Toward physics education in agreement with the nature of science : grade 9 electricity as a case

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TOWARD PHYSICS EDUCATION IN AGREEMENT WITH THE NATURE OF SCIENCE:

GRADE 9 ELECTRICITY AS A CASE

Zeger-Jan Kock

This doctoral thesis was financially supported by Fontys University of Applied Sciences and facilitated by the Eindhoven School of Education (Eindhoven University of Technology). The research was carried out in the context of the Dutch Interuniversity Center for Educational Sciences.

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CONTENTS

CHAPTER 1 GENERAL INTRODUCTION

In the Netherlands the number of people choosing a science or technology related career is below the expected future demand (Techniekpact, 2013), which, so is argued, might jeopardize the country's innovative and competitive power in a knowledge-based global economy. Efforts, such as the Dutch Technology Pact 2020 have been initiated, with the purpose to increase in the numbers of science and technology students in all levels of education, and ultimately to increase the number of people with high technological skills in the working population (Techniekpact, 2013). Cooperation between the technology oriented business community and education is one of the principles of this Pact. The Dutch Technology Pact is part of an international trend: the European Union and organizations in the USA have also expressed ambitions to increase the number of mathematics, science and technology graduates (Business Roundtable, 2005; European Union, 2003). Having an understanding of science, generally described as being *scientifically literate* (Duit & Treagust, 2003), is not only of economic value for a society, but also of cultural importance for an individual in a scientifically and technologically oriented world (Laugksch, 2000).

International studies, such as ROSE and PISA, have indicated that most secondary school students possess a positive attitude towards science and technology in general, but a far less positive attitude towards the sciences as school subjects (OECD, 2007; Sjøberg & Schreiner, 2005). Some studies have pointed out that the negative student attitudes towards the school sciences may be caused by, among others, the personal irrelevance of the curriculum content, a high level of abstraction, a focus on decontextualized factual knowledge and a pedagogy that lacks variety (Lyons, 2006; Osborne & Dillon, 2008; Sjøberg, 2002). In particular physics is considered unpopular compared to other school subjects and is relatively easily associated with terms such as difficulty and unpleasantness (Kessels, Rau, & Hannover, 2006; Taconis & Kessels, 2009).

The understanding of specific theoretical concepts in physics (e.g. electric current, potential difference, and resistance) is problematic for many students (see Duit, 2009, for an overview of research). Theoretical concepts feature in the theories and models of physics. They may have a formal definition, but derive their meaning, at least partly, from their use in scientific practice (Arabatzis & Kindi, 2013), for example from the way they are related to other theoretical concepts, are used to explain natural phenomena, to solve problems, and to interpret experiments. Many students' understandings of theoretical concepts are not in line with scientifically accepted views (Vosniadou, 2007). However, students' *alternative conceptions* (sometimes called misconceptions) are difficult to change and tend to persist, even after receiving instruction. During several decades a large body of research has emerged, devoted to the investigation of alternative conceptions and ways to change students' alternative conceptions by means of instruction. The effects of these instructional efforts have been limited (e.g. Westra, 2006, related to the teaching of mechanics).

Authors such as Cobern and Aikenhead (1998) hypothesized that understanding concepts in the sciences requires the learner to think in terms of a scientific world view. In this enculturating perspective science education is no longer solely seen as the transfer of a body of knowledge, but also as a process in which students gradually get acquainted with scientific norms and a scientific culture (Brown, Collins, & Duguid, 1989; Duit & Treagust, 1998; Gilbert, 2006; Lemke, 2001). Theoretical concepts are then considered cognitive tools used by students in their activities. Research into the nature of science (NOS) has investigated the relevant scientific norms, values, motives, activities and epistemology (Lederman, Abd-El-Khalick, Bell, & Schwarzt, 2002; J. Park, Jang, & Kim, 2009).

This dissertation describes research in physics education aimed at helping students understand theoretical concepts, using the assumption that understanding these concepts can be fostered by education in line with NOS. It is not self-evident that students come to understand theoretical concepts in physics education in line with NOS. Therefore, it is relevant to investigate how such education can be appropriately designed and enacted, and how student learning may then take place.

In this chapter we will first describe the methodology and context of the study, and a general conceptual framework. This is followed by the problem statement, the research questions and a description of the relevance of the work. The chapter ends with an overview of the studies included in the dissertation.

1.1 Methodology and context

In the first studies of this dissertation we have followed the design research approach described by Gravemeijer and Cobb (2006), a cyclic research approach that uses macro-cycles consisting of a preparation phase, a classroom experiment, and a retrospective evaluation. We have chosen this approach, because design research informed by learning theories has provided a way to increase our understanding of learning and instructional processes in the sciences, and at the same time a way to improve educational practice (Leach & Scott, 2008). A key element in design research is the creation of innovative instruction, taking into account the complexity of educational settings and including amongst others the material means to support learning, student tasks, classroom discourse and classroom norms (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). The instruction has not been an end in itself, but has provided an experimental setting enabling us to study aspects of learning and their relation with instruction.

A potentially effective way to innovate in education is to involve practicing teachers in educational design, the more so if the innovation is related to teachers' concerns about student learning (Voogt et al., 2011). Therefore, physics teachers and the author of the dissertation, partly assisted by a teacher educator, collaboratively designed the instruction. The instruction was enacted in grade 9 (age 14) classrooms of the pre-university stream[1] of secondary schooling in the southeastern part of the Netherlands.

Two cycles of design research were carried out. The context of the first cycle was a professional development project for secondary school science teachers, in which three schools and a teacher education institute were involved. In this context one physics teacher expressed the need to improve his grade 9 students' understandings of direct current (dc) electricity. Dc electricity was then chosen as a topic for the design studies. This topic was considered suitable, because of its theoretical content and because it potentially allowed students to build an understanding of phenomena through authentic processes in physics, such as practical investigations and theoretical explanations.

The second design cycle built on the first, so the topic of dc electricity was not changed. In this cycle collaboration took place with three physics teachers who were completing a physics education M.Ed. program at the teacher education institute where the author of the dissertation was employed. Lessons were designed collaboratively, but in both design cycles the teachers remained responsible for details of the lesson preparation and enactment.

The last study of the dissertation was a textbook study on the use of models. Criteria were derived from the literature and applied to pre-university physics textbook series commonly used in schools in the Netherlands.

1.2 Conceptual framework

Physics education in line with NOS lets students experience processes of scientific inquiry in which they create knowledge, in other words experience "science in the making" (Latour, 1987). Some researchers in education have aimed at genuine scientific research or inquiry in real-life contexts to let students experience a scientific culture. Gravemeijer and Cobb (2006), working in mathematics education, have suggested that genuine scientific research is not required, but that the context needs to be experientially real to the students, meaning that it provides a setting for students to act and reason sensibly. This approach has been in line with the claim by Hung and Chen (2007) that students can experience key aspects of a scientific culture in science education through meaningful simulation in the classroom. A traditional classroom culture based on the transmission of knowledge, in which students play a relatively receptive role, does not let students experience scientific

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[1] In the Netherlands, three different streams of secondary schooling exist. Students are streamed based on ability at the end of primary school, usually at the age of 12. The pre-university stream is a six year course providing access to university education.

processes. Instead, a classroom culture is required to promote active involvement of students in science inquiry activities (Cobb & Yackel, 1998). Specific measures are necessary to help students understand theoretical concepts in such a classroom culture.

In this section we briefly review conceptual learning in the sciences, the meaning of a culture of inquiry in the classroom, and research on student understanding of electric circuits.

1.2.1 Conceptual learning in the sciences

Broadly speaking, (a) an individual, and (b) a collective perspective can be distinguished to explain student learning in the sciences. Considering (a), the perspective which describes learning as a process of conceptual change takes the individual as the unit of analysis and places the emphasis foremost on cognitive issues (Treagust & Duit, 2008), although the importance of social processes and of non-cognitive factors in the learning context is generally acknowledged (Pintrich, Marx, & Boyle, 1993). The question in education is how students, starting from their initial conceptions, can be guided to come to an understanding of the scientific concepts of the domain. Classroom activities and instruction are based on an analysis of subject content and on the content-related ideas students bring to the classroom (Leach & Scott, 2002).

Considering (b), sociocultural (Vygotsky, 1978) and cultural historical (Engeström, 1987) perspectives on learning take the collective as a unit of analysis. Scientific concepts come into existence through historical processes in collective cultural activities. These concepts, which derive their meanings from their historical genesis and specific use (Wells, 2008) are the mental equivalents of material tools. Inherent in the cultural use of scientific concepts are the epistemology, conventions, norms and values of the community in which the concepts are used. This suggests that the learning of scientific concepts best takes place when a relevant cultural context is made available to the students (Driver, Asoko, Leach, Mortimer, & Scott, 1994). A relevant culture for science lessons in which students attempt to understand theoretical concepts in relation to phenomena is a culture showing essential characteristics of a scientific research community (Cobb & Yackel, 1998).

The individual conceptual change perspective has to be coordinated with the sociocultural perspective, which views learning as participating in a community of practice. This is likely to lead to a well-balanced curriculum taking into account the complex learning processes in science classrooms (Leach & Scott, 2008; Sfard, 1998; Vosniadou, 2007). In this dissertation we use the interpretative framework of Cobb and Yackel (1996), based on design research studies in mathematics classes. In their framework the sociocultural and individual perspectives are complementary: classroom social norms, shared classroom practices and individual student conceptual understanding are reflexively related.

1.2.2 A culture of Inquiry

There is no consensus among scientists, philosophers of science, and educators on what values and beliefs might be underlying the development of scientific knowledge (Alters, 1997; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). However, there is reasonable consensus on the NOS themes relevant to secondary school students. Osborne et al. (2003) have listed nine consensus themes based on a Delphi study. The list (see Table 1.1) contains items related to scientific processes and items related to scientific epistemology. Abd-El-Khalick, Waters, and Le (2008) have compiled a list of NOS aspects which partly overlaps with the themes identified by Osborne et al. (2003), but is mostly epistemologically oriented. Helping students understand NOS requires explicit focus on NOS during instruction (Abd-El-Khalick et al., 2008) and some authors claim this may best take place through student participation in scientific processes (Duschl & Grandy, 2013).

The purpose of the instruction in our studies has not been to help students understand the themes of NOS explicitly, but rather to allow students to experience "science in the making" as expressed by the themes. Therefore, the NOS themes needed to be translated into classroom activities. We used the NOS themes identified by Osborne et al. (2003) to guide and evaluate inquiry-based instruction, because of their process emphasis. Table 1.1 shows how these NOS themes were described and interpreted to create a culture of inquiry in science classroom. This classroom interpretation of the NOS themes was compiled in full after the evaluation of the first design cycle. Not all parts of the classroom interpretation were included in the design of the first cycle (chapter 2). This applied in particular to the provision of a theoretical starting point.

The classroom interpretation of the NOS themes overlaps with essential characteristics of inquiry instruction (Minner, Levy, & Century, 2010): inquiry instruction engages students with scientific phenomena, either directly or through secondary sources; it emphasizes active thinking and student responsibility for learning; it emphasizes student motivation (for example by building on student interest, curiosity, involvement or focus); and it uses at least some part of an investigation cycle.

Table 1.1

Main NOS themes and their classroom interpretation.

NOS theme	Description	Classroom interpretation
1. Scientific method and critical testing	In science ideas are tested by experiments.	Experiments guided by research questions. Discussion of theoretical expectations before experimentation.
2. Creativity	Science is a creative process (for example, theories and models are created and used to explain phenomena).	Student opportunities to understand, explain and predict phenomena, and to use, discuss and expand models (e.g. computer simulations).
3. Historical development of scientific knowledge	Scientific knowledge develops over time.	Student opportunities to contribute their ideas, also if incorrect. Gradually developing a more sophisticated view on the topic.
4. Science and questioning	Curiosity and questioning are driving forces of scientific development.	Encouragement for students to ask questions and respond to each other. Use of questions to guide experiments.
5. Diversity of scientific thinking	There is diversity in the ways the world might be explored.	A variety of theoretical and experimental tasks. Use of different models and metaphors, and explanation of their roles.
6. Analysis and interpretation of data	Data need to be analyzed and interpreted.	Students discuss their experimental findings in the light of theoretical models.
7. Science and certainty	Scientific knowledge exists at different levels of certainty and may be subject to change based on evidence and interpretation.	Interpretation of evidence on the basis of models and theories.
8. Hypothesis and prediction	Science uses hypotheses and predictions based on theories.	Provision of a theoretical basis on which to base hypotheses and predictions.
9. Cooperation and collaboration in the development of scientific knowledge	Science is a social process (involving cooperation and collaboration, but also discussion, disagreement and criticism).	Student cooperation by working in groups. Teacher led whole class discussions to share ideas and reach consensus.

The teacher needs to provide suitable guidance to the students to enable successful learning (Kirschner, Sweller, & Clark, 2006). In a classroom community of practice this guidance is not only directed to content knowledge but also to norms and practices of the subject culture (Collins, Brown, & Holum, 1991). Cobb and Yackel (1996) have argued that new classroom social norms (students' and teacher's beliefs about their roles and the types of classroom activities) and subject social norms (subject-specific beliefs and values) can be established, but need to be explicitly negotiated. An important step towards creating a new classroom culture is for the teacher to encourage students to share their ideas, by appreciating student contributions as valuable to the scientific process whether or not they corresponded to scientifically accepted ideas (Cobb & Yackel, 1996). The teacher has to make sure then that the ideas become topic of discussions and investigations, in order to help students develop a scientifically acceptable understanding. Other aspects of the teacher's role include exemplifying and explicating scientific values and norms of evidence and argumentation, scaffolding student groups, and introducing material and mental tools of the discipline.

1.3 Conceptual understanding in direct current electricity

Student inquiry activities need to be carefully prepared to enable students to develop the desired conceptual understanding. Anticipating how students will come to construct understanding requires a theory of how relevant learning processes might evolve and of how these learning processes might be evoked and fostered. Thus, instructional activities have to be created as part of a *conjectured local instruction theory* (Gravemeijer & Cobb, 2006): a sequence of "instructional activities, and a conjectured learning process that anticipates how students' thinking and understanding might evolve when the instructional activities are employed in the classroom". The instruction theory is *local* in the sense that it is related to the chosen topic rather than to the domain of science learning in general.

The design of instructional activities in this dissertation was informed by the research literature on student ideas in direct current electric circuits. Students' ideas on this topic often do not correspond to the scientific view and do not easily change through instruction (Duit & Von Rhoeneck, 1998; Engelhardt & Beichner, 2004; Shipstone, 1985; Taber, de Trafford, & Quail, 2006). Student ideas can be idiosyncratic, whilst some common alternative conceptions can also be identified. For example, students who try to solve problems or explain phenomena in direct current circuits, frequently (a) confuse important concepts such as current and voltage; (b) use the idea that current is consumed (or other alternative conceptions of electric current, such as unipolar, clashing or shared current); (c) view power supplies as a source of constant current instead of constant potential difference; (d) have difficulties building and drawing circuits; and (e) do not realize that a change of one element can have an impact on the current in the whole circuit. In terms of physics content the aims of the subsequent local instruction theories of this dissertation were to address students' alternative conceptions and help students build a scientifically acceptable understanding of electric circuits, which would enable them to predict the relative brightness of light bulbs as well as currents and voltages in simple direct current serial and parallel circuits.

1.4 Problem statement and research questions

Physics education in agreement with NOS, such as inquiry in the classroom, is one of the innovative educational approaches that have shown potential for making physics more accessible to students. The approach requires the establishment of classroom social norms analogous to a scientific research tradition (Cobb & Yackel, 1998). It is not self-evident that instruction in agreement with NOS leads to conceptual understanding and not all variations of this type of instruction have been equally effective in promoting understanding (Minner et al., 2010). A wealth of research has indicated that understanding theoretical concepts is notoriously difficult for students (Duit, 2009). Instruction for conceptual understanding has been based on an analysis of subject content and student ideas. However, approaches based on individual conceptual change have had limited success in practical classroom situations. The more recent tendency in the conceptual change research community has been to take a multidimensional perspective on science teaching and learning, in which the importance of affective and social processes is recognized (Duit, Treagust, & Widodo, 2013). It may be fruitful to view perspectives emphasizing classroom norms and perspectives emphasizing individual conceptual change as complementary. Design research with the aim to understand learning processes is then a methodology of choice. Therefore, the overall research question of this dissertation was:

How can physics education be designed and enacted in such a way that it is in agreement with the Nature of Science (NOS) and fosters conceptual understanding in electricity?

This question was studied from three perspectives: (a) instruction and student learning in the classroom, (b) teacher learning and professionalization, and (c) the support provided by the textbook. For each perspective corresponding research questions were formulated.

1.4.1 Instruction and student learning in the classroom

The first study, which focused on instruction and student learning, started with the intention to develop a local instruction theory. However, due to the apparent lack of success of the conjectured local instruction theory in this study, it became important to understand the more general characteristics of instruction that helps students construct conceptual scientific knowledge via a process of scientific inquiry. The research question was adapted to reflect the change of focus:

1. Which inherent characteristics of inquiry-based instruction complicate the process of constructing conceptual understanding?

The second study used an instructional design in which we incorporated what had been learnt during the first study. The research questions were:

2. How effective was the enacted instructional design in terms of the conceptual learning aims of the Grade 9 lessons about electric circuits?
3. How do the learning arrangement characteristics help explain the development of Grade 9 students' conceptual understanding in the inquiry classroom?

1.4.2 Teacher learning and professionalization

The participation of teachers in the second study could be considered as participation in a professional development intervention. To understand how this participation gave rise to teacher learning, we posed the following research questions:

4. What learning did the teachers report after participation in the collaborative lesson design and enactment?
5. To what extent did the teachers change their classroom practice?
6. How can the reported learning and the teachers' classroom practice be related to participation in the professional development process?

1.4.3 Support provided by the textbook

The second design study led to questions about the theoretical support provided to the students, particularly about the provision of a basic theoretical model to foster learning in agreement with NOS. To explore these questions, criteria for the provision of a theoretical model to foster learning in agreement with NOS were formulated based on the literature and applied to commonly used physics textbooks. The study was guided by the following research question:

7. 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 the literature?

1.5 Relevance

The relevance of the studies presented in this dissertation is both theoretical and practical. The chosen form of design research aims at creating innovative learning arrangements which allow for the development of a local instruction theory and for deepening the understanding of the student learning processes in innovative settings (Gravemeijer & Cobb, 2006). Theoretical insights with regard to instructional sequences and understanding learning processes can be developed in such a design study by making a qualitative analysis of the available data, combining various types of data and analytical techniques. It is likely that a tested local instruction theory can contribute to the development of a domain-specific instruction theory, after a series of design research projects such as the one presented in this dissertation. The practical significance lies in the fact that the instruction theory may advise and support teachers who intend to create similar innovative learning arrangements in their classrooms.

From a theoretical point of view, the first study provides insight into some general characteristics of instruction aimed at helping students construct conceptual scientific knowledge via a process of scientific inquiry. The second design study builds upon the first, providing a local instruction theory on dc electric circuits, and contributes to our understanding of how designing instruction that pairs a culture of inquiry to fostering conceptual understanding can work in the classroom.

Innovative education is not possible without teachers learning how to arrange and orchestrate the corresponding learning environment. Therefore, it is relevant to study the learning of the participating teachers. Many guidelines exist regarding the characteristics of successful professional development interventions (Borko, 2004; Van Veen, Zwart, Meirink, & Verloop, 2010). The intervention described in this dissertation was designed with the aim to incorporate relevant guidelines. The cases we have described provide insight into the effectiveness of these guidelines and the extent to which the teacher learning became visible to the students.

Finally, textbooks will need to support science education in line with NOS, because the textbook is an important source for teachers and students. The contribution of this dissertation consists of a set of criteria compiled from literature to evaluate textbook content in this regard. First insights into the ways recent textbooks support education in line with NOS have been obtained by applying the criteria to a series of commonly used physics textbooks.

In terms of practical relevance, the general characteristics of inquiry-based physics education and the local instruction theory may support teachers and teacher educators when they strive for innovative inquiry-oriented instruction. The criteria to evaluate textbooks developed in this dissertation are relevant to those creating and evaluating physics textbooks, be it textbook authors, teachers, and teacher educators.

1.6 Overview of the dissertation

The dissertation consists of six chapters. Chapter 2 addresses research question 1 and describes a first cycle of design research consisting of a preparation phase, classroom experiments and a retrospective evaluation. In cooperation with a secondary school physics teacher, lessons on dc electric circuits were designed and enacted by the teacher in his grade 9 classroom. Data were collected from various sources, such as audio and video recordings, a conceptual test, student work and field notes. From the analysis we have developed insights into the inherent characteristics of instruction aimed at helping students construct conceptual scientific knowledge via scientific inquiry.

Chapter 3 addresses research questions 2 and 3. It reports on a second design research cycle, in which the outcomes of the first cycle were incorporated. Lessons on dc electric circuits were designed in cooperation with three secondary school physics teachers for their grade 9 classes. The chapter reports on the data collected and analyzed during the enactment of the lessons in the classroom of one teacher. The study used similar methods of data collection and analysis as in the first design research cycle. The retrospective analysis has indicated how the enactment of the local instruction theory and the development of classroom norms of inquiry led to the expected learning processes and increased student conceptual understanding.

Teachers need to develop professionally in order to acquire the knowledge, skills and attitudes necessary to understand and enact innovative education. Therefore, chapter 4 addresses research questions 4, 5 and 6 and focuses on the learning of the three teachers who participated in the second design cycle. The teachers' participation in the design and enactment of lessons in a context of classroom inquiry has been described as participation in a professional development intervention. The three teachers have been described as separate cases and common themes among the three cases have been identified and discussed. The results of the study have shed light on some of the underlying mechanisms relevant for this type of interventions.

The design cycles gave rise to questions about the support given to students by the learning materials, in particular about the support in the form of a basic model as a theoretical starting point for inquiry activities. The way such a model is presented to students should afford conceptual and experimental inquiry activities and should respect insights from NOS. Generally, the main source of scientific models in the classroom, both for the students and the teacher, is the textbook. We have studied the ways models of electricity were presented and used in commonly used physics textbooks. Criteria to evaluate models in physics textbooks were operationalized from an interpretation of literature on models and modeling in science and science education. These criteria were used to evaluate the models of electricity in a set of grade 7 to 12 physics textbooks in the Netherlands. Chapter 5 describes this study, which addresses research question 7.

Chapter 6 summarizes and discusses the main findings and conclusions of the studies. It suggests directions for future research, indicates limitations and describes implications for educational practice.

Chapters 2, 3 and 5 have been written as articles for scientific research journals. Chapter 4 has been written as a chapter in an edited book. Each of these chapters can be read independently. Therefore, there is overlap in the theoretical framework and methodological sections of these chapters.

CHAPTER 2 SOME KEY ISSUES IN CREATING INQUIRY-BASED INSTRUCTIONAL PRACTICES THAT AIM AT THE UNDERSTANDING OF SIMPLE ELECTRIC CIRCUITS[2]

Abstract. Many students in secondary schools consider the sciences difficult and unattractive. This applies to physics in particular, a subject in which students attempt to learn and understand numerous theoretical concepts, often without much success. A case in point is the understanding of the concepts current, voltage and resistance in simple electric circuits. In response to these problems, reform initiatives in education strive for a change of the classroom culture, putting emphasis on more authentic contexts and student activities containing elements of inquiry. The challenge then becomes choosing and combining these elements in such a manner that they foster an understanding of theoretical concepts. In this chapter we reflect on data collected and analyzed from a series of 12 grade 9 physics lesson on simple electric circuits. Drawing from a theoretical framework based on individual (conceptual change based) and socio-cultural views on learning, instruction was designed addressing known conceptual problems and attempting to create a physics (research) culture in the classroom. As the success of the lessons was limited, the focus of the study became to understand which inherent characteristics of inquiry-based instruction complicate the process of constructing conceptual understanding.

From the analysis of the data collected during the enactment of the lessons three tensions emerged: the tension between open inquiry and student guidance, the tension between students developing their own ideas and getting to know accepted scientific theories, and the tension between fostering scientific interest as part of a scientific research culture and the task oriented school culture. An outlook will be given on the implications for science lessons.

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[2] This chapter has been published as:
Kock, Z.-J., Taconis, R., Bolhuis, S., & Gravemeijer, K. (2013). Some key issues in creating inquiry-based instructional practices that aim at the understanding of simple electric circuits. *Research in Science Education, 43*(2), 579-597. doi: 10.1007/s11165-011-9278-6

2.1 Introduction

International comparative studies, such as ROSE and PISA, indicate that most students at secondary schools have a positive attitude towards science and technology in general, but a far less positive attitude towards the sciences as school subjects (OECD, 2007; Sjøberg & Schreiner, 2005). In various countries the numbers of students choosing science subjects in tertiary education have shown a relative decrease (OECD, 2006). This has raised concern, as governments strive for a scientifically and technically educated workforce as a condition for their countries to remain innovative and globally competitive in an increasingly knowledge-based economy. In response, for example the European Union and organizations in the USA expressed ambitions to increase the number of mathematics, science and technology graduates (Business Roundtable, 2005; European Union, 2003). Moreover, scientific literacy is considered not only of economic value, but also of cultural importance for individuals in a scientifically and technologically oriented world (Laugksch, 2000).

Of the school sciences, particularly physics is perceived as a difficult and unattractive subject by the students (Taconis & Kessels, 2009). Prototypical for the difficulty of physics is the lack of success many students experience when trying to understand theoretical concepts (such as “force”, “acceleration”, “voltage”). Theoretical concepts in physics cannot be simply understood by themselves in observable terms (Carnap, 1966). Rather, theoretical concepts are invisible constructs related to other concepts in models describing part of physical reality. They are thus embedded in a body of knowledge that cannot be separated from scientific discourse and practices. To understand their meaning students need to familiarize themselves with relevant epistemology, scientific skills and activities, language, symbols, scientific norms and values, which are defining elements of a culture (Phelan, Davidson, & Cao, 1991). In our interpretation this implies that increasing conceptual understanding cannot be separated from increasing students’ familiarization with the culture of the domain. However, becoming familiar with a culture of science is problematic for most students (Aikenhead, 1996). Fostering a culture of science at school can only be successful if it takes place with respect for students, their identities, and world views (Krogh & Thomsen, 2005).

