MODELS OF ELECTRICITY IN PHYSICS TEXTBOOKS: ENABLING OR CONSTRAINING INQUIRY BASED INSTRUCTION?

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Models of electricity were investigated in a series of commonly used secondary school physics textbooks. Earlier studies indicated that students need a basic theoretical model in an inquiry context in which conceptual understanding is important. The way such a model is presented and used should afford conceptual and experimental inquiry activities and should respect insights from NOS. Based on a selection of articles on models in science, models in physics education, and models in textbooks, a list of 16 criteria was compiled to evaluate the extent to which textbook models are in line with NOS. Eight criteria applied to descriptive text, and eight criteria applied to student tasks. The criteria were qualitative in nature and needed to be interpreted and evaluated qualitatively. These criteria were then used to evaluate the models of electricity in a set of grade 7 to 12 physics textbooks in the Netherlands.

Keywords: Models of Electricity in Physics, Inquiry-oriented learning, Textbook study

THEORETICAL MODELS TO SUPPORT INQUIRY ACTIVITIES

A goal of innovative approaches in the secondary school science subjects has been to actively involve students in scientific processes, for example by creating a culture of inquiry in the classroom (Cobb & Yackel, 1998). Inquiry engages students with scientific phenomena, emphasizes student active thinking and responsibility for learning, and uses parts of an investigation cycle (Minner, Levy, & Century, 2010). Inquiry is in line with aspects of the Nature of Science (NOS) considered important for secondary school students (Abd-El-Khalick, Waters, & Le, 2008): (a) ideas are tested by experiments, (b) models form the basis for hypotheses and predictions, (c) theories and models are used to analyze and interpret data, (d) scientific exploration is diverse, (e) science requires creativity, and (f) scientific knowledge develops over time. In physics, theoretical understanding of concepts and models is an aspect of the nature of the subject (Park & Jang, 2005). Students cannot reinvent theoretical ideas entirely by inductive experimental activities, and therefore need a basic model as a theoretical starting point for inquiry (Kock, Taconis, Bolhuis, & Gravemeijer, 2015). The main source of scientific models in the classroom, for the students and the teacher, is the textbook. Several studies have addressed NOS in textbooks (Abd-El-Khalick et al., 2008; Park & Lavonen, 2013), but there has been little attention for the extent to which the theories and models in textbooks are consistent with NOS and thus afford or constrain inquiry activities.

We first describe how criteria were developed to evaluate models in physics textbooks. Then we describe a test of these criteria on grade 7-12 physics textbooks, guided by the research question: To what extent does the way in which models of electricity are presented, explored, and used in a series of secondary school physics textbooks in the Netherlands enable or constrain inquiry-based instruction on the basis of criteria derived from literature?

CRITERIA TO EVALUATE TEXTBOOK MODELS

The criteria were developed based on the review article by Seok Oh and Jin Oh (2011) and the May 2007 special issue on scientific models in the journal Science & Education, complemented by additional articles until no major new insights were found. The articles were summarized, keeping in mind the application to textbooks at secondary school level. The resulting description follows the structure of the article by Seok Oh and Jin Oh (2011): meaning and purposes of models, relation of models with experiments, and multiplicity and development of models. We also discuss the uses of models in the physics classroom and earlier studies of models in textbooks. In the description, we refer to the criteria described later.

Meaning and purposes of scientific models.

In science, models can be defined as abstracted and idealized representations of some aspect of the world (*describing an aspect of the world: criterion* 1), created for a particular purpose (Develaki, 2007). The representational character of models implies that they resemble the selected part of reality (*distinguish model and phenomenon: criterion 2*) (Jonassen, 2008).

