elaborate a bit on the place of dynamical modeling in our physics curriculum. Dynamical modeling has been around since the DMS-program of the eighties, but it still has not got a real foothold in Dutch physics education. A main reason may be that the regular intra-curriculum applications seem to be rather restricted, i.e., some mechanics, the capacitor, heat flow and radioactive decay. Or in other words, time is not a variable in our curriculum. In view of the present role of computer modeling in science it could however be argued that dynamical modeling should get much more curriculum attention. A proper final aim for such a curriculum strand could be to give students sufficient insight in how large scale computer models are designed and succeed in making predictions. To get an idea of the feasibility of this aim we developed an extracurricular lesson sequence on predicting the future temperature of the earth, in view of the uncertainty about the warming up of our planet and climate changes that may go with it. Our aim was to let students get a feeling about how climate scientists work on such an important practical problem and why such diversity in predictions exists, even in spite of the use of 'exact' computers. The following problem-posing story line may give an idea of what we are trying.

This structure should be regarded as still under construction. First I want to emphasize that we are dealing here with a theory-applying modeling process for a practical purpose. Though many details of the problem situation are unknown to our students, the basic theoretical concepts to be applied are known. And if additional theoretical knowledge is needed it is first studied and subsequently applied to model the relevant problem situation. The purpose of the modeling process is this time the solution a practical problem, the prediction of the future temperature, which explains the focus on the reliability and validity of the models. To what extent is this problem validly and reliably solved, thus on methodological aspects. Thus, the required modeling process has much in common with what Hestenes (1987) described as modeling as a specific problem solving strategy.

The topic appears to be feasible though not without problems. More than for regular curriculum topics, this extracurricular topic has a kind of bootstrap structure. Students should start with reducing reality to a very much-simplified first physical model, but lack the necessary experience and situational knowledge to do so. In fact, the first models are precisely intended to provide them with such knowledge and to set them on the right track. The role of the teachers was therefore at first instance more of showing and explicating the how and why of tackling this problem. Often students appeared to be very active at the computer level, however, without paying sufficient attention to the physics of their models. This may explain that little numerical modeling transfer appeared to occur in a next, in fact much simpler, task on modeling radioactivity. This strengthened the idea that to foster such a modeling transfer a procedure should be worked out and taught in some way. This idea also resulted from the analogy with the work of Kortland (2001) who came to the conclusion that for the teaching of decision making in social-scientific issues, it seems to be appropriate to let students, in reflecting on their own decision making experience, end up with an explicated procedure as a metacognitive instrument for acting in subsequent decision making situations

This then poses the question how this modeling procedure can best be formulated and be taught. My guess would be that this could be done as a system of heuristic rules. Research on problem solving, however, has shown that direct teaching of problem solving heuristics has little effect. Better results may be expected if the heuristic stems from reflection on students' own modeling experience. Such a system might provide the required insight in how computer modeling 'works' and it might enhance the possibility that students tackle a next problem in a more structured way. Although it is always the case that the real content-bound creative steps in a modeling process cannot be *forced* to take place, and that the actual process is always strongly embedded in and governed by the actual content at stake, a system of heuristic rules can help to reflectively *structure and repair* the modeling process when its progress has become

Figure 3



problematic. A didactical structure that aims for the explicitation of such a modeling heuristic should start, I think, with an orientation in which the *modeling procedure itself* is problematised as a learning goal rather than the *conceptual problem* to be modeled.. Thus making it relevant for students to finish with a reflective explicitation of that procedure (fig.3).

What could such a heuristic instrument consist of? Of course, this can be formulated at a number of levels of detail, but to give a rather general idea, we think that it should include the following categories:

1. *Analysis and reduction*:
   Analyze and reduce the problem situation in terms of its possibly applicable theories, i.e. determine the appropriate system, its main objects, variables, known and unknown relations;
   Analyze the problem in terms of its dynamical characteristics: what are main influences and what their effects;
2. *Problem solving trajectory*:
   Divide the problem into a series of subsequently solvable partial problems;
   Start with a reduction to a simplified largely known system and model;
   Get a qualitative idea of how that system behaves; in particular as regards feedback loops;
3. *Numerical model construction*
   Implement the model, i.e.: construct the necessary difference equations, determine an adequate time step-size and an adequate set of starting values;
4. *Test and evaluation*
   Test and evaluate the behavior of that model in the light of the first partial problem; determine its accuracy, in particular as regards uncertainties in parameters and numerical approximations;
5. *Fine tuning and adaptation*
   Revise it in view of the next partial problem;
6. *Evaluation*
   Repeat this cycle till the final model is considered adequate in view of the main problem.

So far we have no experience to judge whether the implementation of such a set of heuristics can really foster some procedural transfer. As already said, it should be the outcome of reflective activities so that students should recognize that this set reflects the procedure that they have successfully followed, be it with the guidance of the teacher. As this set presupposes experiential knowledge about coupled feedback processes and numerical procedures, it should better not be the result of one single modeling activity, but be gradually built up and applied at the same time in a series of modeling activities. The regular curriculum topics could provide this preparation, provided that their didactical structures are adapted to this role. Thus we may come to speak of an explicit numerical modeling learning trajectory that does more than simply letting students do some numerical modeling activities without having a clear purpose.

Teacher problems

Now you may ask whether these ideas have any relation with the reality of teaching practice. Let me then first stress that we have tried most of them out, though of course not without difficulties. These difficulties can be summarized into two main categories: i.e. those dealing with giving students sufficient construction freedom, (as is well documented for constructivist-inspired teaching), and those dealing with the problem posing character of our teaching approach.

As regards providing sufficient construction space, most teachers were too quickly inclined to provide students with the right answers and had great difficulty in explaining to students the background and reasons of what they were doing. So they paid attention to the facts of the models, but not to why the models are as they are. Or, in other words, they paid attention to the models but not to the modeling. We also found it to be quite difficult for teachers to pay adequate attention to reflective activities, in particular as regards the problem posing character, such as: what have we found? Did we reach our goal? What remains to be done? Etc. Or, in other words, to let the story line evolve as a real storyline and the motives emerge and play their role. Apparently, a strong tension exists, even for experienced teachers, between on the one hand taking the lead and telling the facts and on the other guiding students adequately in letting them perform, and making them see the point of the required modeling activities (Lijnse, 2005).

Concluding hypotheses

So far I have only dealt with three models of teaching modeling. That is an insufficient experiential base to draw any strong conclusion. Only some hypotheses can be formulated. In the above I have argued for a curriculum perspective on modeling, making distinctions between expressive and explorative modeling, theory generating and theory applying modeling, and between common sense, descriptive, causal and numerical modeling. In a well-designed modeling curriculum, all these ways of modeling should have their appropriate place and function. In addition I have argued that a well-designed problem posing teaching-learning sequence enables us to make a functional coupling between the development of a model and reflection on the nature of that model. In particular: theory generating modeling could gradually lead to functional knowledge of the epistemological boundary conditions for disciplined scientific reasoning; theory applying modeling could gradually lead to the development and functional implementation of a system of modeling heuristics. Providing students with a clear and adequate purpose for their learning processes seems to be the decisive characteristic for such functionalities. However, making this purpose to be a leading thread in students learning, asks from teachers a rather important change, as in general they are not used to teaching both at a didactical *and* a meta-didactical level, i.e. they are not used to paying attention to the required reflective teaching activities.

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