Reform efforts to reduce the difficulty and unattractiveness of the school sciences usually aim at a change of the classroom culture. Ideally, a classroom culture is created in which learning takes place primarily through social activities of the learners, often cooperatively and in contexts that are authentic, that is, bear resemblance to the activities of scientists in professional, academic or life-world situations (Gilbert, 2006; Roth, Van Eijck, Reis, & Hsu, 2008; Wenger, 1998). Science education is then seen as a process in which students gradually get acquainted with scientific norms and culture (Brown et al., 1989;

Duit & Treagust, 1998; Lemke, 2001). In this perspective on learning as participation (Sfard, 1998), theoretical concepts are considered cognitive tools students learn to use in authentic activities.

Insight into the motives, activities, norms, values and epistemology of scientists and physicists is provided by research into the Nature of Science (NOS) (such as Osborne et al., 2003; J. Park et al., 2009) and sociological or anthropological studies of science (Latour, 1987; Traweek, 1988). In a Delphi study, Osborne et al. (2003) found nine NOS themes important for inclusion in the school science curriculum. Among these themes were human questioning and curiosity as a basic motive of science, a perception of the gradual historical development of knowledge, critical empirical testing of hypotheses, and cooperation and collaboration among scientists.

At present, students in most science courses are confronted with the *results* of scientific work, or in the words of Latour (1987), with “ready-made science”. However, familiarization with the culture of science requires students also to experience processes of scientific inquiry in which they create knowledge, in other words experience “science in the making” (Latour, 1987). In a classroom context with a focus on understanding theoretical concepts, this does not mean students are expected to carry out authentic scientific work, but rather a meaningful simulation of scientific practices (Hung & Chen, 2007). A traditional classroom culture based only on the transmission of knowledge, in which students play a receptive role, will not let students experience “science in the making”. A change of the classroom culture is required leading to active involvement of students in authentic science activities.

It is not self-evident that students working in such simulated authentic practices build an understanding of theoretical concepts. Teaching for conceptual understanding should on the one hand include social processes of knowledge building, and on the other hand introduce the subject matter through a curriculum, designed to address the cognitive issues related to students’ conceptual development (Vosniadou, 2007). The challenge then becomes creating instruction in which a classroom culture is fostered, that allows students to experience “science in the making”, in combination with a curriculum that helps students develop conceptual understanding.

This chapter describes a study in which an effort was made to create this type of instruction in a series of physics lessons. The first author and a secondary school physics teacher cooperatively designed a local instruction theory, a sequence of “instructional activities, and a conjectured learning process that anticipates how students’ thinking and understanding might evolve when the instructional activities are employed in the classroom” (Gravemeijer & Cobb, 2006). The instruction theory is “local” in the sense that it is related to the chosen topic rather than to the domain of science learning in general. The teacher remained responsible for details of the lesson preparation and enactment. We expected this cooperation to be more effective than a top-down approach in which materials and instruction would be designed and given to schools to implement (Fullan, 2001; Van Driel, Verloop, Van Werven, & Dekkers, 1997).

The theoretical concepts dealt with in the physics lessons were the concepts current, voltage and resistance in simple electric circuits. The topic was suggested by the teacher as he felt the need to improve his students' understanding of electricity. We considered this topic suitable because of its theoretical content and because it potentially allowed students to build an understanding of phenomena through authentic processes in physics, such as practical investigations and theoretical explanations.

Conceptual problems in electricity have been widely documented: in Duit's well-known STCSE bibliography on students' conceptions and conceptual change (Duit, 2009), several hundreds of publications are listed on learning electricity, starting in the 80's (for example Shipstone, 1985). Over the years remedies have been suggested to overcome students' conceptual problems in electricity, but only with limited success (Mulhall, McKittrick, & Gunstone, 2001) and the topic is still receiving attention (for example Duit & Schecker, 2007; Engelhardt & Beichner, 2004; Hart, 2008; Taber et al., 2006). Coming to grips with the scientific concepts in electricity requires an understanding of the physics involved, which is at least partly at odds with the everyday experiences and ways of speaking about electricity (Duit & Schecker, 2007). We used the educational research literature on simple electric circuits to inform the design of the local instruction theory.

2.2 Aim of the Study

This study is part of a design research project in which lessons are developed combining elements from conceptual change and socio-cultural perspectives on science learning. We started out with the intention to develop a local instruction theory for learning about simple electric circuits in the context of scientific inquiry. Such a local instruction theory would encompass theories about the learning process and about the means of supporting that process. However, during the research the focus shifted from developing a local instruction theory to coming to understand the more general characteristics of instruction aimed at helping students construct conceptual scientific knowledge via a process of scientific inquiry. The reason for this shift was the apparent lack of success of our conjectured local instruction theory. We inferred there had to be some fundamental mechanisms that complicated this kind of instruction and for which the lessons in this study can be considered a paradigmatic case (Cobb & Gravemeijer, 2008). Thus, in the retrospective data analysis our research question evolved to: *which inherent characteristics* *of inquiry-based instruction complicate the process of constructing conceptual understanding?*

2.3 From Theory to Lessons

2.3.1 Design research

We chose design research in this study, because design research informed by learning theories provides a way to improve instruction in the sciences and to improve understanding about learning and instructional processes (Leach & Scott, 2008). A key element in design research is the creation of innovative instruction, taking into account the complexity of educational settings and including amongst others the material means to support learning, student tasks, classroom discourse and classroom norms (Cobb et al., 2003). Innovative instruction may be a goal in itself, but also, as in our case it may function as an experimental setting in which one can study certain aspects of learning and instructional processes.

We followed the approach described by Gravemeijer and Cobb (2006), which consists of a cyclic succession of a preparation phase, classroom experiments and a retrospective evaluation. The preparation phase involves establishing learning goals, starting points of instruction and a conjectured local instruction theory. In the experimental phase, a teacher enacts the lessons while data are collected. This phase can be described as an iterative process of testing and improving instruction. In the retrospective evaluation phase, data collected from the various sources are analyzed to obtain a greater understanding of the learning process and factors influencing this process. In the course of this study our focus was drawn to the more general issues related to this type of instruction, so our emphasis was on what could be learned from the retrospective evaluation rather than on cyclic improvements of the local instruction theory.

The instruction in this study was designed collaboratively by a physics teacher in the pre-university stream of a secondary school in the Netherlands and the first author, assisted by a teacher trainer, the second author. This collaboration was part of a professional development project, in which science teachers from three secondary schools and a teacher training institute were involved. The teacher had about twenty years of experience in an industrial research laboratory of an electronics company and four years of experience as a physics teacher. Four meetings took place within the framework of the professional development project. These meetings were used to develop a common vision on the desired classroom culture of inquiry. In two separate meetings and through e-mail contact the first author and the physics teacher drew up the conjectured local instruction theory, which formed the basis of the lesson sequence.

2.3.2 Understanding learning processes

Broadly, an individual and a collective perspective can be distinguished to explain student learning in the sciences. In the perspective which describes learning as a process of conceptual change, the unit of analysis is the individual and the emphasis is foremost on cognitive issues (Treagust & Duit, 2008). The question in education is how students, starting from their initial conceptions, can be guided to come to an understanding of the scientific concepts of the domain.

Sociocultural (Vygotsky, 1978) and cultural historical (Engeström, 1987) perspectives on learning take the collective as a unit of analysis. Scientific concepts come into existence through historical processes in collective activities taking place in human cultures. In these activities scientific concepts, which derive their meaning from their historical genesis and specific use (Wells, 2008) are the mental equivalent of material tools. Inherent in the cultural use of scientific concepts are the epistemology, conventions, norms and values of the community in which the concepts are used. This suggests that the learning of scientific concepts best takes place when a relevant cultural context is made available to the students (Driver et al., 1994). A relevant culture for science lessons in which students use theoretical concepts to explain and predict phenomena is a culture showing essential characteristics of a scientific research community (Cobb & Yackel, 1998).

Several authors pointed out that coordination of the individual and the collective perspectives on learning is essential to understand the complex learning processes taking place in science classrooms (Leach & Scott, 2008; Sfard, 1998; Vosniadou, 2007). In this study we use the interpretative framework of Cobb and Yackel (1996), based on design research studies in mathematics classes: the socio-cultural and individual perspectives are complementary and classroom culture, shared classroom practices and student conceptual understanding are interactively related.

2.3.3 Establishing a culture of inquiry

In line with sociocultural perspectives on learning, our aim was to create a community of practice (Lave & Wenger, 1991) in the classroom, in which essential processes of scientific research communities would be present: being curious and asking questions, interpreting phenomena, making predictions, experimenting, collaborating, communicating results, discussing evidence and reaching common conclusions (Osborne et al., 2003). In order to create the corresponding classroom culture of inquiry we chose as core elements of the lessons collaborative group work in which students worked on investigative tasks and teacher-led whole class discussions, in which results were presented and discussed, conclusions reached and new questions formulated. This approach has been used in open-ended inquiry lessons in science (Roth & Bowen, 1995), and, in a more structured way, in mathematics classrooms with the aim to help students understand theoretical concepts of the domain (Cobb & Whitenack, 1996).

The investigative activities had an open nature, but were arranged with the purpose to address students' alternative conceptions and create opportunities for them to develop scientific understanding. Students did not receive recipe-type experimental procedures, but were responsible for the details of their investigations. Presentations of results by students to the class and teacher led class discussions were expected be crucial, because student groups would reach different and perhaps paradoxical results they could not interpret without help. In these discussions the class could come to common conclusions and student ideas could serve as a starting point for further investigations. We expected a sense of student ownership (Collins et al., 1991) would be fostered by the increased student responsibility, the efforts invested by student in their investigations, and the possibility of each group to contribute with their findings to knowledge building in the class. This sense of ownership was expected to contribute to student motivation and engagement.

For instruction to be successful, the teacher needs to provide sufficient guidance to the class (Kirschner et al., 2006). In a classroom community of practice this guidance is not only directed to content knowledge but also to norms and practices of the subject culture (Collins et al., 1991). Cobb and Yackel (1996) argue that new classroom social norms (students' and teacher's beliefs about their roles and the types of classroom activities) and subject social norms (subject specific beliefs and values) can be established, but need to be negotiated explicitly.

As an important step in creating a new classroom culture the teacher was to encourage students to share their ideas, by appreciating student contributions as valuable to the scientific process whether or not they corresponded to scientifically accepted ideas (Cobb & Yackel, 1996). However, to help students develop a scientific understanding the teacher had to make sure the ideas then became topic of discussions and investigations. Other aspects of the teacher's role included exemplifying and explicating scientific values and norms of evidence and argumentation, scaffolding student groups, and introducing material and mental tools (such as the ammeter, the distinction between serial and parallel circuits, different types of light bulbs, circuit symbols).

2.3.4 Conceptual problems in simple electric circuits

The design of instructional activities in this study was informed by the research literature on student ideas in direct current electric circuits. Students' ideas on this topic often do not correspond to the scientific view and do not easily change through instruction (Duit & Von Rhoeneck, 1998; Engelhardt & Beichner, 2004; Shipstone, 1985; Taber et al., 2006). When trying to solve problems or explain phenomena in direct current circuits, students frequently (a) confuse important concepts such as current and voltage, (b) use the idea that current is consumed (or use unipolar, clashing or shared current models), (c) view power supplies as a source of constant current instead of constant potential difference, (d) have difficulties building and drawing circuits and (e) do not realize that a change of one element can have an impact on the current in the whole circuit.

In terms of physics content the aims of the local instruction theory were to address students' preconceptions and help students build a scientifically acceptable understanding of electric circuits, which would enable them to predict the relative brightness of light bulbs as well as currents and voltages in simple serial and parallel circuits.

2.3.5 Overview of the lesson sequence

To provide a context for the presentation of the findings of this study, we give an outline of the local instruction theory, in terms of conceptual learning aims and activities. The learning activities should be understood in the context of the classroom culture we aimed for: a culture of inquiry in which curiosity, questioning and the sharing of ideas would be prevalent.

At the start of the lesson series the teacher expressed the aim of the lesson series for the class as a scientific motive: to develop an understanding of the phenomena in simple electric circuits with light bulbs. He then explained the way of working, student products and the assessment of the unit. After that introduction, content related activities had been planned as follows:

1. Activities with the purpose to help students appreciate that electric charge flows in an electric circuit (lesson 1). We expected that the notion of "something" flowing in an electric circuit corresponded to most students' beliefs prior to instruction (Shipstone, 1985) and that this could be made explicit by a demonstration, explanation and discussion of electrostatic phenomena.

2. Activities with the purpose to increase students' skills in drawing and building simple electric circuits and to make students aware that the brightness of light bulbs depends on the

structure of the circuit, such as the serial or parallel arrangement of the light bulbs (lessons 2 and 3). The tasks for student groups consisted of designing and building different circuits with light bulbs and to observe patterns in the brightness of the light bulbs. We expected that initially the teacher would need to assist student groups in drawing and building these circuits. In a class discussion the teacher would have to make the relation between brightness and structure of the electric circuit explicit. Building and drawing electric circuits was part of the activities in the majority of lessons.

3. Activities with the purpose to make student ideas explicit about the flow of electric current in relation to the brightness of light bulbs in different circuits (lessons 4 and 5). Student ideas about this were expected to generally correspond to the well-known alternative conceptions such as the 'current used up' model, but idiosyncratic accounts could be expected as well. A teacher led class discussion was expected to help students appreciate that an answer could be determined by measuring the current in different places in a circuit.

4. Activities with the purpose to make students aware that the brightness of a light bulb is related to the current passing through that light bulb, that current is the same everywhere in a serial circuit and that in a parallel circuit the currents in the branches adds up to a total current (lessons 5 - 7). Measurements using ammeters were expected to help students appreciate that a higher current through a light bulb is associated with a higher brightness. Tasks in which students were asked to measure electrical currents on several places in serial, parallel and combined circuits were expected to help students discover the rules for currents in these circuits. In class discussions the observation that current in a serial circuit depends on the number of light bulbs in series was to be related to an understanding that the thin, coiled filament in the light bulb causes resistance to the flow of current.

5. Activities with the purpose to help students understand that an additional concept, voltage, is associated with differences in brightness in case the same current is passing through two differently rated light bulbs (lesson 7). We expected that observing and analyzing the situation of two differently rated light bulbs in series would help students appreciate the need for an additional concept, which can be distinguished from electric current. We expected the concept of voltage would need to be introduced by the teacher and related to the extent, to which the charge is "pushed" through the circuit. Measurements using voltmeters were expected to help students observe that for two different light bulbs carrying the same current, a higher voltage across the light bulb corresponds to a higher brightness of the light bulb.

6. Activities with the purpose to make students aware that voltage is the same across parallel branches in a circuit, while potential differences across light bulbs in a series circuit add up to the total voltage across a series branch (lessons 8 – 10). Tasks in which students were asked to measure voltages across power supplies, light bulbs and branches in serial, parallel and combined circuits were expected to help students discover the rules for voltages in these circuits.

7. Activities with the purpose to help students better distinguish the concepts of current and voltage (lessons 11 and 12). Tasks in which students were asked to investigate the effect of both current and voltage on the brightness of different light bulbs in a parallel and a serial circuit were expected help students appreciate that voltage and current are different, but connected concepts.

2.4 Research setting and data

2.4.1 Instructional context

The lessons were enacted in a school in the southeastern part of the Netherlands in the urbanized countryside in the period March-April 2009. The school has a student population of 1100, mainly with a Dutch background.

The grade 9 experimental class consisted of 26 students, 11 girls and 15 boys, 14/15 years old. The teacher described it as a “difficult class”, showing little interest in physics, an obligatory subject in grade 9. The students, now in their second year of a physics curriculum, had not studied the topic of electricity before. An initial lesson observation and teacher interview in November 2008 made clear that a typical physics lesson in this class consisted of teacher explanations and subsequent individual student work on textbook problems. Both students and teacher indicated there were few occasions for collaborative group work and practical work. The experimental approach, in which student groups were actively involved in inquiry activities, was new for the class.

In terms of physics content, the learning aims of the experimental lesson sequence were part of the grade 9 physics curriculum as articulated by the physics textbook in use at the school.

2.4.2 Enactment, data collection and analysis

The teacher enacted the lessons in the presence of the first author. Students worked in six mixed-ability groups of four or five boys and girls created by the teacher. Students kept workbooks in which they wrote down their investigations, findings and the common conclusions reached by the class as a whole. The workbooks were assessed by the teacher with respect to evidence of participation and completeness.

After each lesson the teacher and the first author discussed their observations and made amendments to the sequence of activities, for example if expected learning outcomes had not been realized.

The data collection for the study was planned to enable the development of a local instruction theory. Thus, data was needed from various sources in order to analyze the instruction as it took place, students' responses to the instruction and learning outcomes. In line with the suggestions by Gravemeijer and Cobb (2006), all lessons were video recorded and audio recordings were made of the teacher and his interaction with students and of the discussions after each lessons between the teacher and researcher. These audio recordings were transcribed. In addition, we collected all student work books and the researcher's field notes. Brief interviews were held with three randomly chosen students at the end of the lesson series. To assess conceptual understanding, students took a multiple choice conceptual test one day after the last lesson. The test consisted of 20 questions translated from version 1.0 of the DIRECT concept test on resistive electric circuits (Engelhardt & Beichner, 2004).

The retrospective data analysis followed the two-step procedure described by Cobb and Whitenack (1996), based on grounded theory (Glaser & Strauss, 1967): the first step aimed at identifying patterns emerging from the data. These patterns first became apparent from the observations of the lessons and a first examination of the data. We described them as conjectures about the dataset, and subsequently examined the entire body of data to look for confirmations or refutations of these conjectures. This first step of the analysis resulted in a number of conjectures supported by evidence from the data.

The second step was directed at finding explanations for the patterns found in the first step. Here we aimed for descriptions of possible causal mechanisms and processes (Maxwell, 2004). This approach was interpretative in character and led to plausible explanations for our findings[3].

The explanations were again expressed as conjectures and the data were examined looking for confirmations and refutations. From this analysis three tensions emerged related to the inherent characteristics of instruction aimed at helping students construct conceptual scientific knowledge via a process of scientific inquiry.

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[3] The final test of these explanations is beyond the scope of this study: it will consist of lessons amended in line with the explanations in a second cycle of design research.

2.5 Findings

2.5.1 Patterns emerging from the data

Observation of the lessons and a first examination of the data gave the impression that for many students in the class learning had not taken place as anticipated. In this paragraph we describe the picture that emerged. The student investigations often did not lead to the anticipated results. Results obtained in experiments and scientific conclusions reached in discussions seemed not to have made a lasting impression on many students and often seemed forgotten in subsequent lessons. Student statements during class discussions consisted of scientifically accepted knowledge as well as alternative conceptions and observations made during the experiments. The number of scientifically correct contributions did not seem to increase relative to the alternative conceptions. Although student groups carried out the assigned tasks, student engagement was limited.

In order to verify whether our first impressions corresponded with what actually happened in the classroom we framed these first impressions as conjectures that could be tested on the data. In the examination of the data, the starting point was the lesson by lesson account given in the transcripts and we used the videos, field notes, workbooks, test results and interviews in conjunction with the transcripts. In our presentation of the findings the data sources other than the transcripts will be explicitly mentioned when they provided specific information about a conjecture. In the following sections we will examine the extent to which the impressions are confirmed or refuted by the data.

Conjecture 1: Investigations did not lead to the expected results. We analyzed the experimental inquiry activities, which took place in 8 of the 12 lessons. During these activities students made a number of valid observations. For example, in the third lesson group 1 found that the brightness of a light bulb does not depend on its distance to the power supply. In the fourth lesson group 2 found that adding light bulbs to a series circuit reduces the overall current in the circuit. Group 4 found that the current is the same on both sides of a light bulb. However, these examples were exceptions, as there were many instances where students carried out experiments, but did not obtain results that could be meaningfully interpreted. In line with our conjecture, student workbooks indicated that in 6 of the 8 experimental lessons at least half of the student groups did not obtain the expected results. In lesson 2 for example, only one group explicitly related the brightness of the light bulbs to the structure of the circuit. In lesson 7 only one group obtained meaningful measurements, but this group did not formulate conclusions or relate the results to theoretical ideas. In conclusion we can refine the conjecture to the extent that some meaningful results were obtained in the student investigations, but that the majority of investigations did not lead to the expected results.

Conjecture 2: Scientific conclusions reached in class discussions did not make a lasting impression. Parts of nine lessons were spent on class discussions with the purpose to reach shared common conclusions and a joint understanding of electric circuits. In some of these discussions conclusions were reached that were apparently accepted by the class. In contrast to our conjecture, they were referred to in later lessons or, in the case of rejected ideas, no longer played a role in explanations. For example, in the third lesson a group of students developed the idea that light bulbs would be brighter if they were closer to the power supply. This idea was investigated by another group during lesson 4 and subsequently rejected in a class discussion. After being mentioned as incorrect by a student in lessons 5 and 6 during group work, this idea was no longer referred to by any student. However, in line with our conjecture, other conclusions from class discussions were not adopted by many students. This applies to the idea that resistance determines the flow of current through a branch in a circuit, which was first brought up by a student in lesson 6 and then elaborated on by the teacher. The alternative idea that current 'wants to follow the shortest' or 'fastest' path in a circuit (possibly involuntarily introduced by the teacher in lesson 5) kept appearing in student utterances in later lessons. Likewise the idea of charge conservation was mentioned and applied by students on several occasions during class discussions, but 40% of the students did not use this idea in the final concept test. This observation is corroborated by the prevalence in the final concept test of other conceptual problems that had been topic of class discussions (see Table 2.1).

In terms of the conjecture we can conclude that a number of crucial conclusions from the class discussions were only used by a few students in subsequent lessons or in the final concept test.

Table 2.1

Conceptual Problems in Final Concept Test

Conceptual problem	Percentage of students
Use of consumed current model (2 questions)	40, 32
Errors with voltage in parallel circuits	56
Errors with current in parallel circuits	64
Errors with voltage in series circuits (2 questions)	60, 36
Errors concerning total resistance, respectively in parallel and series circuits	48, 60

Conjecture 3: Student statements throughout the lesson series remained a combination of scientifically accepted knowledge, alternative conceptions and experimental observations. During the first whole class discussion at the start of lesson 4 the class listed their findings based on the observation of light bulbs in different arrangements. Apart from describing observations students gave tentative explanations, prompted by the teacher, for example why two light bulbs in series were equally bright. In these explanations some students used alternative concepts (such as “each light bulb uses half the current”), while others employed scientifically correct ideas (such as “current does not disappear”) and occasionally students referred to concrete previous observations. In the class discussions of lessons 5 and 6, after ammeters had been introduced and students were investigating currents in various circuits, descriptions of observations prevailed and most student explanations were based on alternative concepts. In the class discussions of lessons 7 and 8, mainly on current distribution, we saw an increase in scientifically correct explanations, although alternative conceptions were still present. However, in lessons 9 to 11, when class discussions also involved the concept of potential difference, there was a relative increase in student contributions based on alternative conceptions. Table 2.2 shows an overview of the student statements made during class discussions. The table indicates, in line with the conjecture, that during the lesson series there was no relative increase of the use of scientific concepts and student statements remained a combination of scientifically accepted knowledge, alternative conceptions and experimental observations.

Table 2.2
Student Contributions During Whole Class Discussions

	Explanations using			
Lesson no.	alternative concepts	scientific concepts	previous observations	Descriptions of observations
4	3	7	1	8
5	2	0	2	3
6	8	0	3	5
7	2	7	1	0
8	4	9	0	2
9	9	5	1	3
10	8	6	2	2
11	6	5	3	2
12	0	0	1	2

Conjecture 4: Student engagement was limited. After 4 of the 12 lessons the teacher remarked that in several groups engagement in the inquiry activities was limited. This was in agreement with the researcher's observations. Lesson observations indicated that limited engagement applied in particular to group 4, but a random audio recording of group 2 indicated that also in this group only approximately 30% of the time was spent on the inquiry task. In 7 of the 12 lessons the teacher commented on off-task student behavior, while in 4 lessons the teacher asked for silence or asked students to pay attention during whole class presentations and discussions. The presentations and discussions were interactive, but it was the teacher who asked questions and invited specific students to contribute. Only in lessons 6 and 10 students came forward with questions and ideas without being prompted. In the other lessons students did not by themselves respond to work presented by other groups. Lesson observations indicate that during group work students from different groups did not consult each other, although the teacher specifically encouraged this on two occasions. These findings seem somewhat in contrast with individual student interviews after the lesson series: the three randomly chosen students indicated they found the lessons more interesting than the usual physics lessons, because of the hands-on approach, which, they said, also contributed to their understanding.

All workbooks contained evidence of work on the tasks, such as circuit diagrams and observations. However, explanations of phenomena seldom consisted of more than a single brief sentence (such as "current searches for the shortest path"), and often were absent. Predictions in the workbooks, of light bulb brightness, or voltage measurements across light bulbs, were not supported by arguments. Measurements (for example in lesson 12) were recorded by some groups without specifying how the measurements related to the circuit.

In terms of the conjecture, we can conclude that students carried out the assigned tasks, but their engagement to participate in class discussions and in investigative tasks related to the scientific motive of the lesson series (to understand the phenomena taking place in electric circuits with light bulbs) remained limited.

2.6 Understanding the findings

The next step in the analysis was to look for causal explanations that make it possible to understand the findings presented in the previous sections. Plausible explanations were formulated based on our observations.

We had the impression that the open nature of the tasks caused many student groups to carry out the investigations in other ways than expected. We reasoned this could account for the observation that students often did not reach the expected results. During class discussions the students, guided by the teacher, attempted to build conceptual understanding by interpreting their experiments. However, we felt the interpretations based on experiments remained a set of unconnected statements, describing rather than explaining phenomena observed in the electric circuits. This might account for the observation that conceptual understanding did not improve as much as expected and that alternative conceptions remained widespread. Finally, understanding the phenomena taking place in electric circuits with light bulbs, which was the scientific motive of the lessons, hardly played a role when students talked about their motives and concerns. Thinking in line with this scientific motive was also seldom visible in the products asked from the students, such as the workbooks. Thus, we conjectured that student did not make the scientific motive of the lessons their own and that this could account for the observation that student engagement during the lesson series remained less than expected. We translated the above observations into a second series of conjectures. In the following sections we will examine to what extent these conjectures were confirmed or refuted by the data.