Models are used to describe and explain phenomena, as well as to make predictions. To that end models may contain theoretical and unobservable objects that explain mechanisms underlying the phenomena (*explaining theoretical concepts and their relations: criterion 6)* (Clement, 2008). Explanations can take place by showing mathematical relations between variables (*calculations: criterion 13*), or through causal reasoning (Justi & Gilbert, 2003). For students, causal reasoning may be more appealing and understandable than formal mathematical laws. In society, model predictions are used as tools in decision making processes or to manipulate technological systems (Van der Valk, Van Driel, & De Vos, 2007) (*purposes of models: criterion 7; using models to make decisions or manipulate systems: criterion 15*).

Models and experiments

The creation of a model takes place through abstraction and idealization, because reality is too complex to correspond exactly to theory (*abstraction and idealization: criterion 2*) (Halloun, 2007). Consequently, model predictions always have a limited precision, so that an experimental test of a model will only lead to an approximate match or ‘fit’ (*addressing model precision and fit: criterion 11*). Models are used to design experiments and interpret results, but experimental results may also be used to adapt and improve models and theories, for example if model predictions do not correspond to observations *(testing model-based predictions: criterion 10*) (Koponen, 2007).

Multiplicity and development of models

Scientific models can be physical objects, pictures and diagrams, text, mathematical equations, or computer simulations, and in this way provide the necessary language and symbols to think and communicate about aspects of reality (Seok Oh & Jin Oh, 2011). Different models can represent the same target phenomenon (*different models of the same target: criterion 8; using multiple models: criterion 14*). Human agency and creativity are important in determining the purpose and construction of models, the idealizations and use of analogies (*use of analogies: criterion 3*) (Celestino Silva, 2007). Models are often a compromise in which advanced models (high correspondence to the target) tend to be less accessible (Van der Valk et al., 2007).

Models may be developed or modified over time (*historical development: criterion 4; reference to earlier/later school models: criterion 5*). This can be a result of theoretical developments, of empirical evidence, or of a shift in purpose (Park & Jang, 2005).

Models in physics education

Various model-based scientific inquiry processes can be used in education (Halloun, 2007): constructing a model, using a model to solve empirical or theoretical problems, model testing, and adapting a model based on theory or experiment (*model building or evaluation: criterion 12*). Models offer opportunities for causal reasoning (*tasks using conceptual reasoning: criterion 9*) and can be used to promote student understanding, for example by visualizing otherwise invisible mechanisms (Justi, Gilbert, & Ferreira, 2009) .

Simulations using computer models can support various aspects of inquiry (Rutten, Van Joolingen, & Van der Veen, 2012) (*using runnable simulations: criterion 16*). For example, students can construct dynamic models, using graphical, programming or mathematical tools. However, integrating modelling activities into the lessons and the curriculum is still a point of attention and the role of the teacher is demanding (Louca & Zacharia, 2012).

Research on models in textbooks

The way models are treated in science textbooks is seldom in line with inquiry-based instruction. Textbooks often present models as static and final versions of scientific knowledge, ignoring development and limitations. Different models of the same phenomena are not distinguished, the reasons for introducing new models remain implicit, and the connection of visual models to the theory tends to be ignored. Students experiments are mainly used to verify textbook knowledge and not to develop models (Erduran, 2001). Some textbooks models are compiled from historical models in a historically incorrect way (Justi & Gilbert, 2003).

Textbook research in physics education focused more on the content of models in relation to student conceptual understanding, than on NOS-related issues. For example, Stocklmayer and Treagust (1994) investigated the representation of electric current in secondary school textbooks between 1891 and 1991. Early textbooks used fluid models. Most introductory texts from the mid 1960's used a moving charged particle model starting from basic atomic structure and electrostatics (movement of electrons in a circuit). Recently, the field concept has been promoted as a basis to understand electric circuits (Stocklmayer, 2010). Often, analogies from other field of physics, such as water circuits and gravitation, have been seen as helpful for understanding. These are problematic when students do not understand the physics underlying the analogies. Transport or crowd analogies have been introduced and analogies in which electrons have an almost human character and carry energy in an electric circuit (Hart, 2008).

Sangam, Jesiek and Thompson (2011) found conceptual weaknesses in the presentation of DC electricity in an undergraduate textbook. Gunstone, McKittrick and Mulhall (2005) analyzed three senior high school textbooks, and interviewed the authors with regard to the concepts of electricity and the meaning of models and analogies. They noted that the authors had no clear understanding of what a model is, and sometimes did not distinguish models and analogies.

In this paper the emphasis will be less on the conceptual content of the textbooks, and more on the connection with NOS. In our perspective, the models in the textbooks should have the potential to contribute to a culture of inquiry in the classroom.

Evaluating textbook models with the help of criteria

Models in physics textbooks are used to describe and explain content and appear in student tasks and activities. The main aspects of models described in the literature overview were reformulated as criteria to evaluate physics textbooks from an NOS point of view (Table 1).

Table 1 Criteria to evaluate the extent to which textbook models are in line with NOS.

No.	Criterion
	Description of the content
1.	The text describes an aspect of the world.
2.	The text distinguishes the model from the target phenomena by making abstractions, idealizations and simplifications explicit.
3.	The text uses an analogy.
4.	The text addresses the historical development of a model.
5.	The text refers to models of the same target students encountered in earlier or will encounter in later chapters or school years.
6.	The text explains theoretical concepts and objects and their (quantitative and/or qualitative) relations.
7.	The text refers to the purpose for which a model was created.
8.	The text uses different models for the same target.
	Student tasks and activities
9.	The task requires reasoning with model concepts.
10.	The task requires students to express hypotheses before carrying out experiments.
11.	The task requires students to address the precision and fit of a model
12.	The task involves students in model building or model evaluation.
13.	The task requires students to carry out calculations.
14.	The task requires students to address the multiplicity of models.
15.	The task requires students to use a model prediction to make decisions, give advice or manipulate (technical) systems.
16.	The task requires students to use runnable simulations.

Scoring textbooks with the criteria in Table 1 will help to create a perspective on the presentation and use of models of electricity in relation to inquiry-based instruction. However, the criteria are qualitative in nature and need to be interpreted and evaluated qualitatively.

METHOD TO APPLY THE CRITERIA TO TEXTBOOKS

Models of electricity in recent editions of commonly used Dutch physics textbooks for grade 7 to 12, all from the same publisher, were evaluated using the criteria. The textbooks were selected based on the following considerations: (1) the textbooks covered the physics curriculum of grade 7 to 12, so that the development of models on a single topic (electricity) could be studied; (2) the textbooks were published by a single publisher using a consistent pedagogic approach, so that there was coherence in content between the grade levels; (3) recent editions of the textbooks were available; (4) the textbooks were widely used in Dutch schools.

Table 2 Physics Textbooks and chapters used in the study

Grade	Textbook abbreviation	Chapters
7/8	Impact7/8	2. Electricity
9	Impact9	1. Electric appliances
10	Newton10	1. Electricity: electric circuits and energy use 6. Skills: dynamic modeling (*part)*
11	Newton11 4th Ed.	7. Music and telecommunication (*part)* 8. Electric motors and dynamos (*part)*
11	Newton11 3rd Ed.	15. Matter: Particle theory and radiation (*part)*
12	Newton12 3rd Ed.	18. Cathode ray tubes: Electric and magnetic fields (*part)* 19. Matter and radiation: Particle or wave theory (*part)*

Table 2 shows the abbreviated names of the selected textbooks: the name of the book series followed by the grade, and if necessary the edition. Chapters dealing with electricity were studied in full; chapters partly dealing with electricity were studied in part. Some models on other topics (matter, mechanics) were included in the evaluation, to obtain a fair account of how the textbooks paid attention to models. This applies to the Newton10 chapter Skills, from which the sections on dynamic modeling were included (its physics content was mostly taken from mechanics). Similarly, sections in the chapter on the structure of matter did not refer to current electricity, but partly to charged particles and to models, and so they were included.