Conjecture 5: The experimental student tasks were so open that it was difficult for students to obtain the expected results. We expected student groups could carry out their investigative tasks using different approaches, but would still obtain results useful as inputs to class discussions. However, scrutinizing the lesson transcripts and student workbooks, we found the results of student investigations were often less meaningful than expected. Most often, this was the case because the student investigations were less elaborate than expected, in other cases the experimental setup chosen by the students made it impossible to obtain the expected results, and sometimes the students focused on other aspects of the task than foreseen. For example, one of the first objectives was for students to observe that the brightness of light bulbs is related to the structure of the circuit. During lessons 2 and 3, student groups were given the task to build circuits with four light bulbs and to record their observations. The groups were free to decide on the structure of these circuits, but particularly this freedom made it difficult to reach the objective. Transcripts and workbooks indicate that in lesson 2 all student groups focused on constructing working circuits and drawing diagrams, but 5 out of 6 did not pay much attention to the brightness of light bulbs or the circuit structure. Four of the 6 groups drew their diagrams as a realistic image of the circuit on the table, which made it difficult to interpret its structure. After circuit symbols had been introduced at the start of lesson 3, all groups used these to draw their diagrams. However in lesson 3, half of the investigations were less elaborate than expected. Only 3 groups wrote down observations in a way that enabled the comparison of different circuits. In the subsequent class discussion one student remarked on the basis of his group's investigation that a single light bulb is brighter than 2 or 3 light bulbs in series. Another student suggested that light bulbs closer to the power supply are brighter. These two ideas were used by the teacher to formulate research questions in lesson 4. However, apart from these two remarks, in contrast to our expectation, students raised no further points about the brightness of light bulbs in relation to the circuit structure.

In many instances students carried out only part of the expected investigations, either by omitting some of the measurements necessary to draw conclusions (for example all groups in lesson 12), by not recording results in an accessible way (for example 3 groups in lesson 9) or by omitting conclusions and explanations (for example 4 groups in lessons 6).

The students carried out inquiry tasks without stepwise, detailed instructions on how to set up experiments, what to observe and what to record. This open nature of the experimental tasks was considered important to create a culture of inquiry in the classroom. However, on the basis of the above analysis we may conclude that this openness made it difficult or even impossible for many student groups to observe the anticipated patterns in their experiments.

Conjecture 6: Experiments were not sufficient to develop conceptual understanding. We expected many initial student ideas to be scientifically incorrect. But our expectation was that by interpreting observations and experiments and by participating in whole class discussions, students' conceptual understanding would gradually increase. However, we found only a few students used the results of the whole class discussions in their explanations, while alternative conceptions remained widespread.

The data indicate the ideas of the students remained a set of unconnected rules, stated as isolated findings and not synthesized into a coherent "story" (or theory) of how electric circuits work. To illustrate this point we refer to lesson 10, when the student groups listed what they had learned up to then, which was subsequently summarized in a whole class discussion. Typically the workbooks showed statements such as: the higher the current, the brighter the light bulbs; charge prefers to take paths of lower resistance; the lower the number of light bulbs, the higher the current (in a series circuit); the higher the number of light bulbs, the higher the total current (in a parallel circuit). The individual statements had either been established experimentally (the higher the current, the brighter the light bulbs), or stated as a fact by the teacher (charge is conserved), or established jointly by the class and the teacher, with some supporting evidence (charge prefers to take paths of lower resistance). No relations were expressed between the statements and no evidence was present of any attempts to express the statements as a systematic and coherent whole, or to identify underlying mechanisms that might explain those findings. Throughout the lesson series, arguments used by students and teacher in class discussions largely corresponded to statements from this list, although students used alternative conceptions as well. Students expressed their alternative conceptions as similar unconnected statements (such as charge prefers to take the shortest path and charge is used in a light bulb).

The laws governing current, voltage and resistance in simple serial and parallel circuits describe phenomena taking place in electric circuits. The ability to apply these laws to answer conceptual questions about such circuits was the level of understanding aimed for by the lesson series, similar to other inquiry-based introductory courses in electricity (such as McDermott, Shaffer, & Rosenquist, 1996) and most Dutch physics textbooks for grade 9. Retrospectively we realized that finding patterns in observable phenomena is not sufficient to achieve conceptual understanding.

In reflection, we expect helping students to explain, rather than describe, the phenomena in electric circuits in terms of a theory, would allow them to reach an understanding beyond the list of unconnected rules found in this study. However, explaining these phenomena is complex: energy, transferred from the power supply, is emitted by the filament in the light bulb as radiation, while a steady electric current passes through the circuit. For a given power supply voltage, the total current in the circuit is determined by the total resistance. Resistance is in principle a property of the circuit elements and affects the circuit in such a way that the total current is reduced when two light bulbs are placed in series, while the total current increases when two light bulbs are placed in parallel. Increasing the voltage of the power supply increases the current and makes the light bulbs give off more light. An explanation of these phenomena requires students to reason about the interaction between the theoretical concepts current, voltage and resistance. In retrospect, we may argue that student reasoning would have been fostered if they were helped to construct the image of a flow of charged particles being pushed through the circuit by forces originating in the power supply. A basic model of charged particles would have provided the students with a tool to discuss the phenomena in electric circuits in theoretical terms, but the students did not have such a model at their disposal.

In conclusion, it can be understood that many students had no compelling reasons to abandon their alternative conceptions in favor of scientifically correct ideas. A list of unconnected rules, based on experimental findings, but without theoretical tools to connect and explain the phenomena, was insufficient to develop conceptual understanding.

Conjecture 7: Student engagement remained limited, because students did not adopt the scientific motive of the lesson: understanding phenomena in simple electric circuits. Our expectation was that cooperative work on inquiry tasks, combined with a degree of freedom to carry out these tasks, would build on student curiosity and foster engagement. However, we found student engagement during the inquiry activities remained limited. We expected the student groups to develop a sense of agency and ownership, which would motivate students to actively discuss their findings and ideas. However, we found the motivation to participate in class discussions also remained limited.

At the start of the lesson series the teacher told students the purpose of the lessons was to get an understanding of the phenomena taking place in electric circuits. During the lessons students occasionally made remarks about their motives and concerns. The utterances we encountered in the data to a large extent did not show curiosity about understanding simple electric circuits or interest to pursue investigations. For instance, in lesson 2 a student remarked he did not see the purpose of building more than a single circuit. In lesson 3 another student explained her group was not actively involved, because they had already more or less learned to understand electric circuits in the previous lesson. In lesson 5, a student group indicated just trying out different circuits was more fun than a more systematic investigation. In the interviews after the lessons one of the students remarked that “you don’t have to learn a lot of things, but you learn by doing”. When asked to clarify she referred to reading from a textbook as opposed to “making things”. What she had learned in the lessons was expressed by her as “about light bulbs and charges and how you have to measure all these things” and by another student as “the ammeter and where you have to put it and the voltmeter and how you can predict which light bulbs will light”. Their learning is expressed by these students mostly in terms of skills they acquired to handle artifacts and build circuits and not in terms of explaining phenomena using theoretical concepts such as current, voltage and resistance. On this basis we consider it unlikely that these students made the scientific motive of the lessons series their own. An exception is the third interviewed student, who expressed his learning as “what current is, what voltage is”, a copy of how the teacher had expressed the aims of the lessons. In lesson 6, one student behaved in line with a scientific motive by expressing his own theory, albeit naïve, on how current flows in serial and parallel circuits. However, no follow-up was given to his remarks.

From the school motive of task completion it is easier to understand the limited student engagement. For instance, students showed in their workbooks they had carried out the tasks, which made sense, because the teacher would use the workbooks to assess student participation. But students hardly used the workbooks as a tool to share findings and ideas, so it is understandable they did not provide more than the minimum information required. An exception was group 2 in lesson 7 who referred to measurements in their workbooks to clarify to the class that the current goes down when more light bulbs are added in series. Little response from the class to group presentations becomes understandable as active participation in class discussions did not contribute to task completion.

In summary, we may conclude that, although the data contain only limited and indirect indications of student motives, they show a general appreciation for working in groups and building electric circuits, a degree of interest in describing individual phenomena, but, with some exceptions, no substantial interest in explaining how phenomena in electric circuits can be understood theoretically. It is more likely students were driven by the school motive to complete their tasks, which only required the limited engagement we observed.

2.7 Conclusions and discussion

In this study an attempt was made to increase student conceptual understanding of simple electric circuits by creating a classroom culture in which students were actively involved in inquiry activities and shared their findings and ideas in teacher led class discussions. It turned out that both the change of the classroom culture and the understanding reached by the students were only partly realized. We found three tensions to explain this lack of success.

Open inquiry versus guidance and structure. First, there is the tension between open inquiry as a characteristic of scientific practice, and the need to guide and structure the student investigations to obtain empirical results that can be built upon in whole class discussions. Without some freedom the experimental activities would be reduced to the traditional recipe-type school experiments. Without sufficient structure and guidance, the students could not obtain good enough results to function as starting points for theoretical discussions and thinking. As a consequence, the initial ideas of the students were insufficiently challenged and kept appearing in later discussions.

Student inventions versus accepted theories. Second, there is the tension between the need to allow students to invent and adjust their own scientific theories on the basis of experiments and observations and the need to inform them about accepted theories which are too sophisticated to be reinvented by students. Students carried out experimental inquiry activities and these were followed by teacher led whole class discussions. The activities and discussions gave rise to a number of descriptive 'rules' regarding current and voltage in circuits. However these rules did not give students sufficient cause to develop an understanding of the relevant theoretical concepts, nor did the students have a sufficient basis to start thinking theoretically.

Scientific research culture versus school culture. Third, there is the tension between the scientific research culture we want to establish and the existing school culture. In the presence of school and life world related student motives, norms and values, it could not be taken for granted that students would develop a scientific interest and adopt a scientific motive. Changing the classroom culture so that it becomes more in line with a scientific motive, requires a renegotiation of what counts as valid expectations, behavior and interactions during scientific activities in a school context (McClain & Cobb, 2001).

In a realistic classroom situation, the three tensions can be distinguished, but they cannot be seen in isolation. It is likely that lack of success in inquiry activities had an impact on student preparedness to adopt a scientific motive and so, on their engagement. Likewise, the absence of theoretical tools contributed to students' lack of success. In turn, limited engagement will have had an impact on student's success in inquiry activities and the development of their conceptual understanding (Pintrich et al., 1993).

In addition, we may note that the role of the teacher in the lesson series was demanding. He needed skills not required for a traditional classroom teacher working from a textbook. Among these were the ability to keep a clear focus on the scientific motive of the lessons series, cultivating social norms of inquiry, acting as a subject expert without "giving away the answers", setting inquiry tasks, and fostering theoretical discussion. Moreover, the teacher had to find a balance between the aim to let students experience "science in the making" and the constraints of the school context (such as the available time, the timetable, the requirement to produce grades, the fact that the students' inquiry activities were in fact a simulation of scientific practice). This demand on the teacher to navigate between school culture and subject culture corresponds to the role of the teacher as a "culture broker" (Cobern & Aikenhead, 1998). In retrospect, this is an issue that deserved more attention in the design and enactment of the lessons.

2.8 Implications

The three tensions we found in the case of this study are logically related to the nature of physics instruction in which understanding theoretical concepts and processes of inquiry are important. For this reason, we argue the study can be considered a paradigm case (Cobb & Gravemeijer, 2008) for this instruction. For each tension a balance must be found, such that the student activities contribute to conceptual understanding while a culture of inquiry is maintained. On the basis of this paradigm case, we arrive at three recommendations in regard to these tensions.

1. Open student investigations have to be sufficiently structured to enable students to find experimental results, which they can productively build upon. Jaakkola, Nurmi and Veermans (2011) point out that this guidance is more effective when it is not purely procedural, but also directs students to aspects of the experimental situation important for theoretical understanding.

2. Students have to be offered an initial theoretical starting point for constructing scientifically sound theories from empirical data. This will also allow students and teacher to make reasoned predictions that can be experimentally tested and to bring discussions to a more theoretical level. Hmelo, Holton and Kolodner (2000), in a study on improving understanding of complex systems through design challenges, indicate the importance of causal explanations and the necessity to provide students with the tools to give such explanations. In the case of electricity in simple circuits, a model of moving charged particles may be suitable (Sengupta & Wilensky, 2009). The particle nature of this model cannot be invented by the students through experimental guided rediscovery, so essentially it has to be provided to them. We may note that experimental research in physics is seldom directed at discovering laws inductively, but rather takes theoretical notions as the starting point for experimentation, such as the emergence of new theoretical ideas, incompleteness of a theory or conflict between theory and observation (J. Park et al., 2009). Therefore, providing students with theoretical tools is both authentic and necessary to help them construct conceptual understanding.

3. Teachers have to offer the students considerable support to help them shift from school-oriented motives to scientifically oriented motives. Important here is the cultivation of

scientific interest as a motive for investigating natural phenomena. It also requires the establishment and cultivation of classroom social norms by which students are expected to justify their standpoints and try to understand and explain the phenomena they are investigating. According to McClain and Cobb (2001) renegotiation of norms in the classroom is possible, but a complex and challenging task. For instance, the teacher needs to behave and interact in line with the scientific motive of the lessons and encourage corresponding student behavior. It will be most convincing to students if also the assessment of student products is aligned with this motive.

CHAPTER 3 CREATING A CULTURE OF INQUIRY IN THE CLASSROOM WHILE FOSTERING THE UNDERSTANDING OF THEORETICAL CONCEPTS IN DIRECT CURRENT ELECTRIC CIRCUITS: A BALANCED APPROACH[4]

Abstract. Innovative educational approaches in the sciences have emphasized inquiry in the classroom but it is not self-evident that inquiry instruction leads to conceptual understanding. A design research cycle was carried out to investigate how physics instruction, aimed at creating a classroom culture of inquiry, can contribute to Grade 9 students' understanding of theoretical concepts in direct current electric circuits. A hypothesized local instruction theory and classroom pedagogy were created in cooperation with three physics teachers, emphasizing (a) establishing classroom norms of inquiry, (b) providing a theoretical starting point, (c) using targeted experiments guided by conceptual questions, and (d) theory-oriented whole class discussions. After data collection, retrospective analysis of one class showed that in this class the enactment of the local instruction theory and the development of classroom norms of inquiry had led to the expected learning processes and increased student conceptual understanding. Science education promoting the nature of science as inquiry might consider the importance of an effective local instruction theory and the social classroom processes which require science-oriented classroom norms.

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3.1 Introduction

Secondary school sciences, particularly physics, are unattractive, abstract, and difficult for many students (Taconis & Kessels, 2009). The understanding of specific theoretical concepts in physics (e.g., electric current, potential difference, and resistance) is particularly difficult (see Duit, 2009, for an overview of research). A teacher-directed pedagogy purely based on knowledge transfer from the teacher or textbook to the student is generally considered ineffective in making the sciences more attractive and in fostering conceptual understanding (Treagust & Duit, 2008). Over the last decades, innovative educational approaches in the sciences have emphasized inquiry in the classroom. Inquiry in the science classroom requires the establishment of classroom social norms analogous to a scientific research tradition (Cobb & Yackel, 1998). Effective instruction for conceptual understanding is based on an analysis of subject content and student ideas. It is not self-evident that inquiry instruction leads to conceptual understanding and not all variations of inquiry instruction have been equally effective in promoting learning (Minner et al., 2010).

This study is part of a design research project with the aim to identify characteristics of a learning arrangement that provides a culture of inquiry in the classroom and fosters the understanding of simple electric circuits. Potential learning arrangement characteristics were identified in a first design experiment enacted in a pre-university stream Grade 9 class of a secondary school in the Netherlands (Kock, Taconis, Bolhuis, & Gravemeijer, 2013; Chapter 2). The results of the earlier study were used in the current design study that aims to document the critical attributes of inquiry learning and teaching in physics as well as the classroom cultural dimensions that encourage and support Grade 9 students to engage with difficult-to-learn ideas.

3.2 Background

The following sections summarize the nature of inquiry in the physics classroom, conceptual understanding in physics, conceptual problems in understanding electric circuits, design research, and the results of an earlier design study. These areas were reviewed to provide foundations for decisions about instructional design, research procedures, data collection and interpretation and to justify the argument and assertions made.

3.2.1 A Culture of Inquiry in the Classroom

Inquiry learning in the sciences can be considered an enculturation process in which learners participate in a community of practice. The establishment of a culture of inquiry in a classroom requires the development of social norms in line with this culture (Cobb & Yackel, 1998). A culture of inquiry will give students the opportunity to experience essential characteristics of scientific research processes, such as using and creating theories, models and hypotheses, testing ideas by experiments, interpreting data, and being involved in social processes like questioning, discussing, and collaborating (Minner et al., 2010; Osborne et al., 2003). Ideally, the enculturation process and learning to use theoretical concepts go together, in contrast to traditional school textbooks and pedagogy. Some researchers in education aim at genuine scientific research or inquiry in real-life contexts to let students experience a scientific culture. Gravemeijer and Cobb (2006), working in mathematics education, suggested that such a context needs to be experientially real to the students, meaning that it provides a setting for students to act and reason sensibly. We follow this approach in which students are allowed to experience key aspects of a scientific culture in the classroom through meaningful simulation (Hung & Chen, 2007). However, there is a tension between inquiry, which is process oriented, and the accepted approach in most physics lessons, in which mastering problem-solving procedures and task completion are important goals (Kock et al., 2013; Nijland, 2011). Changing the classroom culture requires a change of norms, values, expectations, and behaviors. The teacher can facilitate this change by explicating the new norms, modeling behaviors in accordance with these norms, supporting students to adopt them and by making it rewarding for students to do so. Teacher-facilitated whole-class discussions are a way to establish the classroom and subject-specific social norms of a culture of inquiry (Cobb & Yackel, 1998). Moreover, these discussions help the class to reach consensus on conceptual problems and provide feedback to the teacher on the level of student understanding (Leach & Scott, 2002).

3.2.2 Conceptual Understanding in Physics

The instruction in this study aimed to (a) create a culture of inquiry in the classroom and (b) foster conceptual understanding. Instructional design for conceptual understanding needs to consider the cognitive aspects of student learning (Treagust & Duit, 2008) although the importance of social processes and of noncognitive factors for learning is generally acknowledged. Classroom activities and instruction should be based on an analysis of subject content and on the content-related ideas students bring to the classroom (Leach & Scott, 2002). In a well-balanced curriculum, the individual conceptual change perspective is coordinated with the sociocultural perspective that views learning as participating in a community of practice.

3.2.3 Conceptual Problems in Understanding Simple Electric Circuits

Topics of the instruction were the theoretical concepts involved in direct current (dc) electric circuits. These concepts are difficult for students to understand (Chatila Afra, Osta, & Zoubeir, 2009; Engelhardt & Beichner, 2004). In particular, many students have difficulty drawing and interpreting circuit diagrams, tend to confuse concepts (e.g., current, voltage, and resistance), use incorrect models of electric current (e.g., the idea that current is consumed), view power supplies as constant current sources, and do not realize that a circuit is a system in which a change of one element can have an impact on other circuit elements.

3.2.4 Design Research

The research method used in this study is design research that aims at understanding and supporting learning processes (Gravemeijer & Cobb, 2006). This is a cyclic research methodology with macro-cycles, each consisting of a *preparation phase*, *classroom experiments,* and a *retrospective evaluation*. The *preparation phase* establishes the learning goals, the starting points of instruction, and a conjectured local instruction theory. The school curriculum forms the basis for the learning goals, but they are adapted to create a focus on conceptual understanding. The starting points of instruction rely on the instruction in earlier grades, formative assessment of the target students, and knowledge of common alternative conceptions. The local instruction theory takes into account the learning goals and the starting points of instruction. It involves a sequence of “provisional instructional activities, and a conjectured learning process that anticipates how students’ thinking and understanding might evolve when the instructional activities are employed in the classroom” (Gravemeijer & Cobb, 2006, p. 19). The theory is specific for the chosen topic, rather than for science learning in general, and hence is referred to as *local*.

The instruction is enacted in the *experimental phase*. During this phase, amendments are made to the sequence of activities based on first observations and reflections, for example, if expected learning processes have not been realized (micro-cycles of testing and improving instruction). Data are collected from a variety of sources to enable the development and refinement of the local instruction theory and the evaluation of student learning processes in the *retrospective evaluation phase*. Data analysis in this phase follows a two-step procedure based on grounded theory. The first step identifies patterns emerging from lesson observations and a first examination of the data. These patterns are described as conjectures about the dataset, and the body of data is then examined to look for confirmation or refutation of these conjectures. This first step of the analysis, thus, results in conjectures supported by evidence from the data. The second step is directed at finding explanations for the conjectures. This interpretative approach leads to a description of possible causal mechanisms of how the learning arrangement shaped student learning (Maxwell, 2004).

3.2.5 Results of an Earlier Design Study

A conjectured local instruction theory for learning about electric circuits in an inquiry context was created in an earlier study that formed the first macrocycle of design research (Kock et al., 2013; Chapter 2). However, the student learning processes did not develop as expected during the enactment of this local instruction theory. Therefore, the retrospective analysis was used to identify the mechanisms complicating the process of conceptual understanding in inquiry-based instruction. We framed the study as an instance of the class of issues arising in this type of instruction, a paradigm case (Gravemeijer & Cobb, 2006), and postulated three tensions: between open inquiry and structure provided to students, between accepted theories and student inventions, and between school culture and classroom research culture. A balance must be found for each tension so that student activities contribute to conceptual understanding while a culture of inquiry is maintained. Three guidelines were formulated to create such a balance. First, during inquiry activities, students need support from the teacher and the instructional materials in order to obtain meaningful results. The support helps students move successfully from traditional recipe-type experiments to structured, guided, and more open forms of inquiry (Melville, Bertley, & Fazio, 2013). This is a matter of balance; too much guidance results in a focus on following procedures while too little guidance is likely to result in unfocused inquiry and low-quality outcomes (Leach & Scott, 2002). Second, students have to be offered an initial theoretical starting point for constructing scientifically sound ideas. Students cannot be expected to reinvent theoretical concepts entirely through inductive experimental activities; therefore, student experiments have to be accompanied by deductive, semideductive, or hypothesis-driven considerations. Moreover, most authentic inquiry in physics starts from a theory-driven or hypothesis-driven motive (J. Park et al., 2009). Third, teachers have to support students to move from school-oriented norms toward scientifically oriented norms. These guidelines were used in the preliminary design of the second classroom teaching experiment, described in this study.

3.3 Research Interest

The primary goal of the present study is to understand how the learning arrangement characteristics might support learning in a Grade 9 physics classroom practice (Cobb et al., 2003). We were interested in the mechanisms that allowed for the characteristics to contribute to learning results. However, investigating these mechanisms is only feasible if the learning results are good enough to justify the investigation. Therefore, the research questions (RQ) were considered in sequence. First, the conditional RQ was addressed:

RQ1. How effective was the enacted instructional design in terms of the conceptual learning aims of the Grade 9 lessons about electric circuits?

Second, the main RQ was addressed:

RQ2. How do the learning arrangement characteristics help explain the development of Grade 9 students' conceptual understanding in the inquiry classroom?

3.4 Design of the Lesson Series

We describe the context in which the local instruction theory was created, the learning aims, the way the guidelines from the previous design study were incorporated, and an outline of the preliminary local instruction theory consisting of activities and expectations. We were aware that a complete change of the classroom culture is a lengthy process, that the most likely result of the short lesson series would be steps in the desired direction, and that we might not fully achieve the desired outcome.

3.4.1 Collaboration with Physics Teachers

A potentially effective way to innovate in education is to involve practicing teachers in educational design. Therefore, the instruction was designed collaboratively by a researcher (the first author) and three physics teachers (Mr. Adler, Mr. Bradley, and Ms. Campbell) from three secondary schools in the southeastern part of the Netherlands. The collaboration took place within the framework of a part-time physics education M.Ed. program at Fontys University of Applied Sciences. Teachers from this program were given the opportunity to combine participation in this project with their practitioner research, the final obligatory part of the MEd program. Details of the collaboration and the teachers' learning processes have been described in Chapter 4 (Kock, Taconis, Bolhuis, & Gravemeijer, in press). Nine group meetings of approximately 80 minutes each were held to prepare the lessons and an additional 10 meetings of approximately 40 minutes each during the months in which the lessons were enacted.

3.4.2 Conceptual Learning Aims

The learning aims focused on an understanding of concepts and their relations and use in explaining dc electric circuit phenomena. The potential learning outcomes were summarized as:

- Students are able to interpret circuit diagrams of simple dc electric circuits.
- Students are able to distinguish the concepts of electric current, voltage, and resistance in simple dc circuits consisting of a power source, connecting wires, light bulbs, resistors (wired in series and parallel arrangements), voltmeters, and ammeters and can use these concepts to solve conceptual problems.
- Students can explain the role of the battery/power supply in simple dc circuits and use it to solve conceptual problems.

The intent of the lessons was to have the students arrive at the rules for current and voltage in dc circuits through an inquiry process instead of the teachers giving them the information at the outset. The learning aims address the same topics as the school curriculum and the Grade 9 Dutch physics textbooks. However, these textbooks put most emphasis on using formulas and carrying out calculations.

3.4.3 Incorporating the Guidelines from Earlier Design Study

The three guidelines resulting from the previous macrocycle were incorporated into the instructional materials, and into planned teacher activities and behavior.

Initial Theoretical Starting Point. We provided students with a simple model of electricity as moving charged particles (Sengupta & Wilensky, 2009). The instructional materials contained a basic explanation of this model. Giving students a theoretical starting point was expected to facilitate investigations, rediscovery, and discussions in terms of cause and effect. Therefore, we used a simple model of electricity as moving charged particles.

Structuring Inquiry Activities. The instructional materials provided brief instructions, research questions, and sometimes circuit diagrams for experiments. Class discussions were planned before and after experimental work to discuss hypotheses, outcomes, and explanations.

Supporting the Development of Scientific Norms. The instructional materials provided general information on the approach and assessment to make clear to the students what was expected. They also contained conceptual questions. The teachers were prepared to take student ideas seriously, to build on these ideas in whole-class discussions, and to stimulate student thinking rather than providing ready-made answers. Student tasks and their sequencing were designed such that students had a fair chance of developing a deeper understanding and satisfactory explanations, which would make adhering to the inquiry approach rewarding for them. The questions in the instructional materials aimed to focus the discussions on conceptual issues and were informed by the educational research literature. Assessment was brought in line with the desired classroom culture so that adopting this culture was rewarding for the students in terms of school results. The assessment at the end of the lesson series focused on student understanding. A short conceptual quiz was included in the lesson series to make clear at an early stage that assessment would measure understanding and the ability to explain physics rather than recall of facts and the successful completion of textbook calculations.

3.4.4 Outline of the local instruction theory

The main points of the preliminary local instruction theory for the experimental lessons are outlined. Each point may take a single lesson period or more to fully enact.

Introduction to the approach. An exercise in cooperative problem solving with an introduction by the teacher are expected to help students realize that the classroom norms in the experimental lessons are different from those in the usual physics lessons. Emphasis is placed on active participation, asking questions, cooperation, and personal responsibility for understanding. The teacher explains what is expected in terms of participation, products, and assessment.

Experiment to create a closed circuit. Students are asked to create a closed circuit with a light bulb, single wire, and battery, which is followed by a class discussion evoking student ideas of “what happens” in the circuit and the function of the circuit elements (connecting wires, bulb filament, and battery as the source of electric energy). It is expected that students will come to understand the path followed by *electricity* in a closed circuit with a light bulb. A question about the nature of electricity is now expected to make sense to the students.

Introduction of a theoretical starting point. Students read a brief text on the charged particle model of electric current followed by a class discussion with examples, demonstrations, and computer simulations on electrostatics and current electricity. Students work in small groups on conceptual questions to apply the model to explain current flow in series circuits. It is expected that students will acquire a starting point to talk theoretically about electric circuits; for example, forces between charges and a flow of electrons established in a closed circuit because of the surplus/shortage of electrons at the battery poles. The activities will help students think about consequences of the model (e.g. conservation of charge) and the resistance posed by the light bulb filament. However, the scientifically correct way of talking has to gradually develop by participating in the activities.

Electric current in a series circuit. Students carry out experiments on the brightness of light bulbs and on the current in series circuits. Before the experiment, predictions are solicited based on the charged particle model. The experimental results are discussed in class and followed by conceptual questions. Students are asked to connect the experimental activity of measuring an electric current to the theoretical idea of current as a flow of electrons. This will contribute to an understanding of electric current (charge) conservation and of the effect of resistors in series.

The battery in a circuit. The class discusses the purpose of a battery in a circuit, supported by computer simulations; and students measure open circuit battery voltages. The battery voltage is used as an indication of the difference between surplus and shortage of electrons to help students distinguish electric current and voltage. Students will start to think about the battery voltage as a measure of the "driving force" by which electrons are "pushed and pulled" through the circuit. Moreover, students realize a battery is not a storage vessel of electrons but a neutral device in which electrons are unevenly distributed. Student questions on the ways computer simulations display batteries provide an opportunity to discuss the limitations of models.

Potential differences in a series circuit. Students carry out experiments on the relation between the voltage across the battery and across light bulbs in a series circuit. Before the experiment, predictions are made based on the charged particle model. The experimental results are discussed in class and followed by conceptual questions. The experiment is expected to help students realize a driving force is necessary at every light bulb to overcome the filament resistance. A potential difference provides this driving force. It then makes sense that a potential difference exists across light bulbs in series and that the total corresponds to the potential difference across the battery.

Series and parallel circuits. The students work on conceptual questions related to series circuits, parallel circuits, and simple combined series/parallel circuits, using computer simulations to test their ideas. In teacher-led class discussions, student ideas are summarized to arrive at the patterns (rules) for current and voltage in series and parallel circuits. The understandings that students developed in earlier lessons and the theoretical model are expected to provide a basis for the discussion.

Quantitative experiment on resistance. The teacher introduces resistance as a quantitative measure. Students conduct an experiment to test if the resistance of a resistor is constant in different circuits. The experiment is expected to help students realize that the resistance of a single resistor is a property of the object and not of the circuit, which is a widespread alternative conception (Engelhardt & Beichner, 2004). The experiment requires students for the first time to measure both voltage and current and to use various theoretical ideas and experimental skills.

3.5 Research Setting and Data

Design research by necessity takes place in specific school and classroom contexts. Descriptions of the instructional context and of the process of data collection and analysis are provided to help interpret the results of the study.

3.5.1 Instructional Context and Enactment

The lessons were enacted by three physics teachers in Grade 9 classes selected on the basis of practical considerations: (a) the timetable allowed the researcher to observe lessons in the inquiry classes, and (b) the introduction of a new pedagogy was not likely to produce classroom management issues. This chapter focuses on Mr. Adler's class because lesson-by-lesson meetings to evaluate and redesign instruction were only possible with him, due to the timetable, and his enactment of the instruction most closely approximated the design intention. Mr. Adler's inquiry class consisted of 21 students (10 girls and 11 boys). The 13 experimental lessons of 50 minutes each were enacted over an 8-week period. Apart from the inquiry class, Mr. Adler taught another Grade 9 class of high-ability students who received the usual school curriculum (Hogenbirk et al., 2007). Both classes were part of the pre-university stream and consisted of students from various socioeconomic backgrounds. All students had been taught an introduction to electricity as part of the Grade 8 physics course. Permission to enact the experimental lessons and to collect data was obtained in accordance with school policies.

Mr. Adler's class was observed during one lesson and interviewed prior to the experimental lessons to get an impression of the classroom culture. The observations and student interviews made clear that teacher explanations of physics content were an important component of typical lessons. Occasionally, students carried out experiments, following teacher-directed, recipe-type procedures. Mr. Adler used his own notes to teach the curriculum instead of a textbook. Teacher-student interactions in his classes were apparent as students regularly made remarks or asked questions. However, we concluded that establishing a culture of inquiry would still be a major change to Mr. Adler's practice and a new experience for the students.

Enactment of the lessons in Mr. Adler's class took place in the presence of the first author as an observer and collaborator. The first author occasionally helped groups of students and, at the request of the teacher, contributed to whole-class discussions. In this way, the first author modeled aspects of the pedagogy and helped establish the classroom culture.

3.5.2 Data Collection and Analysis

Data were collected from various sources as recommended in the educational design research literature (Gravemeijer & Cobb, 2006): video and audio recordings of the lessons and of student groups, field notes, student work, a conceptual quiz, a pretest, a posttest, and interviews with four randomly selected students after the lesson series. We made video recordings of all meetings with the teachers and collected relevant documents (e.g., agendas, notes, and e-mails). The student interviews, audio recordings, and postlesson evaluation meetings were fully transcribed. Recordings of student groups were summarized; time stamps maintained the connection with the original recordings and temporal position of the occurrence selected as evidence.

The first RQ was addressed by analyzing the pretest and posttest results. The pretest was based on the expected student prior knowledge and alternative conceptions described in the research literature, covering basic concepts of electric current. It consisted of six multiple-choice items (five of which corresponded to posttest items) and two open-ended items. The posttest covered the topics included in the experimental lessons. It consisted of 29 multiple-choice items translated and adapted from version 1.0 of the DIRECT concept test (Engelhardt & Beichner, 2004) and 8 open-ended items. (These tests are available in Dutch from the first author.) The pretest reliability (Cronbach's $\alpha < 0$) was interpreted as an indication of students having insufficient understanding of the topic to provide consistent answers. The posttest Cronbach's $\alpha = 0.75$ indicated acceptable reliability and internal consistency between item and test performances. The pretest and posttest were discussed with the teachers to establish content validity. We administered the tests to both the inquiry and noninquiry class to get an impression of the differences and similarities of the learning results even though the emphasis of the study was not on comparison of results. The tests were analyzed on an item-by-item basis in relation to the learning aims, and the overall results of the two classes were compared using a *t*-test.

The main RQ was addressed by looking for patterns emerging from the data and by analyzing these patterns. The search for patterns was guided by sensitizing concepts based on the theoretical framework: classroom norms and expectations, level of student engagement, development of student conceptual understanding, and character of the experimental work. Quotations were collected from the lesson transcripts for each sensitizing concept, which were then summarized on a lesson-by-lesson basis. Patterns became apparent from the lesson observations and a first examination of the data; they were described as conjectures. Subsequently, the entire body of data was examined to look for confirmation or refutation of these conjectures. The lesson-by-lesson development, combined with information from the other data sources, made it possible to draw a conclusion about the conjectures. The first author conducted the analysis; but the process, the conjectures, and the evidence were regularly discussed with a team of three educational and design research experts. The analysis revealed information about student learning results and conjectures supported by evidence from the data on the learning arrangement characteristics and student learning processes.

Next, the relations between the patterns were analyzed in conjunction with the student learning results (Gravemeijer & Cobb, 2006). This interpretative step allowed us to describe processes and possible causal mechanisms grounded in the data and to confirm or refute these conjectures. The analysis led to plausible explanations of how the learning arrangement characteristics fostered or constrained student conceptual development.

3.6 Findings

We present the analysis of pretest and posttest results, followed by the patterns emerging from the data to describe how student understanding developed during the lessons. Subsequently, the results of the second analysis are presented in which explanations were sought for the patterns found in the first step.

3.6.1 Student Conceptual Understanding

The mean percentage of correct answers to the multiple-choice pretest and posttest items are shown in Table 3.1. The pretest percentage of correct responses to items on dc current and voltage indicate low levels of understanding at the start of the lesson series. Only the closed circuit was relatively well understood, with almost 60% of the students correctly answering an item about the way to connect a light bulb in a circuit. These low levels of understanding are confirmed by the responses to the open-ended items. Almost 25% of the students used the concepts of electric current and energy in their responses but did not distinguish between these concepts. Just over 50% of the students correctly described a *series connection* while less than 20% correctly described a *parallel connection*. Almost 50% of the students used alternative concepts such as the *current used* or the *unipolar* model.

Table 3.1

Percentage of Correct Responses to Pretest and Posttest Multiple-choice Items

Learning aim	**Inquiry class**		**Non-inquiry class**	
	Pre[a]	**Post**[b]	**Pre**[c]	**Post**[a]
Interpret circuit diagrams				
Need for closed circuit[d]		84		90
Two connections on circuit elements[e]	57	100, 84	60	86, 86
Recognize short circuits[e]		100, 95		95, 81
Interpret pictures/diagrams[f]		95, 95, 68		81, 86, 71
Connection of ammeter and voltmeter[d]		89		71
Understand relevant concepts				
Current as moving charge[e]	29	84, 89	20	71, 81
Conservation of charge[e]	10, 48	89, 84	0, 30	57, 33
Potential difference in series circuit[f]		74, 84, 89		76, 43, 86
Potential difference in parallel circuit[d]	24	63	40	86
Resistance of circuit elements[e]		100, 74		52, 57
Resistance series/parallel arrangement[d]		53		14
Current when resistance is changed[d]	38	63	50	48
Power in a circuit[e]		74, 89		52, 71
Current depends on voltage and resistance[e]		95, 100		81, 43
Potential difference in open circuit[d]		37		57
Understand role of battery				
Battery as a voltage source[e]		58, 21		38, 57
Battery provides energy to the circuit[d]		89		38
M (*SD*)	34 (16)	80^* (9)	33 (18)	65^* (13)

[a] $n = 21$. [b] $n = 19$. [c] $n = 20$.

[d] one posttest question. [e] two posttest questions. [f] three posttest questions.

$^*p < 0.001$.

The posttest responses show students in the inquiry class were able to interpret drawings and circuit diagrams; however, recognizing different representations of parallel circuits proved somewhat more difficult (68% correct). They were able to answer items on current, voltage, and resistance in dc electric circuits (74–100%), in particular on electric current in series and parallel circuits, the brightness of light bulbs or energy converted in light bulbs, the basic rules of potential difference in series circuits, and resistance as a property of circuit elements. Items about the voltage in parallel circuits and about the effects of changing a resistance proved somewhat more difficult (53–63%), particularly an item about open-circuit voltage (37%). Students successfully answered an item on the effect of batteries in series (89%). Items on the battery as a voltage (as opposed to a current) source were more difficult for them (21–58%). Responses to the open-ended items generally confirmed these results. They also showed most students could not predict voltages and resistance in more complicated circuits (e.g., containing a parallel and a series part).

In summary, the conceptual learning aims of the lesson series were to a large extent accomplished in the inquiry class. Moreover, the posttest result of the inquiry class was significantly higher than that of the noninquiry class, $t(38) = 4.076$, $p < 0.001$, $r = .55$, indicating a higher level of conceptual understanding of dc electric circuits. The pretest-posttest gains of the target class and the comparison of the posttests of the two classes justified a further investigation of the student learning processes in the inquiry class and the factors influencing these processes, in which some attention must be given to the ideas that were not so well understood by the students.

3.6.2 Patterns in the Data

A first examination of the data on the experimental lessons suggested four patterns framed as conjectures. The conjectures were then tested on the whole body of data. A fifth conjecture arose in the second step of the analysis when the relations between the patterns were analyzed. More details on lesson and interview excerpts substantiating the conjectures are provided in the Appendix.

Conjecture 1. Classroom norms and expectations were explicitly cultivated by Mr. Adler in interactions with the students. Classroom norms and expectations for the experimental lessons were expressed in the student worksheets: understanding, active thinking and exchanging ideas, using arguments, behaving respectfully and listening to others, being allowed and allowing others to make mistakes, asking questions, and cooperating. In line with the conjecture, Mr. Adler regularly referred to these norms and expectations.

During the first lessons, he made clear that active participation and trying to achieve understanding were more important than making mistakes and obtaining the correct answers from the teacher (e.g., in lesson 1: “Everybody is asking me, is it right, is it right … but in the end, the question is what do you think?”). In later lessons, class discussions developed in which several students came forward with their ideas, so these norms appeared accepted by the students. In lessons 5, 8, and 10 brief discussions took place with students who said they preferred listening to teacher explanations rather than finding answers by inquiry. In his reply, Mr. Adler referred to the effectiveness of the approach (details in the Appendix). In lesson 11, students were concerned about preparing for the final assessment. In that discussion Mr. Adler emphasized, amongst others, the importance of active participation and understanding.

Subject-specific norms, such as explaining phenomena in terms of the charged particle model, were not explicitly expressed. The teacher used the model, and students started to talk in terms of the model. On a few occasions, the teacher’s behavior seemed at odds with the classroom norms of inquiry. For example, during parts of lessons 7, 9, and 13, Mr. Adler explained physics content instead of using a more interactive approach.

Four students, interviewed after the lessons, stated their active participation had increased in comparison to the usual physics lessons (“I used to accept what the teacher says and that’s how it is. But now you got these models and you had to think about it yourself … I pay more attention, because you have to think about it yourself”). Three out of four students mentioned an increased responsibility for learning (i.e., the answers were not provided by the teacher). Two girls mentioned the emphasis on understanding, cooperation, and listening to others as distinguishing elements of the lessons.

A large extent of the data confirmed that Mr. Adler expressed and discussed norms and expectations related to a culture of inquiry and the school culture. Subject norms remained more implicit. Students had noticed active participation and their responsibility to reach understanding as the most visible of these norms.

Conjecture 2. Generally, Mr. Adler’s students were engaged during the lessons. The recordings of student group work during lessons 1, 3, 4, 6, 9, 10, and 12 revealed that on average 80% of the time students talked was on-task. The impression of student engagement was confirmed by the interactions during class discussions, interviews, and assessment results. For example, in all lessons we found students asking content-related questions, coming forward with their ideas, or commenting on each other’s or the teacher’s ideas. Most engagement was shown by a group of about four girls who carried on with the discussion after the lessons. However, in some lessons (particularly 3, 10, and 11) a group of approximately five students (mostly boys) did not actively participate in the whole-class discussions; audio recordings of this group during lesson 9 showed mostly off-task talk (e.g., more than 90% of the time in a 10-minute inquiry task). Therefore, the conjecture was confirmed for the majority of students in Mr. Adler's class while occasionally a minority did not show engagement.

Conjecture 3. Students used the model of charged particles while they developed an understanding of electric circuits. We analyzed the audio transcripts, the conceptual quiz, and three randomly selected student workbooks to find confirmations and refutations of this conjecture. There were two indications of student understanding: (a) students talked or wrote using the theories of school physics and the charged particle model (e.g., demonstrated by students correcting other students) and (b) there was a lack of evidence contrary to understanding (e.g., if students built a closed circuit without discussion or took for granted that current is the same on both sides of a light bulb). We interpreted as lack of understanding student talk or written work inconsistent with secondary school physics.

Student conceptual understanding developed during the lessons. The charged particle model was used in student utterances in all lessons except the introductory lesson and lesson 12, a practical lesson with a quantitative focus. The context in which reference was made to the particle model mostly concerned students asking questions or answering teacher, workbook, and other students' questions. Students initially did not understand basic aspects of electric circuits, such as the precise meaning of a closed circuit, the nature of electric current, and the role of a battery in a circuit. The following examples illustrate how different students talked about electric current at the start of the lesson series and in an interview afterwards (examples from other lessons in the Appendix):

<u>Lesson 1</u>. The electric energy or current has to flow in a closed circuit from the battery to the light bulb and back and because of this the bulb will light. (41:55)
<u>Interview</u>: At the negative side of the battery there is a surplus of electrons, at the positive side there is a shortage.… The higher the difference, the higher the voltage.… Because, the surplus of electrons at the minus side repels the electrons, and the electrons are attracted by the protons at the positive side. So the electrons start to flow and the higher the pushing and pulling forces, the more they start to flow … the higher the amperage. The number of amperes is the current.

The examples show that understanding of a concept grew gradually and evidence of this understanding became apparent in student talk and written work. New ideas, such as the concepts of voltage or parallel circuits, initially gave rise to questions and different, often idiosyncratic, interpretations. Conceptual difficulties shifted to more complicated issues in the course of the lessons such as the distinction between the resistance of a circuit element and of the system as a whole. In those more complicated cases, the teacher's support was necessary for students to reason successfully with the charged particle model. By the end of the lesson series, the better students could explain, in terms of moving charged particles, the cause and nature of the electric current and why the light bulb lights. They could relate their explanation to measurable variables and distinguish the concepts of current and voltage and of current and energy. In conclusion, the conjecture was confirmed by the data although considerable differences between students remained.

Conjecture 4. The student experiments were characterized by inquiry and structure. Student experiments were guided by research questions in the student workbook and by general (instead of stepwise) instructions. Mr. Adler conducted class discussions before and after experimental work. He referred to theoretical ideas discussed before the experiment such as the idea that electrons provide energy to the light bulb and are not consumed (lesson 4). He repeated the aim of experiments ("Is the current before the light bulb equal to the current [after the light bulb]?") and asked for expected outcomes. He brought up theoretical consequences after the experiments (lesson 5: "What can you conclude about what happens in the filament?"). During experiments, students mainly talked about correctly setting up circuits and making correct measurements. When asked by the teacher or first author, students could refer to the research questions and hypotheses and to experimental evidence during theoretical discussions in later lessons.

Mr. Adler used direct instruction with regard to the correct use of an ammeter (lesson 4) or voltmeter (lesson 6) and the circuit students were expected to use (lesson 8). During the experimental work, the teacher and first author provided scaffolding to groups of students about setting up the circuits ("Think, before you build it, of what it will look like on the table.") and about the inquiry nature of the experiment ("What again was the aim of this experiment?"; examples from lesson 4). The teacher and first author also discussed the interpretation of results with students, for example, when they found that students based their conclusions on small deviations from the ideal circuit behavior.

The evidence suggests that the experiments had elements of inquiry. The preparation and follow up linked the experimental work to the development of theoretical ideas. There was additional teacher support during the experimental lessons, which sometimes interfered with the inquiry but allowed students to obtain meaningful results.

Conjecture 5. Classroom norms of inquiry and the enactment of an adequate local instruction theory were instrumental in establishing student engagement and conceptual understanding. The presence of classroom norms of inquiry and the enactment of an adequate local instruction theory were observed in large parts of lessons 1 to 7. In these lessons, students actively participated in response to teacher questions and the tasks set in the worksheets. Engagement and development of understanding went together as indicated in the description of Conjecture 3 and by the conceptual test results. The vignette from lesson 7 in the Appendix is an example of this general pattern. Students challenged each other's ideas and made clear what they did not understand. The teacher responded to the students, pointed to relevant issues, and asked questions. Our interpretation of this pattern is that the interplay of new classroom norms (student contribution of ideas) and local instruction theory (a task set that made sense to the students in a teacher-guided discussion) fostered engagement and made it possible to move toward accepted physics theory and increased student understanding.

However, the general pattern of lessons 1 to 7 did not apply to all students. In lesson 3, a group of boys did not actively participate in the discussions. In lesson 9, the groups worked on conceptual problems and could test their ideas using computer simulations. Most students were engaged, but one group of boys was mostly off-task and other students complained about the low quality of their contributions. In lesson 10, these boys challenged the classroom norms by stating their preference for teacher-directed explanations. One of the boys confirmed this preference in a postlesson interview: teacher explanations allowed him to learn the content without spending the effort to find answers by himself. It appears this group had not accepted the classroom norms of the experimental lessons.

Student engagement and the development of student understanding decreased when lessons did not unfold in line with the classroom norms of inquiry or when the local instruction theory was inadequate. For example, when the teacher gave long explanations of physics content, amongst others in parts of lessons 8 and 11, only a few students interacted with the teacher while others were observed talking off-task and complaining about the teacher talking too long. The results of the conceptual test showed the topic discussed in lesson 11, the effect of changes made to parallel circuits, remained difficult for most students. In lesson 12, the local instruction theory proved inadequate because the research question guiding the lesson was too difficult for students to understand. Students kept asking questions about the setup of the circuit and the measurements to make. This focus on procedural aspects indicated the experiment left little room for inquiry.

Some students remained engaged in the lesson activities even when the teacher did not behave in line with inquiry classroom norms. For example, in lesson 11 a small group of students, mostly girls, participated in the class discussion while others could be observed in off-task talk. According to Mr. Adler, at least one of these girls saw the experimental lessons as an opportunity to improve her physics grades. Her posttest results were among the highest of the class.

The data indicate a confirmation of Conjecture 5 for the majority of students although there is too much diversity to make a firm claim. A small group of boys did not accept the classroom norms and their engagement remained low. A small group of girls remained engaged and on-task even when the conditions of the conjecture had not been met.

3.7 Conclusions and Discussion

We found that student conceptual understanding had increased in Mr. Adler's experimental class, also in comparison to his traditional class. Many students developed the ability to interpret circuit diagrams, to distinguish the concepts electric current, voltage and resistance, and to explain the role of the battery or power supply. While at the start of the lesson series students often reasoned according to the *current consumed* model, this seldom happened at the end. Some topics were still difficult, including aspects of parallel circuits, an electric circuit as a system, and the battery as a source of constant potential difference.

Starting from the introductory lesson, students constructed, voiced, and tested their ideas during experiments and during small-group and whole-class discussions when answering conceptual questions and interpreting computer simulations. Students received feedback on their ideas from peers and the teacher. Reading the text about electric charges and moving electrons provided a starting point for students to develop explanations for the electric phenomena they observed. While they developed ideas on electric current, students raised questions on the role of the battery and of the lamp filament in a circuit, which naturally introduced the need to know about the voltage and resistance concepts. We found that the introduction of battery voltage as a measure of the difference between a surplus of electrons and a shortage of electrons to be helpful. We observed only a few instances in which students incorrectly connected voltmeters and ammeters after the resistances of these meters had been discussed. Early in the lesson series, discussions focused on a single concept; toward the end, discussions involved multiple concepts and the relation between concepts. Most students could apply the current, voltage, and resistance concepts to series circuits but needed help to reason about parallel and combined circuits.

We found that new classroom norms were enacted by the teacher and widely accepted by the students: the teacher engaged, used, and valued student ideas and students were expected to actively contribute ideas, results would be arrived at cooperatively, and *all* students were expected to develop their own understanding. The classroom norms led to a dynamic exchange of ideas, which we interpret as an emulation of scientific activity (Hung & Chen, 2007). The conceptual quiz demonstrated to students that assessment of and for learning would be aligned with an inquiry-oriented culture. The enacted local instruction theory involved the combination of conceptual tools, challenges, and supports that made engagement rewarding for students. As a result, students saw the experimental lessons as a way to understand physics not available to them in the teacher's traditional instruction.

The retrospective analysis showed how the instructional design enacted during the teaching experiment fostered student conceptual understanding while at the same time nourishing the culture of science. This design study may help understand how shaping instruction that pairs the culture of science to fostering conceptual understanding may work out in the classroom, and may be taken as an instance of this broader phenomenon. More specifically, we may conclude that the three characteristics described earlier complemented and reinforced each other (Kock et al., 2013; Chapter 2). The classroom norms of inquiry and science, that recognized potential discrepancies between them and school norms, such as assessment, fostered the willingness of the students to invest in coming to grips with the phenomena they were exploring. The structured character of the activities (e.g. experiments shaped by theory-oriented questions) together with the availability of initial theoretical starting points, ensured that the inquiry-oriented attitude of the students was rewarded, which in turn reinforced the classroom norms. Although learning processes differed between students, this balanced approach gave rise to the growth of the students' conceptual understanding. Thus, the yield of this study consists of a local instruction theory for electrical circuits, and a deeper insight into the way, guidelines for designing instruction that fosters conceptual understanding and meets the demands of the culture of science, play out in practice. Further research could be directed to not only optimizing the local instruction theory but also to developing and investigating a similar balanced approach in other physics topics.

An important aspect of the local instruction theory was the use of the charged particle model for electricity, which might be considered questionable by some physicists. Here, however, the model served as a tool for student thinking and collaborative reasoning, for example, by helping students to distinguish current and voltage (Sengupta & Wilensky, 2009) and to make sense of the computer simulations. Moreover, the conceptual research questions that guided experimental work stimulated students to interpret experimental results theoretically so that these results became more than observed regularities. When students were asked to reason about the effect of resistance in combined series/parallel circuits, the model seemed to reach its limits when its use became complicated for both students and teacher. The charged particle model is one of the models and metaphors of electricity that students encounter in their school career (Hart, 2008). It also might help students to take subsequent steps in learning electricity, such as understanding resistivity and Ohm's law.

The approach followed in the experimental lessons appears suited to the majority of these participating students. Most girls showed enthusiasm, appreciating the peer discussions and emphasis on concepts. However, some students, mostly boys, comfortable with traditional ways of physics teaching, did not show the expected engagement. This could partly be due to the lesson sequence, which may have been too short for these students to adopt the new classroom norms. On the other hand, more differentiation may be required, taking into account different needs while maintaining the characteristics of inquiry.

Without the teacher's ownership and commitment, the lessons could not have been successfully enacted. The teacher appropriated the general goal of the project: making students experience science in the making while fostering conceptual understanding. Moreover, he helped co-design the instructional sequence and adopted the teaching philosophy. Ownership and buy-in are critical features for the implementation of reform-based approaches. However, the lessons also demonstrated it is not easy for teachers to create classroom norms of inquiry and foster conceptual understanding. Demands are made with respect to classroom management and pedagogical content knowledge, encompassing the topic of electricity (Gunstone, Mulhall, & McKittrick, 2009), as well as the local instruction theory and the nature of the desired classroom norms. Mr. Adler and the researcher could evaluate and adapt each lesson directly after the enactment. This is recommended practice for design research cycles (Gravemeijer & Cobb, 2006) and important to develop the local instruction theory. Moreover, enacting inquiry-based instruction in a supportive setting provides science teachers with the opportunity to develop necessary pedagogical content knowledge and classroom competences. Taking part in a design study can be an effective way for a science teacher to develop professionally (Kock et al., in press; Chapter 4).