The author applied the criteria non-uniquely to sections of text and student (sub)tasks, and made qualitative summaries. A second rater scored part of the material. Differences were discussed after which some criteria and rater instructions were reformulated and examples were added. The process was repeated and comparison of the remaining differences indicated that these did not disturb the overall qualitative evaluation arising from the scores. The criteria scores were qualitatively interpreted based on descriptive summaries of the text and task content. The approach required qualitative interpretation, because texts and tasks could meet a criterion to a greater or lesser extent and the criteria carried different weights depending on the context in which they were scored. For example, criterion 13 could be scored for model based calculations in an inquiry task, but also in the case of a traditional textbook calculation problem.

RESULTS

Descriptive paragraphs

Table 3 shows how often descriptive paragraphs met the criteria from Table 1. The table cells indicate the absolute scores, and the scores as a percentage of the total number of paragraphs. Not applicable (n.a.) was scored for paragraphs unrelated to any of the criteria or to electricity. For example: an explanation of unit prefixes (such as kilo-, milli-) was scored as n.a., because it was not related to electricity. In the evaluation n.a. scores were treated as neutral. Chapter 6 from Newton10 and 7/8 from Newton11 were not included in the table, because they contained too little relevant content to justify a score.

Table 3 Criteria scores for the descriptive paragraphs in the physics textbooks

Criterion	Score (percentage)				
	Impact7/8[a] chapter 2	Impact9[a] chapter 1	Newton10[a] chapter 1	Newton11 3rd Ed.[b] chapter 15	Newton12 3rd Ed.[b] chapters 18/19
1	39 (93)	41 (55)	26 (65)	7 (70)	9 (75)
2	2 (5)	1 (1)	1 (3)	7 (70)	0 (0)
3	2 (5)	5 (7)	1 (3)	1 (10)	2 (17)
4	0 (0)	0 (0)	0 (0)	8 (80)	4 (33)
5	0 (0)	0 (0)	2 (5)	2 (20)	0 (0)
6	35 (83)	56 (75)	35 (88)	2 (20)	11 (92)
7	0 (0)	0 (0)	0 (0)	5 (50)	1 (8)
8	6 (14)	5 (7)	14 (35)	5 (50)	4 (33)
n.a.	2 (5)	10 (13)	1 (3)	0 (0)	0 (0)
Total paragraphs	42 (100)	75 (100)	40 (100)	10 (100)	12 (100)

Note.

[a]The chapter was studied in full

[b]Only the parts related to electricity in the chapter were studied.

In the Impact7/8, Impact9, Newton10 and Newton12 3rd Ed. chapters criteria 1 and 6 were scored the most. In Impact7/8 the concepts electric energy, current, and voltage were introduced in connection with phenomena and contexts, which received most attention. In Impact9 the focus was more on the physics concepts and their quantitative relations. The model of electricity was extended with a section on static electricity, but no connection to electric circuits was made. The Newton10 chapter on electricity overlapped with Impact9, with further extension of the theory and applications. Among others, the Newton10 chapter included the concepts of conventional current, electron drift velocity, variable resistors, Kirchhoff's laws, and semiconductor components. Quantitative relations received more emphasis with increasing grade level: the Impact7/8 chapter contained no formulas, Impact9 contained 9 and Newton10 contained 20. Thus, the model of electricity was extended and became more sophisticated, while the core features of the model were repeated in the textbooks.

The texts explained the concepts by means of a model of flowing electrons and the occasional use of water and traffic analogies. The model was offered as a factual account and limitations of the model were not discussed. Criterion 2 (limitations of models) was scored only four times in the three chapters, for example in the case of a limitation of the water analogy (water flow does not need a closed circuit). Concepts introduced in the grade 7-10 books were applied in Newton11: current, voltage and electrons were used to describe electromagnetic phenomena.

The Newton12 3rd Ed. chapters dealt with electric and magnetic fields, the electron, and wave-particle duality. Electric fields were introduced in electrostatic situations.

In the Impact7/8, Impact9, and Newton10 chapters criterion 8 was mainly scored because of the introduction and use of pictures and circuit diagrams, and criterion 3 because of the water and traffic analogies occasionally used. The texts did not address the historical development of the scientific models, nor the development of school science models across grade levels.