Mr. Adler successfully enacted the inquiry-based lesson design in which fostering conceptual understanding and cultural attributes went together. Science education reforms that promote the nature of science as inquiry might consider social and cognitive aspects of doing science and meaning-making processes involving knowledge production as social negotiation and individual conceptual growth and change. An appropriate balance of these aspects requires an effective local instruction theory and a teacher who is skillful in enacting it and in orchestrating social interactions in the classroom.

CHAPTER 4 SUPPORTING TEACHERS TO TRANSFORM THEIR CLASSES INTO A CONTEXT-BASED LEARNING ENVIRONMENT: INQUIRY AS A CONTEXT[5]

Abstract. In this study we describe the second design research cycle from the perspective of a professional development intervention. The participants were three teachers from different schools. The intervention was designed to possess characteristics that according to literature can lead to a successful change of classroom practice and consisted of group meetings and feedback/evaluation meetings. The purpose was to help the teachers establish a culture of inquiry in their classrooms in which students would be facilitated in coming to understand concepts of electricity in simple direct current circuits. The research aim was to understand how the participating teachers developed professionally in terms of reported learning and changes in the classroom. Data were collected in various forms. In the qualitative data analysis the professional development of each teacher was described as a separate case and common themes between the three cases were identified. All three teachers reported new insights with respect to their pedagogical content knowledge (PCK) and classroom pedagogy. Changes of attitude were also reported. The data showed that the change of the classroom culture was noticeable for the students. Individual differences between the teachers with respect to their learning and to the enactment of the lessons could be explained by considering their different starting points as professional educators, the different environments in which they operated, and individual differences with respect to their concerns.

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4.1 Introduction

Context-based approaches in science education, such as context based chemistry or physics are gaining ground. For example, in the Netherlands new context-based curricula have been developed for the natural sciences[6], which will be implemented in the years to come (SLO, 2010). However, in order to create effective context based education, teachers will need to change the classroom culture, the social norms and forms of interaction that shape classroom practice (Cobb & Yackel, 1998). In contrast to the traditional classroom culture based on knowledge transmission, students in context-based curricula will have an active role. In these classrooms there will be an emphasis on the social nature of learning processes, and on activities that reflect essential aspects of authentic situations (Gilbert, 2006). Teachers will need to develop professionally to acquire the knowledge, skills and attitudes needed to transform the culture in their classrooms in line with these new requirements (Hewson, 2007; Pintó, 2005). Providing teachers only with new teaching materials will generally not bring about the desired change of teaching practice (Fullan, 2001; Vos, 2013), because even with support, many teachers may not adopt the pedagogy behind the teaching materials (Van Driel et al., 1997).

A promising way to create successful innovation is to involve teachers in the development of reform based lessons and lesson materials (Coenders, Terlouw, Dijkstra, & Pieters, 2010; Stolk, De Jong, Bulte, & Pilot, 2011). Being involved in the design process may help teachers to acquire the subject knowledge and pedagogical understanding required to enact the lessons and for the lessons to address teachers' educational concerns. Moreover, teacher learning is expected to be fostered by co-designing and enacting lessons, because it creates a sense of ownership and stimulates reflection (Coenders, 2010; Pintó, 2005). In this chapter we will describe a professional development process in which three secondary school physics teachers and a researcher, the first author, were involved. Collaboratively the teachers and the first author designed a series of lessons with the aim to bring the classroom practice of the teachers more in line with context based education and in particular, to establish a culture of inquiry in their classrooms. The lessons were enacted by the teachers in their regular classes. In our research on this intervention, the aim was to understand how participating in the process led to professional development of the teachers in terms of reported learning and changes of the classroom culture. We will describe the

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[6] The words 'science' and 'science education' potentially refer to all scientific domains. However, in the context of this chapter these words refer to the natural sciences generally taught at secondary school level: chemistry, biology and physics.

professional development processes of each teacher as separate cases and discuss common themes among the three cases. The lessons resulting from the intervention are also subject to research. As a cycle in an Educational Design Research (EDR) project (Gravemeijer & Cobb, 2006) we will study which factors foster student understanding of theoretical concepts in physics when a culture of inquiry is created in the classroom. In this chapter we focus on the professional development process of the three physics teachers. The study of the lessons will be published separately.

4.2 Context based education in this chapter

Several authors identified problems in the traditional science curricula, such as the overload of topics and concepts, the teaching of science as a collections of isolated facts, the lack of transfer of science learning and the lack of perceived relevance of the curriculum (Gilbert, 2006; Osborne & Dillon, 2008). The use of curricula based on contexts has been proposed as a way to overcome these problems. According to Duranti and Goodwin (1992) a context involves a focal event, that is, the phenomenon being contextualized, and a field of action in which the focal event is embedded and which gives meaning to the event. Gilbert (2006) described the function of context in education as follows:

> Thus, the function of "context" is to describe such circumstances that give meaning to words, phrases, and sentences. A context must provide a coherent structural meaning for something new that is set within a broader perspective.

Using attributes of educational contexts identified by Duranti and Goodwin (1992) in combination with theories on learning, Gilbert (2006) transformed these attributes into criteria to evaluate models of contexts relevant to chemistry education. As he formulated these criteria in a way that is not specific to chemistry education, they can be used to evaluate models of context in the other natural sciences as well:

1. A context has to include an authentic situational setting, which must be valued by the students and provide the framework for a community of practice in the classroom.

2. The student tasks must bring about a behavioral environment in which students can interact with relevant subject related concepts.

3. The students have to be helped to develop subject specific language related to the focal event

4. Students have to be given the opportunity to relate focal events to extra-situational background knowledge.

To structure the ways contexts are used in education, Gilbert described four models, with increasing compliance to the criteria. In the first two models of context the emphasis is on an authentic situation arising from the student life-world, from the worlds of professional and academic work, or from contemporary issues. In the last two models, the emphasis is on context as activities in which students participate, either individually or collectively. One possible perspective on the fourth model, which comes close to meeting all the criteria, is "a context as social activity" in which students' learning is fostered by participating in a community of practice. Gilbert (2006) observed that a course design using "context as a social activity" is infrequently found, "perhaps because of the resource demands that it makes, for example, on teachers' subject knowledge and pedagogical content knowledge. As an example of this model Gilbert referred to Realistic Mathematics Education (RME) (Cobb, Stephan, McClain, & Gravemeijer, 2001). In RME the teacher's aim is to establish a culture of inquiry in the classroom (Cobb & Yackel, 1998) by negotiating relevant classroom social norms, and subject specific social norms. In line with these norms, teacher and students develop subject specific practices, allowing students to learn mathematics by a process of guided reinvention. Cobb and Yackel (1998, p. 158) emphasize that "the culture established in a mathematics classroom is in many ways analogous to a scientific research tradition". The starting point in RME is a situation that is *experientially real* to the students (Cobb, Yackel, & Wood, 1992; Freudenthal, 1981), which does not refer to a context that corresponds in all aspects to a situation in the students' life-worlds, but rather to an educational setting in which the students can act and reason sensibly.

A scientific research tradition is also relevant in a physics learning environment in which the context is formed by the social activities of the participants. However, teachers need to develop professionally to create the required culture of inquiry in their classrooms. The professional development process described in this chapter had the aim to help the teachers establish a culture of inquiry in their classrooms in which students would be facilitated in coming to understand concepts of electricity in simple direct current circuits. No genuine academic inquiry was aimed for (as the physics behind these circuits has long been known), but rather a meaningful simulation of inquiry processes at the level of the students (Hung & Chen, 2007).

4.3 Inquiry

In science education the term *inquiry* can mean different things (Minner et al., 2010). In their review study Minner, Levy and Century compiled essential characteristics of inquiry instruction in science education:

- It engages students with scientific phenomena, either directly or through secondary sources.
- It emphasizes active thinking and student responsibility for learning.
- It emphasizes student motivation (e.g. by building on student interest, curiosity, involvement or focus).
- It uses at least some part of the investigation cycle (pose questions, design investigations, process and interpret data, draw conclusions, communicate).

As there are various ways to create instruction with these characteristics, we describe in general terms the type of instruction envisioned in this project. The instruction had the purpose of allowing students to experience a meaningful simulation of, in the words of Latour (1987), "science in the making". During the lessons, groups of students would engage with the relevant phenomena through theoretical and experimental investigative tasks and through computer simulations. Tasks would call for explication of student ideas, reasoning and explanations, rather than for factual recall or for solving calculation problems. Ideas would be presented and brought together in teacher led class discussions which would have a prominent place in the lessons. The amount of lesson time devoted to teacher explanations and student work on standard textbook problems was expected to be greatly reduced as compared to traditional lessons.

The topic of the lessons, theoretical concepts in electricity, is generally considered difficult for secondary school students (Duit & Von Rhoeneck, 1998; Shipstone, 1985; Taber et al., 2006). An earlier study indicated students cannot be expected to rediscover these concepts through inductive experimental activities (Kock et al., 2013; Chapter 2). Developing understanding through experiments and developing a theoretical understanding need to go hand in hand. To be able to develop a theoretical understanding, students need to be provided with theoretical tools, language and symbols. Based on the results of the earlier study we suggested that students be provided with the essence of a theoretical model, such as a model of moving charge, through which they could engage in theoretical talk. We considered this an authentic approach to inquiry, as also in physics research experimental work is often induced by theoretical considerations (J. Park et al., 2009).

Student inquiry activities need to be carefully prepared, otherwise students are unlikely to construct the desired conceptual understanding. This applies in particular to an abstract and complicated topic such as electricity. Anticipating how students will come to construct understanding requires a theory of how relevant student learning processes might evolve and on how these learning processes might be evoked and fostered. Thus, instructional activities have to be created as part of a *conjectured local instruction theory* (Gravemeijer & Cobb, 2006): a sequence of "instructional activities, and a conjectured learning process that anticipates how students' thinking and understanding might evolve when the instructional activities are employed in the classroom".

4.4 Teacher Professional Development

Professional development is defined by Fullan and Stiegelbauer (1991) "the sum total of formal and informal learning experiences throughout one's career from pre-service teacher education to retirement". Interventions in this area can be regarded as activities with the purpose to improve the quality of teachers, their instruction and the learning of their students (Van Veen et al., 2010). Professional development activities are often seen as a precondition for educational innovation, because innovations require teachers to take on a new role and change their practice (Borko, Jacobs, & Koellner, 2010; Vos, 2010). However, many professional development activities do not lead to lasting changes of teaching practice (Fullan, 2001). In a recent review study Van Veen et al. (2010) synthesized characteristics of professional development interventions that successfully led to a change of classroom practice. In a literature study on teacher learning in collaborative curriculum design Voogt et al. (2011) came to similar characteristics. We list the most important of these:

- The intervention is preferably related to specific teacher concerns and teachers are involved in the aims of the intervention, problem formulation and analysis.
- The content of the intervention is directed towards subject content, subject didactics and the learning of students.
- Teachers learn actively and can contribute their own experiences, exchange experiences and collaborate with colleagues.
- Teachers are exposed to actual classroom practice and coaching takes place after the initial training.
- Professional development is directed at teams of teachers rather than at individual teachers.
- A substantial amount of time is available for the intervention.

Van Veen et al. (2010) further noted that the interplay of these characteristics and issues of school organization and facilitation have an impact on the effectiveness of a particular intervention. In this study we intended to create an intervention with these characteristics. However, the setting of the intervention did not allow us to work with teams of teachers from the same school. Instead, we worked with teachers from three different school.

4.5 Description of the intervention

The professional development intervention we describe in this chapter was facilitated by the first author, who had eight years of experience as a physics teacher and three years as a teacher trainer. The purpose of the intervention was to change the practice of the participating physics teachers. More specifically, the aims were:

(1) To collaboratively design and enact a lesson series in which a culture of inquiry would be created in the classroom that would help students understand the theoretical concepts in simple electric circuits.

(2) To create learning opportunities for the teachers so that they would come to understand the physics content of the lesson series in relation to the pedagogy and learning environment we aimed for, and their role in it.

As participants we recruited volunteer physics teachers from a part-time Master of Education (MEd) program at Fontys University of Applied Sciences in the Netherlands. Teachers from this program were given the opportunity to combine participation in the intervention with their practitioner research project, the final obligatory part of the MEd program. We expected this arrangement to be beneficial for the participants, so that it would compensate for the required investment in time and effort. In terms of teacher professional development, the participants had the opportunity to develop knowledge, attitudes and skills relevant for creating a culture of inquiry in their classrooms. Moreover, the lesson series they would co-design was expected to increase the conceptual understanding of their students on the topic of electricity. Teachers could participate if they taught a grade 9 class in the pre-university stream of education in which lessons on electricity were to be enacted, if they were interested in the topic of electricity and in inquiry as a context, and if they were prepared to relate their practitioner research to a particular interest or concern regarding the teaching of electricity. The participants were provided with relevant research literature, received guidance and could benefit from group discussions and joint data collection. The time investment asked from the teachers to participate in the intervention was to a large extent be covered by the time allocated for their practitioner research projects. This eliminated the need for additional facilitation, for example by the respective schools. Meetings could be easily organized as the teachers visited the university on a weekly basis for the MEd program.

The phase of the intervention in which instruction was designed consisted of collaborative group meetings between the teachers and the first author. The content of these meetings was as follows:

- A detailed discussion of the physics concepts and the student conceptual problems in the grade 9 curriculum on electricity. The purpose of this discussion was to (a) increase awareness that the topic of electricity is difficult for students, (b) arrive at a common vision of the understanding expected from the students at the end of the lesson series and (c) share ideas and experiences on how students' conceptual understanding could be improved. Relevant research literature and an overview of student conceptual problems known from the research were provided to the participants.
- A discussion of how a model of moving charged particles (electrons) could be used at the level of grade 9 students to explain the theoretical concepts and the phenomena related to simple electric circuits. An earlier round in the design research project (Kock et al., 2013; Chapter 2) suggested that students' theoretical thinking and talking could be fostered by providing students with a basic theoretical model. The model we decided to use bears resemblance to the model suggested by Licht (1987). The discussion included the common metaphors used in teaching electricity and made connections with models based on the electrical field concept, beyond the grade 9 level. From the University of Colorado (University of Colorado, 2010) a number of interactive computer simulations were available on the internet that illustrate different aspects of a charged particle model[7]. It was discussed how these simulations could be used in the lessons. The discussion resulted in a written summary of the model prepared by the first author.

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[7] The interactive simulations illustrated aspects of a simple charged particle model, but not a single simulation illustrated the entire model. For example, one interactive simulation illustrated the attraction and repulsion between electric charges, others illustrated the flow of electric current or the voltage across a battery. We considered it important for the teachers to understand in detail what could and what could not be illustrated by each of the interactive simulations.

- Discussion of a pedagogy suitable to create a culture of inquiry in the classroom. A number of aspects were discussed: the use of models, the importance of students' ideas, subject specific practices such as students' active involvement in explanations and reasoning, the use of language and symbols and how experiments could be related to theory. An earlier round in the design research project (Kock et al., 2013; Chapter 2) suggested that in order to successfully create of a culture of inquiry in the classroom, it was important to find a balance between the freedom for students to investigate and the structure provided by the teacher and the teaching materials, and to find a balance between the development of a scientific motive and the existing school motives. So we discussed how a new classroom culture could be initiated by the teachers and what concrete measures could be taken in the lessons to maintain these balances. A written summary was made of the discussion.
- Design of the instructional activities as part of a conjectured local instruction theory. The local instruction theory capitalized on the model of moving charged particles and contained a sequence of preplanned experimental and theoretical tasks and activities. It was developed in the course of several meetings. After each meeting the first author elaborated the results of the discussions into a lesson outline for the teachers and, in a later stage, into worksheets for students. In the subsequent meeting the lesson outline and worksheets were discussed by the group and amended if necessary.
- Additional topics: the assessment of the lesson series and practical issues related to logistics.

After the enactment of lessons had started, brief feedback and evaluation meetings took place (approximately 10 minutes) between the teacher and the first author. If such a meeting was not possible due to the teacher's timetable, the lessons were evaluated during the group meetings. The group meetings further focused on preparation of subsequent lessons, extensions or modifications to student materials and the teacher's role. In terms of EDR these aspects of the meetings can be considered micro cycles of evaluation and design (Gravemeijer & Cobb, 2006). Where possible, enactment of the lessons took place in the presence of the first author, who occasionally assisted in the enactment of the lessons, for example by helping groups of students who were working on tasks and, on request of the teacher, by contributing during whole class discussions. The purpose of this assistance on the one hand was to model aspects of the pedagogy for the teachers and on the other hand to help create the classroom culture necessary for the lesson study.

Recruitment in the MEd program during September 2009 resulted in the participation of three teachers. The group meetings started in December 2009 and lasted until July 2010. A total of 19 group meetings were held, lasting between 30 minutes and two hours, in which each teacher participated for approximately 15 hours. The first teacher enacted the lessons in March/April 2010, the two other teachers in June/July 2010. The meetings ended when all three teachers had enacted the lesson series. Thereafter, the teachers continued working individually on their practitioner research projects.

4.6 Research questions

We expected the participating teachers would learn to change their classroom practice towards a more context-based approach, in particular towards an approach with a 'context as social activity'. To understand how participation in the professional development process gave rise to teacher learning, we posed the following research questions:

1. What learning did the teachers report after participation in the collaborative lesson design and enactment?
2. To what extent did the teachers change their classroom practice?
3. How can the reported learning and the teachers' classroom practice be related to participation in the professional development process?

4.7 Method

4.7.1 Participants

Three physics teachers from a group of 11 MEd students at the Fontys University of Applied Sciences volunteered to take part in the professional development process. The teachers, Mr. Adler[8], Mr. Bradley and Ms. Campbell, taught at three different secondary schools in the south of the Netherlands. The school where Mr. Adler taught was located in a medium-sized town and had an urban character, while Mr. Bradley and Ms. Campbell taught at schools in smaller towns in the urbanized countryside. Mr. Adler had been a physics teacher for 19 years; Mr. Bradley had been a physics teacher for 9 years, after working for 17 years in the automotive industry; Ms. Campbell was in her second year as a physics teacher, after working as a library assistant at the school for several years. All three

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[8] All names are pseudonyms

taught grade 9 classes in the pre-university stream of their school. Mr. Adler and Ms. Campbell decided to enact the experimental physics lesson in one of their classes and teach the usual school curriculum in the other class. Mr. Bradley decided to enact the experimental lessons in 2 of his classes and the usual school curriculum in the other 2. Class sizes varied between 20 and 25 students.

4.7.2 Data collection and analysis

Data collected during the intervention consisted of video recordings of all group meetings, agendas, notes, e-mails, teachers' proposals for practitioner research and two interviews of 10-20 minutes with each of the teachers. One interview took place shortly after the enactment of the lessons in 2010, a second interview in the first months of 2011 after two of the teachers had enacted the lesson series for a second time. Also included were the reflections Mr. Bradley and Ms. Campbell wrote at the end of their practitioner research projects, as they contained remarks about their learning. We video recorded one lesson of each teacher before the enactment of the experimental lessons to have an example of the teachers' "normal teacher practice". Further data on the classroom practice consisted of video and audio recordings of lessons (for technical reasons one lesson could not be recorded), field notes by the first author, interviews with three randomly selected students per teacher directly after the lesson series and a student questionnaire administered immediately before and after the lesson series. The questionnaire contained among others 22 items on how students experienced aspects of the learning environment in the lesson series on electricity as compared to the physics lessons before this lesson series. The items were related to student activity, inquiry, self-directedness and cooperation, consisting of statements such as: during physics lessons I carry out experiments; in physics lessons I discuss with other students how to solve problems. Students indicated on a scale from 1 (never) to 5 (very often) how often the situation in the statements occurred.

The items were adapted from the questionnaire by Blumberg (2008), with a few items added from the Constructivist Learning Environment Survey (Taylor, Fraser, & Fisher, 1997). Before the lesson series students were asked to focus on their usual physics lessons ($\alpha = 0.910$) and after the lessons to focus on the lesson series on electricity ($\alpha = 0.915$).

To arrive at case descriptions for the three teachers we followed a stepwise procedure of data reduction. Based on the agendas, notes, video and audio recordings, we made a descriptive summary of all meetings (group meetings and evaluation meetings after the lessons) in terms of the activities that had taken place and the topics that had been discussed. To process video and audio data, we used the f4 transcription software (Burgdorf, 2010). Time stamps in the summaries referring to the video and audio files allowed the different sections of the summaries to be traced back to the original recordings. Similarly, we made descriptive summaries of all lessons based on the video and audio recordings and on the teacher's field notes. Teacher and student interviews were transcribed. Data on the teachers from the interviews, e-mails, proposals and reflections were organized in matrix form (Miles & Huberman, 1994). The matrix contained information on the teacher background, self-reported teacher learning and reflections about the professional development process as a whole. The next step of the analysis was to use the summaries to make brief descriptions of each teacher's lessons with regards to the following aspects of context-based education and inquiry: situational setting, student interaction with subject specific concepts and language, responsibility for learning, level of activity and participation, level of cooperation among students, instructional methods used by the teacher. We included information on coaching by the first author, teacher reflections after the lesson and student interview data in the descriptions. Using these characterizations of the lessons, the matrices with teacher data, the student questionnaires and the original data sources where necessary, we were able to describe each teacher's case following a roughly chronological order.

A number of measures were taken to ensure reliability of the results, which was especially important as the first author acted both as a facilitator of the intervention and as a researcher. First, we used data triangulation by taking data from various complementary sources: video and audio recordings, teacher and student interviews, a questionnaire and additional documents. Second, in the case descriptions we referred to the original data sources, so that the statements we made can be traced back to these sources. Third, results in various stages of the analysis were discussed by all authors of this chapter. Fourth, a member check was carried out. Comments made by the teachers after reading the case descriptions were incorporated in the final version of the text. In fact, only minor modifications were necessary.

4.8 Case descriptions

Summary information about the three teachers and their participation in the professional development process is shown in Table 4.1. Mr. Bradley and Ms. Campbell had started the experimental lessons in May, which limited the maximum available number of lessons due to the start of the summer vacation. For Mr. Adler this limitation did not apply as he had started the lesson series in March. Mr. Adler's timetable made it possible to have a brief preliminary evaluation meeting after each lesson, apart from the weekly group meetings. Mr. Bradley's and Ms. Campbell's timetables did not allow for these meetings, so that a first evaluation of the lessons took place during the weekly group meetings.

Table 4.1
Overview of the three cases

Case	Physics Teaching Experience	Grade 9 Physics classes	Number of experimental lessons	Lesson by lesson evaluation
Mr. Adler	19 years	1 experimental 1 non-experimental	13	12 after lessons and 5 group meetings
Mr. Bradley	9 years	2 experimental 2 non-experimental	11	2 after lessons and 4 group meetings
Ms. Campbell	2 years as teacher 9 years as tutor	1 experimental 1 non-experimental	12	1 after lessons and 5 group meetings

In the paragraphs below we describe the three cases of Mr. Adler, Mr. Bradley and Ms. Campbell. Throughout the text we refer to the different data sources in the following way: (SI) student interviews, (TI) teacher interviews, (O) lesson observations, (M) meetings, (D) documents.

4.8.1 The case of Mr. Adler

At the time of the intervention Mr. Adler taught two grade 9 classes in one of which he tried out the experimental lessons on electric circuits and in the other taught his usual lessons on this topic. His usual lessons typically consisted of teacher explanations (often calculation examples) of which students made notes. Occasionally students worked on problems. An initial lesson observation showed a classroom atmosphere in which students were used to ask questions if something was not clear, or to come forward with their ideas if prompted. In the opinion of an interviewed student, the teacher explanations were easier to understand than the explanations in the textbook. (SI, O).

Mr. Adler had three concerns he wanted to address in the experimental lessons. First, he usually took for granted that approximately one third of the class would not understand the topics he taught. However, for the experimental lessons his aim was that all students would participate and reach an acceptable level of understanding (M). Second, he was unhappy with his present use of metaphors in the lessons on electricity. He had the impression the metaphors limited student understanding. (M) Third, he wanted to use the experimental lessons to experiment with forms of group work, to enrich his repertoire of teaching methods and because he believed students' understanding of electrical circuits would increase if students in small groups interacted and solved problems together (D, TI).

To start creating a culture of inquiry, Mr. Adler told the class in the first lesson that their ideas and contributions, also if not immediately correct, could help the class to solve problems and could lead to common understanding. He kept encouraging students to listen to each other's ideas, to exchange their ideas, and that together the class had the ability to solve problems and obtain explanations. He also pointed out that students were responsible for active participation (for example that he was not going to provide them with single correct answers to conceptual problems) (O). In the lesson evaluation meetings Mr. Adler was encouraged to keep taking student ideas as a starting point for discussions. After the third lesson he remarked that the interactions during class discussions gave him insights into students' ideas that were not available through his usual teaching method (M).

To help all students in the class to come to understand electric circuits, Mr. Adler involved many students in the class discussions, in particular those who found physics difficult and those who were generally not motivated for the subject. He adapted the lesson planning and kept returning to a topic until he had the idea all students had reached a sufficient level of understanding (M, O). The perceived level of student understanding was discussed during the after-lesson evaluation meetings. In comparison to his other class the teacher noticed a higher ability of students in the experimental class to reason about electric circuits. He also noticed an increased level of student motivation and participation and even found students explaining physics problems to each other at school in their own time (M). Audio recordings of student groups during lessons indicated students saying they were more active in these lessons. A small group of students (mostly girls) often remained after classes to keep discussing what they had not understood. Mr. Adler thought this engagement might partly be caused by students seeing these lessons as an opportunity to get a good grade, which would enable them to choose physics in their subject package in the following year (M). When giving tasks and leading class discussions the teacher focused on understanding physics in terms of the particle model, explaining phenomena and making predictions before experiments were carried out or simulations were shown (O). Students started talking about electric circuits in terms of the particle model, especially during class discussions. Occasionally, Mr. Adler was insecure about his application of the particle model (for example whether or not to define current as the speed of electrons) or was unable to respond to student questions (in particular where the model reached its limits such as in the explanation of what happened inside a battery). Aspects of the model were again talked about during after-lesson evaluations and group meetings (O, M). During class discussions he used various computer simulations and encouraged students to predict and explain their working. Occasionally the first author intervened in the classroom to clarify confusion about the particle model or the limitations of the simulations (O).

A number of practical investigations had been prepared with an emphasis on research questions to be answered by the students, rather than recipe-type procedural experiments focusing on obtaining correct measurement values. The research questions and topics of the practical investigations were given in the student worksheets. Mr. Adler provided the students with additional structure by pointing out the focus of the experiments and conducting class discussions in which students were asked to predict in theoretical terms what the outcomes of the experiments would be (O). He considered the way students carried out the experiments (e.g. by making correct circuits and placing meters correctly in circuits without receiving explicit instruction on how to do this) as a sign they knew what they were doing (M).

In retrospect Mr. Adler remarked that the lesson series, and observing a colleague teaching the same topic in a more traditional way, had made him realize teacher explanations did not help much to increase students' understanding of electric circuits. He added it was more effective to let students think together about how things work and to let them explain phenomena to each other, either in groups or in whole class discussions. He had also come to the conclusion that it is very difficult to teach the topic of electricity without using at least some metaphors (apart from the particle model), but was aware that it is important to indicate the limitations of these metaphors to the students. Mr. Adler was in doubt whether the student experiments contributed enough to student understanding. He still had the impression that theory and experiment were two different worlds for most students and suggested the experiments could be made more open ended. In general this teacher was pleased with the collaboratively developed lessons and teaching materials, although he was concerned students who had missed lessons were not given a complete explanation of the theory in the worksheets (TI).

Students had noticed that the experimental lessons had been different from their usual physics lessons. Two girls, interviewed after the lessons said they had been more active than in the usual physics lessons. They also said the class discussions, and the higher demands made on their own thinking had contributed to their conceptual understanding.

Two interviewed boys mentioned in particular differences in the type of tasks and the increased number of experiments. That is, the boys reported in particular differences related to the design of the lesson series and not so much to the classroom culture (SI). Results of the student questionnaire indicated Mr. Adler's students experienced a significantly higher constructivist orientation in the experimental lessons on electricity (N=21, M=66.5, SD=12) as compared to their usual physics lessons (N=20, M=55.9, SD=12) using related-samples Wilcoxon signed ranks test (T=12.0, p=0.001, r=0.53). The effect size of 0.53 can be considered a large effect (Cohen, 1992). In particular, the responses to items on the questionnaire showed Mr. Adler's students experienced they cooperated more with other students, carried out more experiments, had more opportunities to investigate things by themselves and had more opportunities to develop their own ideas.

Approximately nine months later, Mr. Adler repeated the lesson series with a new grade 9 class. More than during the first enactment, he experimented with different types of group work. He had also made sure to take enough lessons to enact the lessons series and not to rush through the content. In his view, the response of the students was similar to the first enactment. But in general he was more satisfied with the approach, as he felt more prepared for the questions that came from the students and knew better "where he wanted to go". (TI).

4.8.2 The case of Mr. Bradley

At the time of the intervention Mr. Bradley taught four grade 9 classes in two of which he tried out the experimental lessons on electric circuits, while he taught his usual lessons on this topic in the other two classes. His classes typically consisted of teacher explanations, student work on textbook problems, and approximately one experimental activity per chapter or topic. While solving textbook problems, students usually worked together in small groups. In a lesson observed before the start of the experimental lessons on electricity Mr. Bradley introduced a new topic (heat related phenomena). In this lesson he used various instructional methods: a brief demonstration of heating water, with the purpose to evoke student prior knowledge on heat, a class discussion guided by (Socratic) teacher questions, teacher explanation and student work on problems (O, SI).

In Mr. Bradley's view the aim of the lessons was to improve students' conceptual understanding of electric circuits, such that they could express their ideas on the relevant theoretical concepts in a scientifically correct way. In his opinion just carrying out calculations using Ohm's Law did not lead to real understanding. Moreover, he wanted students to see the connection between the physics lessons and the real-life world. For example students would ideally have an understanding of what happens when a light is switched on. Mr. Bradley called this the “concept-context story”. (TI). He had the impression the experiments students carried out in traditional lessons on electricity did not contribute much to conceptual understanding. He expected the use of computer simulations that visualize what happens inside an electric circuit, in line with the particle model used in the experimental lessons, could be used to improve students’ understanding. In particular, he expected that the use of computer simulations in which students could see what happens inside a circuit, in combination with hands-on experiments, would help students relate experiments to theory and develop scientific conceptions (D).

In the first lesson, Mr. Bradley explained to the class how the way of working in the lessons on electric circuits would differ from his usual lessons. The class was going to use and gradually extent a theoretical particle model to explain the phenomena taking place in electric circuits. Students were going to carry out experiments, exchange ideas, discuss and learn from each other. Mr. Bradley encouraged students to be actively involved and look for solutions. All contributions were welcome to help the understanding of the class forward. He told the class the work of physicists had similar characteristics: theories are built through many different contributions that gradually lead to consensus. During the lessons the teacher conducted a number of class discussions, which were characterized by Socratic type questioning. In a group meeting after the second lesson Mr. Bradley was encouraged to see if these discussions could be built more around student ideas. He let students work in groups, on conceptual questions set in the student worksheets and in most lessons the student groups used computer simulations and/or carried out experiments. Problems the groups did not finish during lesson periods were set as homework (O). In general Mr. Bradley consistently used the particle model, showing only some hesitation in discussing student questions transcending the limitations of the model, such as questions related to the processes inside a battery and how rechargeable batteries work (O, M). Occasionally during class discussions, the first author intervened, for example to model the use of questioning (e.g. by asking students to predict what was going to happen before switching on a simulation).

Mr. Bradley said he had to get used to the approach of the experimental lessons. Initially the lessons felt chaotic to him and he sensed a lack of structure and progress. He sensed also the students had to get used to the new method. During group work he did not find them engaged and he had the idea they did not develop an attitude of inquiry. These observations were discussed during the group meetings and collaboratively ways were sought to increase student engagement and make their work more effective. For example Mr. Bradley started to give students different roles during group work (scribe, time keeper, etc.) after Mr. Adler had told about his positive experiences with this approach (M, O). For Mr. Bradley the opportunity to exchange experiences and ideas with other physics teacher was one of the benefits of the collaborative lesson preparation and the group meetings (TI).

In retrospect Mr. Bradley mentioned working with the theoretical particle model as one of the things he learned. In his view it was important to start with a simple model which was gradually extended, while students used simulations and experiments to verify the model and connect it to their existing knowledge. Another thing he had learned was to keep students actively involved in the lessons by asking the right questions. He had noticed that the more he was "on top of it", the more engagement he saw with the students (TI). Mr. Bradley remarked some ideas he initially had about student learning had turned out incorrect. For example the computer simulations, in spite of the fact that they visualized otherwise invisible aspects of electric circuits, did not immediately clarify the theoretical model for the students. He had come to the conclusion that the use of computer simulations has to be accompanied by specific student tasks in order to contribute to student understanding (D). Moreover, Mr. Bradley had expected the tasks on the worksheet were clear for the students without further explanations, but found in reality they were not. He suggested the worksheets could be written more clearly on some places. Finally, he had the opinion that physics culture could have come more to the fore in the lessons, but that more specific ideas on how to do this would have to be included in the lesson preparation (TI).

Interviewed students, especially the girls, had noticed the experimental lessons had been different from their usual physics lessons. One boy did not see a lot of difference in the teaching methods. However, he appreciated aspects of the lesson design: the incremental pacing and the use of simulations and experiments. Three girls appreciated the discussions in peer groups, in particular, as one girl remarked, because explanations by the teacher were usually directed to boys who were better at physics. The girls also appreciated the simulations and experiments, and the lack of calculations and formulas. The lessons had not changed their opinion of physics as a subject (SI). The questionnaire showed the students in Mr. Bradley's two classes experienced a significantly higher constructivist orientation in the experimental lessons on electricity as compared to their usual physics lessons. Results from the related-samples Wilcoxon signed ranks test are shown in Table 4.2.

Table 4.2
Mr. Bradley's students' judgement on the lessons on electricity in comparison with their usual physics lessons (using Related-Samples Wilcoxon Signed Ranks test)

Class	N pre	Pre Mean (SD)	N post	Post Mean (SD)	Test Statistic T	p	effect size r
1	24	60.9 (13)	22	68.5 (12)	77.0	0.009	0.39
2	23	61.9 (13)	14	68.9 (7)	46.5	0.045	0.38

The effect sizes of 0.39 and 0.38 can be considered medium effects (Cohen, 1992). In particular, as in the case of Mr. Adler's students, the responses to items on the questionnaire showed Mr. Bradley's students experienced more cooperation with other students, carried out more experiments, had more opportunities to investigate things by themselves and had more opportunities to develop their own ideas. However, the students in one class considered the experimental lessons less relevant for the world outside school than their usual physics lessons.

Approximately 6 months later, Mr. Bradley enacted the lesson series again with a new grade 9 class. He felt the second enactment was easier, because he knew what was going to happen. He felt more able to encourage the students, for example by emphasizing that student contributions did not necessarily have to be correct to be valuable for the class as a whole. As he sensed his students were insecure, because in the new lessons they had a higher responsibility for their own learning, he showed students the progress they had made after a few lessons. During his second enactment of the lessons, the focus for Mr. Bradley was even more on making students explain and discuss the physics to each other in theoretical terms. To this end he kept asking questions, while his whole class explanations were kept to a minimum.

Mr. Bradley proposed to his colleagues to use the experimental lessons as the standard way of teaching introductory electricity in the school. However, his colleagues did not like the absence of calculations in the experimental lessons. They considered these calculations necessary to prepare students for the physics lessons of the 10th grade. Moreover, they were critical of the model of charged particles used in the lessons. They considered this model incomplete and suggested that concepts such as the electrical field would have to be included. The end result of the discussion was that the experimental lessons were not used as a model for the school, but that Mr. Bradley could use them in his lessons.

Reading educational research literature on student conceptual problems related to electricity confirmed Mr. Bradley's idea that the topic of electricity is difficult for students. From taking part in the project he learned that instruction, in order to be successful, has to take student learning as a point of departure, instead of the content as presented by the textbook. However, no perfect instruction for the topic of electricity has been found yet. In the end he considered the experimental lessons equally successful as his usual approach, and a welcome variation for the students (D, TI).

4.8.3 The case of Ms. Campbell

At the time of the intervention Ms. Campbell taught two grade 9 classes in one of which she tried out the experimental lessons on electric circuits, while she taught her usual lessons on this topic in the other class. According to her students, physics lessons of this teacher typically consisted of brief theoretical explanations, after which students worked in groups on textbook problems. During this work, Ms. Campbell walked from group to group, making sure the students remained on task and answering student questions. Usually unfinished problems would be set as homework. To help students prepare for tests, she provided a summary of the theory on the board, briefly before the date of the test. According to one student these summaries were a very useful part of the physics course (SI, O).

Ms. Campbell was aware that electricity is a difficult subject for students. Getting better insight into students' conceptual problems and finding ways to help students understand the concepts of electricity were her concerns (TI, D). Moreover, she said she was open to experiment with new teaching approaches and to see if they worked for her, especially as she had only a limited experience as a physics teacher. For Ms. Campbell it was important the students were engaged during the lessons (M).

In the first lesson Ms. Campbell told the class the purpose of the lessons was to come to an understanding of what happens in electric circuits. She explained that the focus would not be on formulas and calculations. Instead, students would have to solve conceptual problems, find out how electricity works and what happens inside electric circuits. Student ideas would not be judged as right or wrong, but every idea could be useful and could contribute to get a complete picture of electrical phenomena. Ms. Campbell referred students to the worksheets to read about the way of working during the lessons and about the assessment (O). During the lessons she occasionally repeated she expected students to actively discuss and try to understand the topic. In the group meeting after the second lesson, she concluded some students seemed to actively participate while others were off task most of the time. Ms. Campbell was encouraged to use students' ideas where possible and to avoid giving answers students could find out by themselves. She conducted whole class discussions, but most of the time her students worked in small groups on conceptual problems from the worksheets or on experiments. As in her usual physics lessons she set unfinished problems as homework. The lesson observations of class discussions showed some students participating and coming forward with ideas, while a large part of the class remained off task. After consulting Ms. Campbell, the first author started to assist her in conducting class discussions, and to model aspects questioning, the use of computer simulations and the whiteboard. Ms. Campbell consistently used the particle model as a way to explain the phenomena in electric circuits. Students were observed talking about electric circuits in terms of the particle model. In group meetings the particle model was discussed, first before it was introduced in the classroom and later when issues concerning the model had arisen during the lessons (for example regarding the limits of the model when describing what happens inside a battery; Ms. Campbell remarked that the particle model was incomplete in this respect). Moreover computer simulations and their relation with the particle model were discussed during the group meetings.

In retrospect, Ms. Campbell found it useful to prepare the lessons collaboratively with other physics teachers. Discussing the way of working and the sequence of activities helped her think about her own role during the lessons. She also found it useful to develop the particle model together, because it gave her a clear picture of what was important for the students to understand. Moreover, although in terms of physics content the model was not new for her, it differed from the way electricity was treated in most textbooks. In the textbooks she used, electricity was explained in terms of metaphors, such as trucks carrying energy through a circuit, or water flowing through pipes. In Ms. Campbell's opinion the particle model was closer to physical reality than these metaphors and student understanding was fostered by the use of the model in the lessons. She expected it to be of use as a background for students also at a later stage, when they would have to carry out calculations and solve more difficult problems in electricity. In her view the particle model had been used consistently and had been extended on a lesson by lesson basis. In this way the lessons had gradually contributed to the development of student understanding. The regular group meetings during the enactment of the lessons were useful for Ms. Campbell in order to discuss the effectiveness of the approach and the development of student understanding. Moreover, the meetings were useful to get ideas from the other teachers (in particular from Mr. Adler). For example, Ms. Campbell decided to spend a lesson discussing the outcomes of student experiments theoretically, instead of continuing with the next topic (TI).

Looking back at the lessons, Ms. Campbell said she had learned to make students think by themselves instead of providing them with correct answers. She had noticed that during the first lessons students had to get used to the new way of working in class, but later a number of students came forward with their own ideas. This corresponds to the observations made by the first author. In general Ms. Campbell found the students more active in the experimental lessons than in her usual lessons. Students had to think, discuss and carry out experiments before they were given explanations. She said she could manage students working in small groups, but found it difficult to dominate class discussions. In her opinion the parts of the lessons in which students worked independently in small groups had been more effective than the teacher led class discussions (TI).

Four students, interviewed after the lesson, had noticed differences in comparison with their usual physics lessons. Especially they had noticed differences related to the lesson design, namely with respect to the student tasks, the type of problems and the pacing. One girl appreciated that understanding was the main aim of the lessons rather than carrying out calculations. Another girl appreciated the variety of activities and the opportunity to talk with others in whole class activities. Three of the four interviewed students indicated they preferred to work by themselves rather than in groups (SI). The questionnaire showed Ms. Campbell's students did not experience a significantly higher constructivist orientation in the experimental lessons on electricity (N=20, M=55.4, SD=14) as compared to their usual physics lessons (N=9, M=51.1, SD=15) using a related-samples Wilcoxon signed ranks test (T=17.5, p>0.05). The results of this class were affected by the fact that only 9 students from this group completed the questionnaire prior to the lessons.

Ms. Campbell thought the approach of the experimental lessons was generally successful, because the students had obtained good grades in the test for the topic. In her view the approach can be used for other topics as well, but a separate phase of preparation is needed, similar to the preparation of the lessons on electricity. In a follow-up interview a year later, she indicated she made some changes to her lessons as a result of her participation in the intervention. She started asking students for their own ideas when at the beginning of a new topic. She was less inclined to put the theory on the board for students to copy and sometimes used worksheets she prepared herself, instead of the problems from the textbook (TI).

4.9 Conclusions and Discussion

In the previous sections we described the cases of three teachers participating in a professional development process. One of its aims was to collaboratively create inquiry-based instruction as a form of context-based education. Another aim was to help the teachers to develop the knowledge and skills necessary to understand and enact this way of instruction. A number of activities took place in the framework of the professional development process: discussion of the physics content and a particle model, collaborative development of lessons and conjectured learning processes, enactment of the lessons, and reflection. Input to the process was provided based on research literature and on an earlier round of research and coaching took place in the period that the lessons were enacted. Thus, the professional development process had a number of the characteristics of successful professional development interventions listed by Van Veen et al. (2010) and Voogt et al. (2011): subject content and student learning were the starting points of the discussions, teachers' concerns and experiences were integrated in the process, teachers shared experiences and collaborated, classroom coaching was included and the process took a substantial amount of time. We set out to understand how participation in this process gave rise to teacher learning.

4.9.1 Reported teacher learning and changes in classroom practice

Topics of the first and second research questions were respectively the learning reported by the teachers and the changes of classroom practice. All three teachers reported new insights with respect to their pedagogical content knowledge (PCK; Shulman, 1986). For example, Mr. Adler mentioned he had learned to use metaphors on electricity more effectively, Mr. Bradley said he had learned to work with a simple theoretical model of electricity that was gradually extended while student understanding increased, and Ms. Campbell said the model had helped her to get more insight into the aspects of electricity that were important for students to understand. The teachers also reported learning related to the pedagogy used in the classroom. Amongst others, for Mr. Adler this consisted of a realization that teacher explanations were of limited use to promote student understanding and that the group activities during the lessons had increased the student ability to reason about electrical phenomena. Mr. Bradley had gained insight into the possibilities and limitations of using computer simulations and into questioning as a way to promote student thinking. and Ms. Campbell had realized the importance of encouraging students to think by themselves and taking student ideas as a starting point. Also changes of attitude were reported, such as increased confidence after a second enactment of the lessons (Mr. Adler and Mr. Bradley).

The classroom practice during the experimental lessons had been noticeably different from the teachers' usual lessons and according to the students had moved the classroom culture towards a culture of inquiry (significantly for two of the three teachers). Students indicated they cooperated more with others, carried out more experiments, had more opportunities to investigate things by themselves and had more opportunities to develop their own ideas. We can conclude that changes took place in the teachers' cognitions and attitudes, and in teaching practice, favorable to the creation of context-based lessons. Moreover, changes of classroom practice lasted beyond the time frame of the intervention.

4.9.2 Teacher learning and participating in the professional development process

Topic of the third research question was how the reported learning and the teachers' classroom practice are related to participation in the professional development process. The case descriptions show teacher learning was fostered and constrained by the combination of activities, the teachers' contextual situations and their starting point as professional educators. Professional learning in this study took place in various ways and was a dynamic process rather than linear and sequential. This is in line with the *interconnected model of professional growth* proposed by Clarke and Hollingsworth (2002). This model consists of four domains in which change can be initiated. Three domains are part of the everyday professional life of the teacher: a Personal Domain of teacher knowledge, beliefs and attitudes, a Domain of Practice, which refers to teachers experimenting with new approaches and a Domain of consequence in which teachers interpret outcomes. The fourth domain is the External Domain offering support and sources of information. Change initiated in one of the domains can lead to change in other domains through processes of enactment and reflection. The changes take place in a 'change environment' such as the school organization, aspects of which may hinder or facilitate the professional growth process. Clarke and Hollingsworth distinguish short term teacher change resulting from participation in professional development activities and longer lasting 'teacher professional growth'. Voogt et al. (2011) showed the model is also suitable to describe learning processes taking place in teams of teachers who collaboratively designed instruction. We will refer to the interconnected model of professional growth mainly to illustrate the dynamic nature of the teachers' learning processes.

In the following sections we will elaborate on the relation between teacher learning and their participation in the professional development process, using four themes, which were at the core of the intervention: (1) fostering the understanding of theoretical concepts, (2) creating a classroom culture of inquiry, (3) the teachers' concerns, and (4) the reflection and feedback on the enactment of the lessons. Then we will discuss the impact of some factors external to the intervention, in particular the starting point of the teachers prior to the intervention and the situation at their schools.

4.9.3 Fostering the understanding of theoretical concepts

The collaborative discussion of physics content followed by the development and enactment of the lesson series played an important role in the learning process of the teachers. Based on the idea that students need to be provided with theoretical tools to help them talk about phenomena in theoretical terms, rather than as a collection of facts (Kock et al., 2013; Chapter 2) , we discussed a model of moving charged particles at the level of the students, and ways of using this model to help students overcome conceptual problems. Moreover, we discussed the use of metaphors and various interactive computer simulations and the role of experiments in relation to the particle model. These ideas were not new to Mr. Adler, Mr. Bradley and Ms. Campbell, and they were already aware that understanding electricity in simple direct current circuits is difficult for grade 9 students. However, they indicated that using such a model productively as a theoretical tool in physics instruction in grade 9 was new to them. The discussion and lesson development allowed them to develop a deeper understanding of the physics content in relation to student learning and understanding. There is evidence from research that also for teachers the concepts of electricity are often not without problems (see for example Gunstone et al., 2009). Enacting the lessons made the teachers aware of the limits of their own understanding, in particular concerning the limitations of the particle model. For example, students asked questions Mr. Adler and Mr. Bradley were unprepared for, such as how a rechargeable battery works. During their second enactment of the lessons, four to six months after the first, Mr. Adler and Mr. Bradley did not encounter such unexpected situations. This indicates Mr. Adler and Mr. Bradley had learned from the combination of teaching experiment, coaching and continued discussions during collaborative group meetings. In terms of Clarke and Hollingsworth's (2002) Interconnected model of professional growth several domains of teacher change were addressed during the intervention: the intervention started with input from the external domain and personal domains (the theoretical model, the teachers' concerns) , while professional development was enhanced by the domain of practice (enactment of instruction) and domain of consequences (interpretations of lesson outcomes). As the changes lasted beyond the time frame of the project we can talk of professional growth: changes of teacher competences that were more than momentarily.

4.9.4 Classroom culture of inquiry

We can discern a similar pattern when considering the changes of classroom interaction and social norms (Cobb & Yackel, 1998), and the creation of a classroom culture of inquiry. Central in the approach were a focus on understanding and explaining, and an interest in student ideas. It was hoped that a classroom culture could be created in which students would actively investigate and try to understand electrical phenomena, through experimental and theoretical tasks. The teacher had to initiate and maintain the change of classroom culture, supported by the available materials (student worksheets, computer simulations). Moreover, the teacher had to orchestrate whole class discussions, work in small groups and individual work. Ideas to change the classroom culture were initiated in the external domain, on the basis of literature and earlier research. The ideas were discussed during the group meetings and where possible incorporated in the design of the lessons. However, to change the classroom culture also a change of teacher behavior was needed (domain of practice). To some extent this change of behavior could be included in the lesson planning. For example, as agreed all three teachers started to explain to their classes the new way of working in the experimental lessons, as well as the expectations and the assessment. But to a large extent the teachers had to change their behavior by responding in new ways to situations that arose during the lessons. For example, instead of explaining physics content, the teachers were expected to encourage students to express their ideas. These changes were fostered by means of modeling and coaching during and after the lessons. Interviews and questionnaires show that the change of the classroom culture was noticeable for the students, although by varying degrees.

4.9.5 Teachers' concerns

The changes to the lesson content and changes of the classroom culture were initiated in the external domain, but were in line with relevant concerns of Mr. Adler, Mr. Bradley and Ms. Campbell (the personal domain). They were concerned about the limited student understanding and had conjectures of how this could be remedied: for example by using metaphors in a different way or by combining experiments and computer simulations. Some of their conjectures were made the topic of practitioner research projects. They were also interested in deepening their understanding by reading literature on student conceptual problems in electricity and in discussing and trying out suggestions to change their teaching. Mr. Adler and Mr. Bradley decided to repeat the lesson series in the following school year and made modifications to their lessons to make them more successful. We see these as indications that the teachers developed a commitment and co-ownership of the project aims. Thus, the experimental lessons became teaching experiments in which they could test their ideas.

4.9.6 Feedback and reflection

All three teachers mentioned learning experiences due to the feedback and coaching they received, even though Mr. Bradley and Ms. Campbell received coaching and feedback less frequently than Mr. Adler. Mr. Bradley and Ms. Campbell particularly valued the exchange of ideas and the feedback from the other teachers during the collaborative group meetings. These ideas and feedback most of the time concerned suggestions on how to solve particular classroom situations, for example how to make student groups work more effectively by assigning different roles to students. The coaching, during and after the lessons, was usually related to the lesson content and to what the teachers could do to establish a culture of inquiry, in line with the aims of the lesson series and the teachers' concerns.

All three teachers reflected on the enactment of the lessons and on the way students responded during the lessons and the extent to which expectations were met. These reflections led to new insights related to the teachers' concerns, For example, in this way Mr. Bradley gained insight into the effective use of computer simulations. Reflection on the lessons also led to insights not directly related to the teachers' original concerns. For example, Mr. Adler noticed that in the experimental lessons the level of students understanding was more visible to him. He also noticed the increased understanding of the experimental class in comparison to the non-experimental class. For Mr. Adler this positive feedback served as an incentive that increased his enthusiasm for the project. For Mr. Bradley and Ms. Campbell positive results from the experimental lessons were less evident in the day to day lessons. However, their commitment was high enough to keep experimenting. Mr. Bradley changed aspects of his teaching approach after the first enactment of the lessons, on the basis of his reflections. He felt the response of the class during the second enactment of the lessons was more successful than when he tried it for the first time. Reflecting on her lessons, Ms. Campbell gained insight into ways to foster students' active thinking and into instructional methods that suit her (such as group work) and those that don't (such as whole class discussions).

Coaching and feedback made it possible to address the teachers' needs at an individual level. This is in line with Fullan (1985) who argues that, besides practice, feedback is essential when teachers learn new skills, because this learning is an incremental and developmental process. Continued practice, coaching, reflection and collaborative discussions helped sustain the teachers' developments.

4.9.7 The teachers' starting points and contextual situations

Mr. Adler, Mr. Bradley and Ms. Campbell reported different learning experiences and were not equally successful in moving their teaching practice towards context-based education. This can be understood at least partly from their starting points as teachers and from the contextual situation (the change environment) in which they worked. Although in all three cases the classroom culture changed in the experimental lessons, the largest effect was seen in Mr. Adler's class, followed by Mr. Bradley's. Prior to the intervention, students in Mr. Adler's class already were used to coming forward with their questions and ideas. In combination with his long experience as a teacher and his resolve to include all students, this can help us understand why the culture in Mr. Adler's classroom changed the most. On the other hand, the classroom management required for the new pedagogy was difficult to handle for Ms. Campbell, who was only in her second year as a physics teacher.

Another factor likely to have influenced teacher learning and the changes of teacher practice, is the frequency of feedback and reflection meetings. Mr. Adler received feedback more often than Mr. Bradley and Ms. Campbell and adaptations to his lessons could be made more frequently. On the other hand Mr. Bradley and Ms. Campbell started their lessons later and could use some of the experience already gained during the first enactment. Although it is difficult to determine the impact of this difference, lesson by lesson evaluations were an important aspect of the approach and in this respect the conditions for Mr. Bradley and Ms. Campbell were not optimal.