Parts of the chapter on matter in Newton11 3rd Ed. described the historical development of models (criterion 4). The text gave an account of the development of models of matter in a historical succession, such as the kinetic gas theory, atoms, the Rutherford and Bohr models of the atom, the atomic nucleus, and elementary particles. The text defined models as increasingly sophisticated representations of invisible reality and addressed model limitations as well as simplifications. Making models was described as a human activity with the purpose to explain phenomena. According to the text a more sophisticated model did not make the older model useless, but the refinement of the new model enabled it to explain more phenomena. The parts of the Newton12 3rd Ed. chapters also paid some attention to historical developments.

In summary, the analysis showed that the textbooks in the study explained phenomena in current electricity submicroscopically by means of a model of flowing electrons and macroscopically by means of quantitative relations between concepts (such as Ohm's law). The explanations were presented as a complete account of facts about nature, with little attention to NOS aspects such as model development or limitations. The models were extended in subsequent years. The consequences of the extensions (electrostatics, electric fields) for current electricity were hardly addressed. The historical development of models of matter was described in the grade 11/12 texts, with some attention to model limitations and idealizations.

Student tasks

Table 4 shows how often (parts of) student tasks met the criteria. Not applicable (n.a.) was scored when (part of) a task could not be related to a criterion or to electricity. For example: a factual recall task did not apply to any of the criteria. Impact7/8 and Impact9 show high scores on n.a., because many part questions concerned factual recall, and situations not related to electricity. Criterion 14 was scored in Impact7/8, Impact9 and Newton10 when tasks involved graphical representations of circuits (interpreting and drawing sketches and circuit diagrams).

The majority of the tasks in Impact7/8, Impact9, and Newton10 addressed conceptual understanding and mathematical relations (calculations) in models of electricity, but did not specifically address the model nature of these concepts and relations. Hence, the tasks did not differ from standard textbook conceptual or calculation questions. Two tasks in Impact7/8, one in Impact9, and three in Newton10 asked students to use model-related reasoning to support decision making (e.g. selecting an electric appliance based on a model of energy use/costs; determining if cars can feasibly be powered by solar energy). The task complexity increased with increasing grade level.

Table 4 Criteria scores for student tasks and activities in the physics textbooks

Criterion	Score (percentage)				
	Impact7/8 chapter 2	Impact9 chapter 1	Newton10 chapter 1	Newton11 3rd Ed. chapter 15	Newton12 3rd Ed. chapters 18/19
9	40 (38)	91 (51)	76 (66)	9 (69)	4 (100)
10	1 (1)	5 (3)	2 (2)	1 (8)	0 (0)
11	0 (0)	0 (0)	0 (0)	1 (8)	0 (0)
12	1 (1)	12 (7)	12 (10)	6 (46)	1 (25)
13	7 (7)	86 (48)	44 (38)	6 (46)	3 (75)
14	13 (12)	30 (17)	35 (30)	0 (0)	2 (50)
15	2 (2)	1 (1)	3 (3)	0 (0)	0 (0)
16	0 (0)	1 (1)	0 (0)	2 (15)	0 (0)
n.a.	70 (67)	54 (30)	17 (15)	2 (15)	0 (0)
Total tasks	105 (100)	179 (100)	115 (100)	13 (100)	4 (100)

Newton11 3rd Ed. Also contained standard textbook conceptual questions and calculation tasks. However, some tasks addressed aspects of modeling: students were asked to use computer models (on gas laws), to develop a model of an unknown object in line with Rutherford's experiment, to compare and evaluate historical models, to explain current, voltage and resistance in terms of the free electron model, and to compare given data to model calculations.

The tasks in Newton12 3rd Ed. included conceptual questions and calculations in various contexts, at the level of the national exam. One question asked students to consider the idea of an electric field in a current carrying wire, creating a connection between the model discussed in the chapter and the theory of current electricity studied earlier.