Contextual factors played a role in the effect of the intervention on the longer term. Mr. Adler and Mr. Bradley had the possibility to repeat the lesson series the next school year and decided to do so, which gave rise to new learning experiences. The opportunity of teaching the lesson series a second time was not available to Ms. Campbell as she did not teach a grade 9 class the following school year. However, Ms. Campbell decided to make changes to her general physics teaching practice based on what she had learned. Colleagues of Mr. Adler and Mr. Bradley responded in different ways to the experimental lessons. Mr. Adler's colleagues asked for advice on how to improve students' understanding on electricity, while Mr. Bradley's colleagues questioned aspects of the experimental lessons. The examples illustrate that on the one hand the points of departure of the teachers and on the other hand the context in which the professional development took place, afforded and constrained the results that could be obtained.

4.10 Coda

The intervention described in this chapter appears effective in changing the knowledge and practice of teachers, towards a more context-based approach. It can be seen as a paradigm case illustrating the underlying mechanisms of this type of interventions. The driving force behind the professional development process is the teachers' willingness to invest in changing their teaching practice, in order to obtain better results in terms of student understanding and active inquiry. There are two important prerequisites for this process to start and continue. The first prerequisite is for the teachers to believe that a new instructional approach could work. An agenda for educational innovation matching with classroom concerns of the participants can foster this belief. Moreover, the teachers then have a real interest in the results of the innovative lessons and are likely to develop interest and commitment. The second prerequisite is for the teachers to have the means at their disposal to have a fighting chance in the classroom. They will have to be helped with research-based ideas to develop innovative education. A local instruction theory has the potential to provide such ideas, while general guidelines on context-based education are not domain specific and detailed enough (Leach & Scott, 2008). Earlier research already showed the importance of a well-balanced local instruction theory (Kock et al., 2013; Chapter 2).

As the different activities of the intervention complemented each other, it is comprehensible that change became apparent in various domains of Clarke and Hollingsworth's Interconnected model of professional growth (2002). During the initial discussions on lesson content and pedagogy, and during the collaborative design of instruction there was input from educational research, but also room for the teachers to raise their own classroom concerns. This opened the possibility to provide coaching on an individual basis and to reflect on issues that really mattered to the participants, while keeping a focus on the local instruction theory and the chosen pedagogy. The enactment of the lessons in combination with classroom coaching made the teachers realize the consequences of the chosen approach in practice. Feedback and reflection gave new insights and led to modifications of the local instruction theory and the instructional materials.

The teachers experienced success when they noticed increased student participation and understanding. These experiences amplified commitment and interest. Through these experiences the teachers' learning processes are more likely to become self-sustaining and to lead to lasting changes of teaching practices towards a more context-based approach. However, all three teachers also experienced some setbacks and less successful activities. The cases of Mr. Bradley and Ms. Campbell show that a noticeable increase of student participation and understanding is not always easy to accomplish. Coaching, feedback and the possibility to exchange experiences appeared to help teachers persist in the light of less successful experiences.

The study concerned an intervention with a specific purpose and setting, and only three participants. Obviously, it cannot be taken as a blueprint to be used directly in interventions at a larger scale. Moreover, the results indicate particular modifications to the intervention could increase its effectiveness. First, feedback and reflection are probably most effective on a lesson by lesson basis, as in the case of Mr. Adler. Mr. Bradley and Ms. Campbell might have been more successful if they had received more frequent feedback. In the planning of similar interventions, lesson by lesson feedback and reflection has to be an important consideration. Next, research findings indicate professional development interventions are more successful when teams of teachers at a school are involved (Van Veen et al., 2010), whereas the teachers in this study cooperated without the involvement of colleagues at their schools. Mr. Bradley's colleagues were somewhat skeptical about the experimental lessons. Without support it might be difficult for him to further develop the approach and sustain his learning process. A similar intervention in collaboration with a team at a school would have a different dynamic and could be a topic of further study. Finally, in this study we developed a local instruction theory and a prototype of a lesson series, which need further optimization. The teachers mentioned areas of improvement, such as the wording of certain tasks, the balance between student freedom and structure, and the inclusion of specific tasks to support student work with computer simulations.

CHAPTER 5 MODELS OF ELECTRICITY IN PHYSICS TEXTBOOKS: ENABLING OR CONSTRAINING INQUIRY-BASED INSTRUCTION?

Abstract. Models of electricity were investigated in a series of commonly used secondary school physics textbooks. The earlier studies indicated that students need a basic theoretical model in an inquiry context. 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.

5.1 Introduction

Over the last decades innovative approaches in the secondary school science subjects have attempted to bring science education more in line with insights from the Nature of Science (NOS) (Duschl, 2008). A process goal of these approaches has been to actively involve students in scientific processes, for example in authentic scientific activities (Roth et al., 2008), by using meaningful contexts (Gilbert, 2006), through curricula based on modeling activities (Halloun, 2007) or by the creation of a culture of inquiry in the classroom (Cobb & Yackel, 1998; Minner et al., 2010). In physics, the product goal of helping students understand theoretical concepts and models has remained important, because attempting to understand phenomena theoretically is a typical aspect of the nature of physics (J. Park & Jang, 2005). Students cannot be expected to reinvent theoretical concepts and models entirely by inductive experimental activities, and therefore they need to be given a basic model as a theoretical starting point for inquiry activities (Kock, Taconis, Bolhuis, & Gravemeijer, 2015; Chapter 3). In an inquiry context, the way a model is presented to students should afford conceptual and experimental inquiry activities and should respect insights from NOS.

The main source of scientific models in the classroom, both for the students and the teacher, is the textbook (Abd-El-Khalick et al., 2008). Several studies have addressed how aspects of NOS are represented in textbooks (Abd-El-Khalick et al., 2008; D.-Y. Park & Lavonen, 2013). However, what has received little attention is the extent to which the content and use of scientific theories and models in textbooks are consistent with NOS and thus afford or constrain student inquiry and conceptual understanding. In this chapter the focus will be on theoretical models of electricity in secondary school physics textbooks. Criteria to evaluate models in physics textbooks were operationalized from an interpretation of literature on models and modeling in science and science education. These criteria were used to evaluate the models of electricity presented in a set of grade 7 to 12 physics textbooks in the Netherlands. As electricity is a broad field, we the emphasis of the study was on models involving the core topics electric charge, current, voltage and resistance.

5.2 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?

5.3 Theoretical framework

In the following we summarize the aspects of NOS and inquiry-based instruction relevant for the textbook analysis of this study, and the role of models in physics and physics education. Finally, we briefly outline models of electricity commonly used in physics textbooks.

5.3.1 NOS and Inquiry-based Instruction

The term NOS refers to the values and beliefs underlying the development of scientific knowledge (Lederman, 1992). There is no consensus on what exactly constitutes NOS, but there is reasonable consensus among researchers on the aspects of NOS relevant to secondary school students. From the lists of consensus aspects given by (Abd-El-Khalick et al., 2008) and (Osborne et al., 2003) we note those pertaining to the creation and use of models: (a) theories and models form the basis for hypotheses and predictions in science, (b) scientific ideas are tested by experiments, (c) theories and models are used to analyze and interpret data, (d) there is diversity in the way the world may be explored, (e) science requires creativity, and (f) scientific knowledge develops over time. Helping students understand NOS requires explicit focus on NOS during instruction (Abd-El-Khalick et al., 2008). The purpose of inquiry-based instruction is not to explicitly discuss NOS, but to allow students to experience "science in the making" as expressed by the NOS aspects (a) – (f).

Inquiry instruction engages students with scientific phenomena, emphasizes student active thinking and responsibility for learning, and uses parts of an investigation cycle (Minner et al., 2010). It is important that student inquiry activities are carefully prepared, because otherwise students are unlikely to construct the desired conceptual understanding, in particular concerning abstract and complicated topics. Therefore, these activities should be part of a local instruction theory: a sequence of "instructional activities, and a conjectured learning process that anticipates how students' thinking and understanding might evolve when the instructional activities are employed in the classroom" (Gravemeijer & Cobb, 2006, p. 19).

The provision of a theoretical starting point, or basic model, on which students can build and which they can expand, is an important feature of a local instruction theory in inquiry-based instruction at secondary school level (Kock et al., 2013; 2015; Chapters 2 and 3). This presents an authentic approach to inquiry, because experimental work in physics research is usually guided by theoretical considerations (J. Park et al., 2009). For example, the model provided to students in (Kock et al., 2015; Chapter 3) consisted of a text in which a brief and strongly simplified charged particle model was described. The students and teacher used it as a tool that helped develop conceptual understanding in combination with student experiments, computer simulations, conceptual questions and classroom discussions. It provided a language to qualitatively describe, explain and predict phenomena in electric circuits, such as the brightness of light bulbs. This first model of electricity for the students reached its limits when they tried to use it in relatively complicated situations, such as in combined series/parallel circuits. The study did not consider the extent to which this model helped students familiarize themselves with various textbook models of electricity in subsequent years, such as the electric field model, and the quantitative laws such as Kirchhoff's laws and Coulomb's law.

5.3.2 Models in science

The use of models in science and in science education has been widely studied (Justi & Gilbert, 2002; Matthews, 2007; Seok Oh & Jin Oh, 2011; Van der Valk, Van Driel, & De Vos, 2007). The description below was first of all based on the review article by Seok Oh and Jin Oh (2011) on what teachers should know about models and modeling, and on the May 2007 special issue on scientific models in the journal Science & Education. These articles were summarized, keeping in mind the intended application to textbooks at secondary and high school level. Therefore, we did not consider articles referring to a strictly mathematical treatment of models. Additional articles (Besson, 2010; Clement, 2008; Jonassen, 2008; Justi & Gilbert, 2003; Lesh & Doerr, 2000; Louca & Zacharia, 2012; J. Park et al., 2009; Rutten, Van Joolingen, & Van der Veen, 2012; Van der Valk et al., 2007) were used to complement the findings, in particular on the use of models in education and on NOS, until no major new insights were found. The description is structured along relevant aspects of models: the meaning and purposes of models, the relation of models with experiments, and the multiplicity and development of models. We also discuss the uses of models in the physics classroom and results of earlier studies of models in science textbooks. Reference is made to the criteria to evaluate models in textbooks described later in the chapter.

Meaning and purposes of scientific models. Lesh and Doerr (2000, p. 10) gave the following general definition of models: "Models are conceptual systems (consisting of elements, relations, operations, and rules governing interactions) that are expressed using external notation systems, and that are used to construct, describe, or explain the behaviors of other system(s)—perhaps so that the other system can be manipulated or predicted intelligently." 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)*, which are created for a particular purpose (Develaki, 2007; Seok Oh & Jin Oh, 2011). The representational character of models implies that they qualitatively, functionally or formally resemble *(distinguish model and phenomenon: criterion 2)* the selected part of reality (Jonassen, 2008). Models may contain theoretical objects and concepts that are not directly observable (Seok Oh & Jin Oh, 2011) and that through their relationships explain mechanisms *(theoretical objects and their relations: criterion 6)* of the phenomena the model aims to describe (Clement, 2008). Using these theoretical objects and concepts in models is what gives meaning to them (Halloun, 2007). Both realist and empiricist standpoints exist among philosophers of science and scientists regarding the nature of the non-observable objects and concepts in scientific models (Koponen, 2007; Seok Oh & Jin Oh, 2011).

Models are used to describe and explain phenomena, as well as to make predictions (Seok Oh & Jin Oh, 2011). Developing explanatory models is a central goal of most sciences (Clement, 2008). Explanations can take place by showing mathematical relations between variables *(calculations: criterion 13)*, such as in Boyle's law, or through causal reasoning, using, among others, unobservable theoretical objects and concepts present in the model (Besson, 2010; Justi & Gilbert, 2003). For students, the latter may be more appealing and understandable than formal mathematical laws, as it better corresponds to causal reasoning in everyday life (Besson, 2010). In society model predictions are used as tools in decision making processes or to manipulate technological systems (Van der Valk et al., 2007). The models involved can become very complicated and large-scale, such as in the case of climate models *(purposes of models: criterion 7; using models to make decisions, give advice, or manipulate systems: criterion 15).*

Finally, models facilitate thinking and communicating about aspects of reality by providing the necessary language and symbolic resources. In particular this is facilitated by the use of analogies, non-linguistic resources such as graphs and diagrams, and runnable simulations of phenomena, such as computer simulations (Seok Oh & Jin Oh, 2011).

Models and experiments. The creation of a model necessarily takes place through abstraction and idealization, because reality is too complex to correspond exactly to theory *(abstraction and idealization: criterion 2)*. This allows a model to capture the essence of phenomena while leaving out many details (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 *(addressing model precision and fit: criterion 11)*. The concept of 'model fit' is used to describe how well a model corresponds to observations and whether this fit is good enough depends on the model's purpose. Experimental setups and results may be matched to theoretical models, but models may also be adapted to correspond better to experimental phenomena (Koponen, 2007). When models are used in empirical testing of predictions, it is important to take into account the idealizations and assumptions that apply to the model (J. Park et al., 2009).

Some philosophers of science distinguish general fundamental theories (such as Newtonian mechanics) from models. In this view models pertain to specific phenomena and are created from the fundamental theories in combination with abstracted and idealized features of the phenomena (Develaki, 2007; Matthews, 2007). A purpose of these models is to mediate between theory and reality or experiment. Experimental results or observations can be understood in terms of the theory through the model, and the model may be used to design experiments and create predictions based on the theory *(testing model-based predictions: criterion 10).*

Multiplicity and development of models. Scientific models can be built in many ways, including through the creation of physical objects, pictures and diagrams, text, mathematical equations and computer simulations (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 is important in determining how a model is constructed, what idealizations and heuristics are used (Celestino Silva, 2007), what the purpose of the model is, and how the target phenomenon is interpreted (Seok Oh & Jin Oh, 2011). Models are often a compromise between accessibility and correspondence to the target, where more advanced models with higher correspondence to the target tend to be less accessible (Van der Valk et al., 2007). Model creation always involves an element of creativity. For example, analogies are often looked for and used *(use of analogies: criterion 3)* when models are created to describe new phenomena (Celestino Silva, 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, or of empirical evidence, such as discrepancies with data (Minner et al., 2010; Osborne et al., 2003; J. Park & Jang, 2005; Van der Valk et al., 2007). Another reason to change a model is a shift in its purpose (J. Park & Jang, 2005; Van der Valk et al., 2007).

5.3.3 Models in physics education

There is widespread agreement that models have a role to play in physics education in line with the Nature of Science. According to Halloun (2007) important scientific inquiry processes suitable for transfer into education are the construction of a new model, the use of an existing model for solving empirical or theoretical problems, model testing and the adaptation of models based on theoretical or empirical considerations *(model building or evaluation: criterion 12).* Halloun proposes to organize the entire physics curriculum around such modeling activities. Seok Oh and Jin Oh (2011) and Van der Valk, Van Driel and De Vos (2007) agree that working with models and carrying out modeling activities should receive more emphasis in science classes. Besson (2010) stresses the possibilities explanatory models offer for causal reasoning *(tasks using conceptual reasoning: criterion 9).* Some authors point out the importance of models to promote understanding, for example by using material or computer models to visualize how things work, or to visualize different levels of representation, such as macro and sub micro levels in chemistry (Justi, Gilbert, & Ferreira, 2009; Seok Oh & Jin Oh, 2011).

Computer based models in which phenomena can be simulated are particularly suitable for student activities aimed at creating, testing, and using models, as well as for generating and testing hypotheses. A review study (Rutten et al., 2012) reported positive learning results when traditional lectures were replaced or enhanced by computer simulations. The authors noted that computer simulations can support various aspects of inquiry *(using runnable simulations: criterion 16)*, but that integration of the activities into the lessons and into the curriculum is still a point of attention. Various computer environments exist in which students can construct dynamic models, using graphical, programming or mathematical tools. Research on the use of these systems in science education is ongoing. Recent studies indicate that the student learning processes to a large extent depend on the characteristics of the tool used, and that the role of the teacher in such learning environments is demanding (Louca & Zacharia, 2012).

5.3.4 Research on models in textbooks

The way models are treated in science textbooks does not always do justice to NOS and inquiry-based instruction. In chemistry education the content and use of models in textbooks is criticized by researchers taking this viewpoint, for example in (Erduran, 2001). Textbooks often present models as static and final versions of our knowledge. The development and limitations of the models are ignored. Different models of the same phenomena are not clearly distinguished and the reasons for introducing new models are not made explicit. Chemical models are often used for visualization, but the connections to abstract concepts and theory are often ignored. Experiments are mainly used to verify textbook knowledge and are not related to the development of models. Textbooks are also criticized for using “hybrid models” (Erduran, 2001; Justi & Gilbert, 2003), models containing elements from various historical models that paint a historically incorrect picture of scientific development.

Research in physics education focused to a large extent on the content and appropriateness of models offered to students, in relation to problems of conceptual understanding, but to a lesser extent on NOS-related issues. For example, Stocklmayer and Treagust (1994) investigated the way electric current was represented in secondary school textbooks between 1891 and 1991. Most introductory texts from the mid 60's used a moving charged particle model starting from a basic understanding of atomic structure and of electrostatics: a potential difference gives rise to the movement of electrons in a circuit. Earlier textbooks relied on fluid models of electricity, the origins of which can be dated to the time before Faraday's field concept. Recently attempts have been made to use the field concept as a foundation to understand electric circuits, first at tertiary, and later at high school level (Stocklmayer, 2010). These models require the idea of surface charge on circuit wires to create electric fields and, at a more advanced level, Poynting vector theory to explain energy transport in electric circuits (Galili & Goihbarg, 2005). Often analogies from other field of physics, such as water circuit and gravitational analogies, have been used to foster student understanding of the concepts of electricity. Hart (2008) considers many of these as problematic because they assume an understanding of the physics theories underlying the analogies, which students often do not possess. Various other analogies therefore have been introduced such as a transport analogy, "teeming crowds" and anthropomorphic analogies, in which electrons are given a human character, carrying energy through the circuit.

Sangam, Jesiek and Thompson (2011) studied the presentation of DC circuit theory in an undergraduate textbook from the perspective of student conceptual understanding, but not from an NOS or inquiry viewpoint. The instrument they developed for the textbook analysis is structured around presentation features, conceptual features focused on misconceptions, and analogies. In the textbook they analyzed they found a number of conceptual weaknesses that might promote student misconceptions. Gunstone, McKittrick and Mulhall (2005) analyzed three senior high school textbooks, and interviewed their authors with regard to the central concepts of electricity and with regard to the meaning of models and analogies. They noted that the authors had no clear understanding of what a model is, and that model and analogies were sometimes not distinguished.

In the present study there will be less emphasis on the detailed conceptual content of the textbook, and more on the connection with NOS, because the perspective guiding the study is that the models presented in the textbook should have the potential to contribute to a culture of inquiry in the classroom.

5.3.5 Evaluating textbook models with the help of criteria

Models in secondary school physics textbooks are used to describe and explain physics content. Moreover, they appear implicitly or explicitly in student tasks and activities. The main aspects of models and their use described in the literature overview were reformulated as criteria to evaluate physics textbooks from an NOS point of view. These criteria, listed in Table 5.1, provide a model-oriented perspective to examine physics textbooks.

Table 5.1
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 5.1 will lead to a qualitative description to answer the question to what extent the presentation and use of models of electricity in the textbooks enable or constrain inquiry-based instruction. Textbooks may not explicitly state that models are used or that student tasks involved modeling activities, while from an NOS point of view the content or task still fit the description of one or more of the criteria. Moreover, the criteria are qualitative in nature and thus need a qualitative evaluation.

5.4 Method

5.4.1 Selection of physics textbooks and chapters

The criteria of Table 5.1 were applied to physics textbooks in Dutch pre-university physics education. The selection of the textbooks was guided by 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; for the purpose of the study this was considered more interesting than the comparison of textbooks for the same grades.
2. The textbooks were published by a single publisher using a consistent pedagogic approach, so that coherence in content between the grade levels could be expected.
3. Recent editions of the textbooks were available.
4. The textbooks were widely used in Dutch schools.

After examining textbook series from different publishers one textbooks series was selected for grade 7 to 9 and one for grade 10 to 12, both from the same educational publisher. In the Netherlands separate physics textbook series exist for grades 7 to 9 and for grades 10 to 12 as a result of the Dutch pre-university curriculum (*VWO*), in which students at the end of grade 9 select the subject package for their final examination in grade 12. All students will study some physics in grades 7, 8 and/or 9, while physics is not obligatory for all students in grades 10 to 12. The selected textbooks series use the same pedagogic approach and are widely used in Dutch secondary education (market leaders). New editions of the textbooks for grade 7 to 11 have recently been published to adapt the books to recent curriculum changes. The new grade 12 textbook was not available at the time of the study. The previous edition of the grade 11 and grade 12 textbooks were also studied, to ensure that all relevant content was included.

Table 5.2
Physics Textbooks and chapters used in the study

Grade	Textbook	Chapters	Pages	Abbreviation
7/8	Impact NaSK 1-2 Havo/VWO (Betlem, 2011)	2. Electricity	55-95	Impact7/8
9	Impact Physics 3 VWO (Betlem, 2013)	1. Electric appliances	7-81	Impact9
10	Newton: high school Physics. 4 VWO main text (4th Ed.) (Flokstra & Groenewold, 2012)	1. Electricity: electric circuits and energy use 6. Skills (dynamic modeling)	6-45 n.a.	Newton10
11	Newton: high school Physics. 5 VWO main text. (4th Ed.) (Flokstra & Groenewold, 2014)	7. Music and telecommunication 8. Electric motors and dynamos	n.a. n.a.	Newton11
11	Newton: Physics for the second phase. VWO information book 2 and student task book 2 (3rd Ed.) (Kortland et al., 2007a) (Kortland et al., 2007b)	15. Matter: Particle theory and radiation	n.a.	Newton11 3rd Ed.
12	Newton: Physics for the second phase. VWO information book 3 and student task book 3 (3rd Ed.) (Kortland et al., 2008a) (Kortland et al., 2008b)	18. Cathode ray tubes: Electric and magnetic fields. 19. Matter and radiation: Particle or wave theory.	n.a. n.a.	Newton12 3rd Ed.

Note. Page numbers are shown for the chapters studied in full. For the chapters studied in part the page numbers give no indication of the amount of material, so n.a. is shown.

The criteria of Table 5.1 were applied to the chapters on electric phenomena in each textbook. Table 5.2 shows the selection of textbooks and chapters. The table also shows the abbreviated names used in the chapter for the textbooks: the name of the book series followed by the grade, and if necessary the edition. The chapters on direct current electricity were studied in full. Other chapters contained sections featuring relevant concepts, such as electric charge or charged particles, current, voltage, and resistance. The relevant parts of these chapters were studied, that is, the sections referring in some way to these concepts. In the Newton10 chapter Skills, the sections on dynamic modeling were included. Physics content in these sections was mostly taken from mechanics, but we decided to analyze it, in order to provide a fair account of the sections' content on modeling. Similarly, relevant sections in the chapter on the structure of matter did not refer to current electricity, but to some extent to charged particles and to models, and so they were included.

5.4.2 Applying the criteria to the textbooks

The chapters in the Impact and Newton 4th ed. textbooks consist of numbered sections and unnumbered subsections. Subsections are further divided using headings. Numbered student tasks are provided at the end of the subsections. Some of these tasks in the Newton textbooks (in particular experiments) are available on worksheets that need to be downloaded from the textbook's website. The chapters in the Newton 3rd ed. textbooks consist of numbered sections and headed subsections. Student tasks are provided in a separate book. Experiments and optional topics can be downloaded from the textbook's website.

The units of analysis of the chapters studied in full were the headed paragraphs and the numbered students tasks, including the tasks available online. The applicable criteria were scored for each paragraph or task and qualitative notes were made summarizing the content or task in keywords. The scores were not unique: a paragraph or task could relate to more than one criterion. The paragraphs and tasks pertaining to electricity were handled in the same way in the chapters only partly studied.

A second rater scored 17% of the total material to assess if the list of criteria could be reliably applied. Differences between the scores of the two raters mainly concerned different interpretations of the criteria. The researchers discussed these differences after which some criteria and rater instructions were reformulated and examples were added. A second and third rater then scored 19 and 21% respectively of the total material. Differences still existed between the scores of the first rater and these raters, in particular for criteria 1, 9, and n.a.. Distinguishing criterion 1 from n.a. was complicated by the condition that a description should be relevant for the topic (electricity) in order to score criterion 1. Distinguishing criterion 9 from n.a. was complicated by the condition that this criterion was not scored in the case of simple recall. Differences also existed for criterion 8, mainly caused by a rater's failure to recognize simultaneous use of more than one model (e.g. textual description and diagram). In spite of the differences criteria 1 and 9 received high scores from all raters. Criterion 8 was most often scored when the textbook provided a mathematical or graphical representation apart from a textual description. Thus, the analysis of the differences between the raters indicated that these differences did not disturb the overall qualitative evaluation arising from the scores.

The criteria scores were qualitatively interpreted on the basis of descriptive summaries of the text and task content to arrive at an evaluation of the use of models in relation to NOS. This was required, 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 experimental inquiry task in line with NOS, but also in the case of a traditional textbook calculation problem.

5.5 Results

We present the criteria scores and a qualitative evaluation of the descriptive paragraphs and the student tasks. The qualitative evaluation is structured along the relevant aspects of models used in the theoretical framework.

5.5.1 Descriptive paragraphs.

Table 5.3 shows how often descriptive paragraphs met the criteria listed in Table 5.1. The table cells indicate the criterion scores, as an absolute frequency, and as a percentage of the total paragraphs. Not applicable (n.a.) was scored when a description could not be related to any of the criteria or to the topic of electricity. For example: an explanation of unit prefixes (such as kilo-, milli-) was scored as n.a., because it was not related to the topic; a technical description of the chemical reaction in a fuel cell (with no reference to electric charge) was scored as n.a. for the same reason. In the qualitative evaluation n.a. scores were treated as neutral because they were not related to models of electricity. Chapter 6 from Newton10 and chapters 7 and 8 from Newton11 were not included in the table, because so little textbook content was related to electricity in these chapters that quantitative scores were not justified.

Table 5.3

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.