All books contained student experiments: 15 in Impact7/8, 25 in Impact9, and 22 in Newton10, some downloadable as worksheets from the book's website. Ten experiments in Impact7/8, 20 in Impact9, and 16 in Newton10 were related to the textbook models and theories of electricity. For example, in Impact9 an experiment aimed at extending the model of electric circuits by a stepwise investigation of the rules for current and voltage in parallel/series circuits. In the remaining experiments the aim was to produce a particular electric circuit or artifact (e.g. a simple electric motor), to show phenomena, to investigate a fact (e.g. the efficiency of a light bulb), or a relation between variables (e.g. the power of a solar cell depending on the load).

The amount of student guidance varied. Most experiments were guided by stepwise instructions with detailed descriptions of student actions, followed by one or more (conceptual) questions. The experiments and questions referred to macroscopic concepts such as electric current, voltage and resistance. They made no reference to the electron flow model of electric current. With increasing grade level the instructions became less detailed, but the Newton10 worksheets still contained specific guidelines and *fill in the blanks* spaces for results. Newton11, Newton11 3rd Ed. and Newton12 3rd Ed. contained optional open-ended investigations. In Newton11 3rd Ed. and Newton12 3rd Ed. the investigations were described with general guidelines rather than detailed instructions. Some investigations asked for internet-based research, others for the use of a computer simulation, experiments and/or design.

In Impact7/8 and Impact9 the experimental aims remained implicit (e.g. "In this experiment you will investigate the current and resistance in a series circuit"), so that the emphasis was on the students' hands-on activities. In Newton10 the aims were explicit and research questions were given for the four optional activities at the end of the chapter. In Newton11 all experiments were guided by research questions. In Impact7/8 and Impact9 one of the experiments followed an inquiry cycle, in which students were asked to experimentally test their prediction with some choice as to the approach. In some experiments predictions or expectations were asked (5 in Impact 9), at times after the description of the experimental steps ("did the results correspond to your expectations?").

In all textbooks some modeling activities were present, in which students extended, modified or evaluated theoretical ideas (criterion 12). Mostly these were part of recipe type experiments. For example, Impact 9 contained an inquiry task using a simulation; in Newton10 the experimental tasks included finding quantitative relations between variables by means of a mathematical relation or a graph; in Newton11 one of the tasks involved investigating the limitations of a given mathematical relation; two tasks in Newton11 3rd Ed. asked students to compare and evaluate historical models (criterion 12); in Newton12 3rd Ed. a conceptual task included applying the model of an electric field to an electric circuit.

Chapter 6 of Newton10 contained two sections on inquiry and modeling skills respectively, mainly addressing technical aspects (e.g. data processing). The text in the modeling section explained simple dynamic models in physics and their creation using computer software. The related exercises were all taken from mechanics. Only one task was inquiry oriented: students were asked to create a dynamic model, compare the model results to experimental results and evaluate the model prediction.

In summary, the analysis showed that few student tasks were aimed at NOS aspects of models and modeling. However, many tasks paid attention to student conceptual understanding of the theory. Most experiments showed a theoretical intent, which often only became apparent from questions at the end of the instructions. In most experiments detailed stepwise instructions were used, and seldom an inquiry cycle. A few tasks asked for model related activities, such as supporting decisions or, evaluating models. The books for grade 11 and 12 contained end of chapter optional inquiry tasks. Dynamic models (unrelated to electricity) and models of matter (indirectly related to electricity) were explicitly addressed as models.

The models of electricity used in the books were a submicroscopic model of moving electrons, and macroscopic relations between current, voltage, resistance and energy. The macroscopic models used various representations (e.g. text, graphs, formulas). The microscopic model was occasionally used in explanations, but the tasks emphasized the macroscopic model.

DISCUSSION AND CONCLUSIONS

The results showed that models were treated differently in the textbooks, depending on the grade level. The books for grades 7 to 10 paid little attention to processes of knowledge development and the model nature of the physics knowledge. The theory was presented as a factual description, in which the historical development of our knowledge of electricity, or the development as it takes place for students in the course of the school years, did not come to the fore. The books for the higher grades explicitly addressed models, in ways more consistent with inquiry-based instruction. Examples are the chapter on dynamic modeling for grade 10 and the chapter on matter for grade11. Models were presented as fallible descriptions of reality in a more or less historical sequence, with some attention to model limitations and idealizations.

In student tasks most emphasis was on the macroscopic concepts, although the relation to submicroscopic models was occasionally addressed. Experiments came with recipe-type instructions; they seldom asked students to go through (parts of) an inquiry cycle. The theoretical aims of experiments became apparent only by the conceptual questions at the end of the task, and not by asking students to express and substantiate expectations. Only the optional tasks in the grade 11/12 3rd Ed. chapters were clearly inquiry oriented.

We conclude that the way the theory was presented and elaborated in the lower-grade books and in parts of the higher-grade books was difficult to reconcile with an inquiry approach, because little was left for students to find out. Student activities that would fit such an approach, such as using models to explain phenomena, relating submicroscopic models to macroscopic concepts and relations, and using models to inform decisions, appeared only to a limited extent. The exploration, evaluation and revision of models was not fully supported by the textbooks, although this would be helpful for students to understand phenomena and bring them in contact with scientific ways of thinking (Louca & Zacharia, 2012). The models of electricity were treated in a conventional way (Erduran, 2001): models were presented as final versions of human knowledge, and experiments were seldom used to develop, evaluate and revise models. The importance of models was recognized in the textbooks for grades 10 to 12, but not in the textbooks for the earlier years. Moreover, a consistent connection between models, modeling activities and inquiry was absent. Of course textbook authors face complicated choices when they have to decide what content to include for different grade levels. However, presenting models as facts and postponing models as purposeful representations of an aspect of the world (Seok Oh & Jin Oh, 2011) might misrepresent the nature of science for younger students. This may have a lasting negative impact on their view of science (Lyons, 2006).

An approach in line with NOS might use inquiry tasks, and not just explanations, to help students understand the relations between different models, such as the submicroscopic and macroscopic models of electricity. In higher grades more attention might be given to the electric fields concept and its role in electric circuits, as promoted by Galili and Goihbarg (2005) and Stocklmayer (2010). Model limitations deserve attention, because limitations are inherent in the model concept, and might point to new models with higher explanatory power.

The textbooks paid considerable attention to conceptual understanding, both in the descriptive text and the student tasks, which could provide a starting point for a more inquiry-based approach in future editions. Textbook authors could introduce the model nature of the theory at an earlier stage than in grade 11/12 in combination with more theoretically and experimentally oriented inquiry activities to bring the textbooks more in line with NOS.

The study indicates the possibilities offered by the textbook, but we did not investigate how these possibilities are used in practice. Another limitation of the study is that only textbooks from a single publisher were included. Additional research is needed to apply the criteria we developed to a wider range of textbooks.

It is important for textbook authors and teachers to be aware that models are used whenever electricity is taught and that models have a relation with scientific inquiry processes. Textbook authors could consider introducing the concept of a model as an abstracted and idealized representation of some aspect of the world at an earlier stage than in grade 10/11. In this way students may come to realize that they are constructing increasingly more sophisticated models of reality. Inquiry-based conceptual, experimental or simulation-oriented student activities could be directed towards modeling, for instance by asking students to compare model predictions, or to compare model predictions to experimental data. In some cases this requires only relatively small modifications of the tasks, such as introducing research questions and asking students to predict experimental outcomes before starting hands-on activities.

Instruction in line with NOS receives widespread attention as a means to make physics lessons more meaningful to students. It is important to critically examine the way textbooks, in descriptive content and student tasks, enable this type of instruction. We expect that the criteria compiled in this study are helpful for physics teachers selecting textbooks with an inquiry orientation, as well as for textbook authors.

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