Meaning and purpose of models. The Impact7/8, Impact9, and Newton10 chapters displayed a similar pattern in the descriptive paragraphs: criteria 1 (description of phenomena) and 6 (concepts and their relations) were scored more often than the other criteria. In Impact7/8 phenomena and contexts received most attention, and the concepts electric energy, current, and voltage were introduced in connection with these phenomena and contexts. Compared to Impact7/8, the focus in Impact9 was more on physics concepts and their quantitative relations, while phenomena and practical applications remained important. At the end of the chapter a section was included on static electricity. This was an extension of the model of electricity offered in the chapter, but it was not explicitly related to electric circuits. The Newton10 chapter on electricity overlapped to a large extent with Impact9, with further extension of the theory and applications. Among others, the Newton10 chapter included the concept of conventional current, electron drift velocity, variable resistors, Kirchhoff's laws, and semiconductor components (diode, MOSFET, LDR, NTC). Quantitative relations between concepts received more emphasis with increasing grade level: the Impact7/8 chapter contained no formulas in the text, the Impact9 chapter contained 9 and Newton10 contained 20. Thus, the models of electricity in the textbooks were extended and became more sophisticated with increasing grade level, although the core features of the models were repeated in the grade 7-10 textbooks.

The texts explained the concepts of electricity by means of a model of flowing electrons and the occasional use of water and traffic analogies. The model of flowing electrons 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 when the text indicated a limitation of the water analogy (water flow does not need a closed circuit), or of a diagram (electrons are much smaller and more numerous than drawn). Concepts introduced in the grade 7-10 books were used in Newton11: current, voltage and electrons were used to describe electromagnetic phenomena.

The Table 5.3 scores of the Newton12 3rd Ed. chapters generally followed the pattern described for Impact7/8, Impact9 and Newton10. The Newton12 3rd Ed. chapters dealt with electric and magnetic fields, with cathode rays and the electron, and with the wave-particle duality. Electric fields were introduced as a way to analyze electrostatic situations, unrelated to electric circuits (except in one student task).

The Newton11 3rd Ed. chapter on matter differed from the other chapters, because it explicitly addressed the limitations of models and described a historical sequence of discoveries leading to the development of new models to overcome these limitations. The chapter described a model as increasingly sophisticated representations of invisible reality. The creation of models was related to scientific work as a human endeavor, with the purpose to explain phenomena.

Multiplicity and development of models. In the Impact7/8, Impact9, and Newton10 chapters criterion 8 (different models of the same target) was mainly scored because of the introduction and use of pictures and circuit diagrams, and criterion 3 (use of analogies) because of the water and traffic analogies of electricity occasionally used in the three chapters. The texts did not address the historical development of the models, nor the development of school science models over the course of the different grade levels.

Parts of the chapter studied in Newton11 3rd Ed. addressed the historical development of models (criterion 4), in contrast to Impact7/8, Impact9 and Newton10. The text gave an account of the development of models of matter in a historical succession, such as the kinetic gas theory, the theory of atoms, the discovery of electric charges and of electrons, the Rutherford and Bohr models of the atom, models of the atomic nucleus and the discovery of elementary particles. The chapter occasionally mentioned that the models were presented in a simplified fashion. According to the text a more sophisticated model did not make the older model useless for its original purpose, 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 textbooks in this 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 not presented as models, but as a complete account of facts about nature, with little attention to NOS aspects such as model development or limitations. The models were repeated and 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 12 text.

5.5.2 Student tasks

Table 5.4 shows how often (parts of) student tasks met the criteria listed in Table 5.1. The table cells indicate the criterion scores, as an absolute frequency, and as a percentage of the total tasks. Not applicable (n.a.) was scored when (part of) a task could not be related to any of the criteria or to the topic of electricity. For example: a task asking for factual recall of a textbook phrase was scored as n.a., because recall does not apply to any of the criteria. Impact7/8 and Impact9 show high scores on n.a., among others because many part questions concerned factual recall, and knowledge about aspects of phenomena and contexts, not related to electricity.

Meaning and purpose of models. Criterion 9 (conceptual reasoning) had the highest score in all books except in Impact7/8, in which it had the second highest score. Many alternative conceptions (such as the *current consumed model* of electric current) were addressed in the conceptual questions.

Table 5.4

Criteria scores for student tasks and activities 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
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)

Note.

[a] The chapter was studied in full

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

Criterion 13 (calculation tasks) had the second highest score in all books except Impact7/8. Thus, the majority of the tasks in Impact7/8, Impact9, and Newton10 required conceptual understanding and the ability to carry out calculations. These tasks addressed concepts and mathematical relations used 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. A few tasks asked students to use model-related reasoning to substantiate a decision: in Impact7/8 two such tasks were found (e.g. selecting a fuse based on information on the current through lamps), in Impact9 one (selection of an electric appliance based on energy use/cost calculations), and in Newton10 three (e.g. a stepwise calculation task to determine if cars can feasibly be powered by solar energy). An increase in the complexity of tasks was seen with increasing grade level.

Newton11 3rd Ed. contained standard textbook conceptual questions and calculation tasks similar to those in the other books. 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 (Rutherford's experiment).
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.

Models and experiments. All books contained experimental student tasks: 15 in Impact7/8, 25 in Impact9, and 22 in Newton10. The experiments in Newton10 and Newton11 were downloadable as worksheets from the publisher's companion website. Ten experiments in Impact7/8, 20 in Impact9, and 16 in Newton10 were directly related to the models and theories of electricity offered in the textbook. For example, in Impact9 an experiment was aimed at extending the model of electric circuits by a stepwise experimental investigation of the rules for current and voltage in parallel and series circuits. In the experiments not related to theory the aim appeared to be to produce a particular electric circuit (e.g. using a MOSFET as a switch) or artifact (e.g. a simple electric motor), to show phenomena, to find a fact (e.g. the efficiency of a light bulb), or to find a relation between variables (e.g. the power produced by a solar cell depending on the load).

The amount of student guidance varied between textbooks and experiments. Most experiments were guided by stepwise instructions with detailed descriptions of student actions, followed by one or more (conceptual) questions about the activity. 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 some aspects of the experiments, such as details of relatively simple electric circuits, were left to the students. However, the Newton10 worksheets contained detailed instructions and 'fill in the blanks' spaces for results.

In Impact7/8 and Impact9 implicit experimental aims were provided (e.g. "In this experiment you will investigate the current and resistance in a series circuit"), so that the emphasis was on the hands-on activities of the students. In Newton10 there were explicit experimental aims, and in Newton11 the experiments were guided by research questions. Newton10 only used research questions for the four optional activities at the end of the chapter. In Impact7/8 and in Impact9 one of the experimental tasks followed steps of an inquiry cycle, in which students were asked to formulate a prediction and experimentally test it with some choice as to the approach (e.g. investigate the energy use of an appliance with an energy meter). In some experiments with stepwise instructions 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").

Newton11, Newton11 3rd Ed. and Newton12 3rd Ed. contained optional tasks at the end of the chapter: students could choose from a number of open-ended investigations. In Newton11 detailed worksheets were provided, while in Newton11 3rd Ed. and Newton12 3rd Ed. the investigations were described with general guidelines (e.g. "you will investigate the bending of an electron beam in the magnetic field of a bar magnet"). Some investigations asked for internet-based research, others for the use of a computer simulation, experiments and/or design.

Modeling activities and multiplicity of models. Modeling activities by students included those in which students extended, modified or evaluated theoretical ideas provided to them (criterion 12). In all textbooks these activities were present. In most cases the activities took place as part of recipe-type experimental student tasks. In Impact 9 there was an inquiry-based simulation task (students were asked to investigate the relation between current and electric energy at constant voltage) and a theoretical reasoning task in which conceptual statements had to be evaluated. 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 line with the descriptive text of the chapter. In Newton12 3rd Ed. a conceptual task included applying the model of an electric field to the situation of an electric circuit.

Chapter 6 of Newton10 dealt with student skills in physics and two sections explicitly focused on inquiry and modeling skills respectively. Three exercises used electricity related topics as the context for the task (e.g. to find the relation between power and resistance of electric appliances), with an emphasis on data processing skills. The text in the section on modeling explained the nature of simple dynamic models in physics and how they could be created using dedicated computer software. Questions in the book and worksheets downloadable from the companion website provided exercises on various aspects of dynamic modeling, all taken from mechanics. The content of this chapter addressed mainly technical aspects of inquiry skills and dynamic modeling. Only one task at the end of the chapter, again related to mechanics, was inquiry oriented: the task asked students to first create a dynamic model, compare the model results to the results of an experiment and hence to evaluate the model prediction.

Criterion 14 (multiplicity of models) was scored in Impact7/8, Impact9 and Newton10 when tasks involved the use of graphical representations of electric circuits (interpreting and making sketches, drawings and circuit diagrams).

In summary, many tasks appeared aimed at student understanding of the theory of electricity, but most conceptual and calculation tasks did not specifically consider that electric phenomena are described by models. Most experiments showed a theoretical intent, which often became apparent from the questions at the end of the experiment. The majority of experiments used detailed stepwise instructions, leaving little room for inquiry. However, a few tasks used typical model related activities, such as using model-based reasoning to inform decisions, comparing and evaluating models, finding the limitations of a mathematical relationship, and comparing results of model calculations to experimental results (in mechanics). The 3rd Ed. books for grade 11 and 12 contained optional inquiry tasks at the end of the chapter.

5.6 Conclusion and discussion

In this study a list of qualitative criteria was created based on research literature to evaluate if the models in physics textbooks were in line with inquiry-based instruction. The criteria were applied to models of electricity in a series of secondary school physics textbooks in the Netherlands, with a few extensions to models of matter and dynamic models in mechanics. The criteria scores were interpreted qualitatively together with summaries of the textbook content to answer the research question: To what extent does the way in which models of electricity are presented, explored, and used in those textbooks enable or constrain inquiry-based instruction?

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 knowledge presented to the students. The theory about electricity was basically presented as a factual description, in which the historical development of our knowledge about electricity, or even the development as it takes place for the students in the course of the school years, did not come to the fore.

The books for the higher grades more explicitly addressed models, and also in ways that were to some extent consistent with inquiry-based instruction. This started with a chapter on dynamic modeling (unrelated to electricity) in grade 10 and was most pronounced in the chapter on models of matter (indirectly related to electricity) in grade11, 3rd Ed.. Models were presented as fallible descriptions of parts of reality in a more or less historical sequence, while some attention was given to model limitations and idealizations.

The basic theory of electricity in the textbooks consisted of a submicroscopic model of moving electrons, and of macroscopic models relating the concepts electric current, voltage, resistance, and energy. A variety of representations of these models featured in the chapters: text, pictures, circuit diagrams, graphs and mathematical relations. In the explanatory text, the microscopic model was used to explain the macroscopic concepts at the level of secondary school physics. For example, electric current was described as moving electrons, the voltage of a battery as a measure of the force exerted on the electrons, and the electric energy as the energy given to electrons when they pass through the battery. The models were repeated from grade to grade, and extended by introducing new ideas (e.g. free electrons, static electricity and forces between charges), and more complicated applications (serial / parallel electric circuits, semiconductors). The electric field was introduced in grade 12 and its relation to the earlier models was addressed in a single student task. An outlook on other or more sophisticated models of electricity, such as models used in tertiary education, was not provided, except that the 11th grade book occasionally pointed out that the models were described in a simplified fashion.

In student tasks the emphasis was mostly on the macroscopic concepts, although the relation with submicroscopic models was addressed in a few conceptual questions. Most experiments came with recipe-type instructions and the students seldom had to go through (parts of) an inquiry cycle. The theoretical perspective 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 topics at the end of each chapter of the third edition grade 11/12 books had a more open inquiry character.

Summarizing, the way the theory was presented and elaborated in the lower grade books and part of the higher grade books is difficult to reconcile with an inquiry-based approach, because little was left for students to inquire. Student activities that would fit inquiry, 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. However, the textbooks did pay 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.

The exploration, evaluation and revision of models, which can help students in constructing an understanding of phenomena and bring them in contact with scientific ways of thinking (Louca & Zacharia, 2012), was not fully supported by the textbooks. The models of electricity were treated in ways that are conventional in science education (Erduran, 2001): models were not presented as approximate representations of reality, but as final versions of human knowledge, and experiments were seldom used to develop, evaluate and revise models. Although the importance of models was recognized in the textbooks for grades 10 to 12, this was not reflected in the textbooks for the earlier years. Moreover, a systematic and fundamental connection between models, modeling activities and inquiry processes 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 thus postponing the concept of a model as a representation of an aspect of the world created for a particular purpose (Develaki, 2007; Seok Oh & Jin Oh, 2011) to the higher grades has the risk of misrepresenting the nature of science for younger students. This seems unnecessary, may have a negative impact on their view of science (Lyons, 2006), and it remains uncertain if this can be repaired during later school years.

An approach in line with NOS might use experimental and theoretical inquiry tasks, and not just textbook explanations, to help students understand the relations between different models, such as the submicroscopic and macroscopic models of electricity. In this respect it is unfortunate that models and concepts of dc electric circuits and of electrostatics are usually presented as descriptions of practically unrelated phenomena. In higher grades attention might be given to the more abstract concept of the electric fields and its role in electric circuits, as promoted by some researchers (Galili & Goihbarg, 2005; Stocklmayer, 2010). Reference could be made, at least conceptually, to submicroscopic models of conductivity and resistance, in metals and semiconductors. The limitations of models deserve attention in such tasks, because they are inherent in the model concept, and because they make the need for more advanced models with higher explanatory power understandable. Choices will have to be made because of limited instruction time and other practical considerations, as long as the selection contributes to student understanding of the nature of the models at hand and offers opportunities for inquiry.

This study was limited to textbooks and did not include other factors shaping classroom instruction, the most important of which is the teacher. The textbook is important for student learning, because teachers tend to rely heavily on it to guide their instruction (D.-Y. Park & Lavonen, 2013). However, many teacher decisions will have an impact on the extent to which the textbook content will enable or constrain inquiry-based instruction in daily classroom practice. For example, the teacher has to make a selection of student tasks, has to decide on their sequence and timing, on the way students receive instruction before experiments and on the feedback they receive afterwards. The choices the teachers make and the mutual expectations of teachers and students with regard to their roles shape the classroom social norms (Gravemeijer & Cobb, 2006), which in turn determine whether a culture of inquiry can thrive in the classroom. The study indicates the possibilities offered by the textbook, but how these possibilities are used in practice, was not investigated. As the support for inquiry-based instruction from the textbooks in this study is limited, one may generally expect that this will be even less in practice, due to the various constraints faced by the teacher. A teacher will face practical constrains such as the school organization and timetable, Moreover electricity is often a difficult topic for teachers (Gunstone et al., 2005) and an inquiry-based approach is not easy to enact. Yet, teachers who are able to create a culture of inquiry in their classroom may overcome the shortcomings of a textbook.

Only textbooks from one publisher were studied and that constitutes a limitation of the study. Books from two editions had to be included to get a complete overview of topics related to electricity from grade 7 to 12. This means that the results of the study do not provide a general overview of the current state of physics textbooks in the Netherlands. There is reason to believe that the study still provides a reasonable indication of this state: most books were recently published and the books are widely used in schools throughout the country. Additional research is needed to compare the approach to models of electricity in a wider range of textbooks.

5.7 Implications for educational practice

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 developing an understanding of 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 different model predictions, or to compare model predictions to experimental data. In some cases this requires only relatively small modifications of the student tasks currently in the textbooks, such as introducing research questions and asking students to consider experimental outcomes before starting the hands-on activities.

Instruction in line with NOS receives widespread attention as a means to make physics lessons more meaningful to students. Physics departments at schools selecting physics textbooks should critically examine the way the textbook, in its descriptive content and its student tasks, enables the intended type of instruction. The list of criteria developed in this study can be helpful to physics departments looking for suitable textbooks.

Instruction using models, modeling activities, and inquiry may be relatively new for teachers, especially in the lower grades. Presumably, teachers will need support to enable them to incorporate these ideas in their instruction, in particular if this support is hardly provided by textbooks. Moreover, teachers will need to know what sequence of models and what type of inquiry activities will be successful in fostering student understanding of electricity over the course of the school years. Centres of teacher education may invest in developing this type of instruction by experimenting with approaches and instruction sequences, together with (student) teachers. On the one hand this may lead to practical knowledge of models and teaching sequences that can be used in the classroom, while on the other hand it may lead to professionalization of the participating teachers. Generally, design research is a suitable methodology to investigate questions of innovative instruction sequences and associated learning processes. In this case, the design questions are not limited to relatively short lesson sequences, but span the grades 7 to 12 to accomplish a physics curriculum using models in line with NOS for the study of electricity.

CHAPTER 6 CONCLUSIONS AND DISCUSSION

6.1 Brief overview

Science education researchers have emphasized the importance of creating inquiry approaches in line with the Nature of Science (NOS) in the classroom (Duschl, 2008; Osborne & Dillon, 2008). Through such approaches students can experience (simulated) scientific processes, such as inquiring and asking questions, interpreting phenomena, making predictions, experimenting, collaborating, communicating results, discussing evidence and collaboratively reaching conclusions (Osborne et al., 2003). However, the understanding of subject specific concepts, models, and theories has remained important in science education. Understanding concepts in science lessons that follow inquiry approaches in line with NOS is not automatically guaranteed. In this dissertation we have investigated how these two aims can be productively combined in physics lessons. The main research question of the dissertation has been the following: *How can physics education be designed and enacted in such a way that it is in agreement with the Nature of Science (NOS) and fosters conceptual understanding in electricity?*

This question has been studied from three perspectives: (a) student learning in the classroom, (b) teacher learning and professionalization, and (c) the support provided by the textbook.

A cyclic design research approach was chosen to develop an understanding of student learning processes in relation to learning activities and instruction. In the design of the instruction we considered student inquiry at the core of physics education, in agreement with NOS. Two cycles of design research are described in chapters 2 and 3. Lessons were developed on the topic of electricity for pre-university grade 9 students, in cooperation with physics teachers. Involving teachers in the lesson development was expected to foster their commitment and to help them understand their role in the envisioned instruction. The teachers, so it was hoped, were likely to develop professionally when they were involved in a project aimed at systematically changing classroom practice. Therefore, teacher learning was investigated. This learning, and the extent to which it could be related to changes in the classroom are described in chapter 4. Finally, coming to understand, using, and creating models are essential activities in physics, and the literature indicates that these activities potentially fit in well with an inquiry-based approach in line with NOS. Moreover, the textbook is an important source of information in most lessons for both students and teachers. Criteria were developed to evaluate textbook models in relation to inquiry-based instruction. The criteria, the basis on which they were developed, and how they were applied to the chapters on electricity in a series of grade 7 to 12 physics textbooks are described in chapter 5.

In this chapter the most important findings and conclusions of the studies are summarized and discussed in order to answer the main research question. Directions for future research are suggested, and selected strengths and limitations of the studies are provided. The chapter ends with implications for educational practice.

6.2 Main findings and conclusions

6.2.1 First design research cycle: key issues in creating inquiry-based instruction

The first cycle of design research started with the intention to develop a local instruction theory (see chapter 2) for learning about direct current (dc) electric circuits in the context of scientific inquiry. A local instruction theory consists of the instructional activities related to a selected topic and the expected student learning processes in response to the instruction (Gravemeijer & Cobb, 2006). Drawing on a theoretical framework based on individual conceptual change and socio-cultural views on learning, instruction was designed addressing well-known and common conceptual problems and attempting to create a physics (research) culture in the classroom (Cobb & Yackel, 1998). Twelve lessons were designed in cooperation with a physics teacher and enacted in the teacher's pre-university stream[9] grade 9 classroom (age 14). The core elements of the lessons were formed by collaborative group work, where students worked on investigative tasks, and whole class discussions led by the teacher, in which results were presented and discussed, conclusions reached and new questions formulated. During the enactment of the lessons an iterative process took place of testing and adapting instruction. However, it became clear that the conjectured local instruction theory was not successful, and the focus of the study shifted from developing a local instruction theory to answering the following research question: which inherent characteristics of inquiry-based instruction complicate the process of constructing conceptual understanding?

Data were collected in the forms of pretests and posttests, video and audio recordings, field notes, and students' written work. Retrospective analysis of the data took place following the two-step procedure described by Cobb and Whitenack (1996), based on grounded theory. The first step consisted of identifying patterns in the data. The search for patterns was guided by sensitizing concepts based on the theoretical framework. Patterns became apparent from the lesson observations and a first examination of the data; they were described as conjectures about the dataset. Subsequently the data were examined using the constant comparison approach, looking for confirmations or refutations of the previously identified conjectures. The first step resulted in a number of conjectures supported by

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[9] In the Netherlands, three different streams of secondary schooling exist. Students are streamed based on ability at the end of primary school, usually at the age of 12. The pre-university stream is a six year course providing access to university education.

evidence from the data. The second step was directed at identifying possible causal mechanisms and processes to account for the patterns found in the first step.

From the analysis of the data three tensions have emerged: (a) the tension between open inquiry as a characteristic of scientific practice, and the need to guide and structure the student investigations to help students obtain empirical results that can be built upon; (b) the tension between the need to allow students to invent and adjust their own ideas on the basis of inquiry activities and the need to inform them about accepted theories that were deemed to be too sophisticated to be reinvented; and (c) the tension between fostering scientific interest as part of a scientific research culture in the classroom and the existing task-oriented school culture.

We have hypothesized that these three tensions inherently exist in physics education that is in agreement with NOS and fosters the understanding of theoretical concepts in electricity. Based on the results of the study we formulated recommendations for a second design cycle, aimed at a productive balance between the extremes of each of the tensions: (a) to provide structure to student investigations to enable students to find useful experimental results, (b) to offer an initial theoretical starting point for constructing scientifically sound theories from inquiry activities, and (c) to offer support to help students shift from school oriented motives towards more scientifically oriented motives.

6.2.2 Second design research cycle: a balanced approach

In the second study a conjectured local instruction theory and classroom pedagogy were created in cooperation with three physics teachers for the grade 9 topic of electricity, taking into account the findings of the first study. The lessons emphasized establishing classroom norms of inquiry using, among others, a theoretical starting point, targeted experiments guided by conceptual questions, and theory-oriented, whole-class discussions. The goal of the study was to understand how the learning arrangement characteristics might support learning in the classroom. Two research questions were addressed, the first of which was conditional to the second:

1. How effective was the enacted instructional design in terms of the conceptual learning aims of the Grade 9 lessons about electric circuits?
2. How did the learning arrangement characteristics help explain the development of Grade 9 students' conceptual understanding in the inquiry classroom?

The data collection and the retrospective analysis took place following the same method as during the first study. The retrospective analysis focused on one teacher's class, because lesson-by-lesson meetings to evaluate and redesign instruction had only been possible with this teacher, and his enactment of the instruction most closely approximated the design intention.

In answer to the first research question the analysis of the pretest and posttest results showed that the conceptual learning aims of the lesson series had to a large extent been accomplished in this classroom. Student conceptual understanding had increased: many students had developed the ability to interpret circuit diagrams, to distinguish the concepts electric current, voltage and resistance, and to explain the role of the battery or power supply. While at the start of the lesson series students often reasoned according to the current consumed model, this rarely happened at the end. Selected topics, such the electric circuit as a system, the battery as a source of constant potential difference, and some aspects of parallel circuits, were still difficult for the students. In answer to the second research question, we found that the new classroom norms were consciously enacted by the teacher and by most, though not all, of the students. In particular, the teacher often made clear that students were expected to actively contribute ideas, that results would be arrived at cooperatively, and that all students were expected to develop their understanding. He appreciated and used student contributions. Generally, the students were engaged during the lessons. The students made use of the theoretical starting point, a charged particle model of electricity, while they developed an understanding of electric circuits. It appeared more difficult for the students and the teacher to refer to the model in their reasoning when circuits became more complicated. Apparently, the model then reached the limits of its usefulness. The experiments carried out by the students were characterized both by structure and by inquiry. During the experiments there was additional teacher support, which sometimes interfered with the inquiry, but allowed students to obtain meaningful results. Whole class discussions linked the experiments to the development of theoretical ideas.

In the data analysis we paid attention to the ways in which student ideas on physics concepts developed in the classroom when the norms of inquiry were present or absent, and when the local instruction theory was adequate or inadequate. We found that the classroom norms of inquiry and the enactment of an adequate local instruction theory fostered the engagement and the conceptual understanding of most students. We concluded that the enacted local instruction theory involved a combination of conceptual tools, challenges, and supports that made engagement rewarding for students. The balance created in the three tensions identified in the first study worked out successfully in this class and the elements emphasized in the design reinforced each other. As a result, students saw the experimental lessons as a way to understand physics not available to them in the teacher's traditional instruction. The study thus yielded a local instruction theory for electric circuits and deeper insights into the ways the guidelines formulated after the first study played out in practice.

6.2.3 Teacher professionalization

In the third study we described the second design research cycle from the perspective of a professional development intervention. The participants were three teachers from different schools, with 19, 9, and 2 years of teaching experience respectively. The intervention was designed to possess characteristics that, according to literature, can lead to a successful change of classroom practice: subject content and student learning were important starting points, teachers' concerns and experiences were integrated in the process, teachers shared experiences and collaborated, classroom coaching was included, and the intervention took a substantial amount of time. The intervention had the purpose to help the teachers establish a culture of inquiry in their classrooms in which students would be facilitated in coming to understand concepts of electricity in simple direct current circuits. A culture of inquiry requires classroom social norms analogous to a scientific research tradition (Cobb & Yackel, 1998), so that students can experience both essential scientific research processes and related essential social processes (Minner et al., 2010).

The intervention consisted of group meetings and feedback/evaluation meetings. In the group meeting the topics of discussion were: the physics concepts and student conceptual problems in electricity for grade 9 students, a model of moving charged particles and how it could be used at the level of the students, a pedagogy suitable to create a culture of inquiry in the classroom, design of the instructional activities as part of a conjectured local instruction theory, the assessment of the lesson series, and practical issues related to the enactment of the lessons. Feedback and evaluation took place during the enactment of the lessons, partly on an individual basis, partly as group meetings.

The research aim of the study was to understand how the participating teachers developed professionally in terms of reported learning and changes in the classroom, and was guided by the following research questions:

1. What learning did the teachers report after participation in the collaborative lesson design and enactment?
2. To what extent did the teachers change their classroom practice?
3. How can the reported learning and the teachers' classroom practice be related to participation in the professional development process?

Data were collected in various forms including video and audio recordings of group meetings, feedback meetings and lessons, agendas, notes, e-mails, teacher and student interviews and a student pre/post questionnaire. In the qualitative data analysis the various sources were organized in such a way that the professional development of each teacher could be described as a separate case and common themes between the three cases could be identified.

All three teachers reported new insights with respect to their pedagogical content knowledge (PCK) and classroom pedagogy. The discussions and lesson development had helped them to develop a deeper understanding of the physics content in relation to student learning and understanding. The ideas introduced in the intervention had generally not been new to the teachers, and they had already been aware that understanding direct current electric circuits was difficult for grade 9 students. However, using these ideas productively as tools in physics instruction was new to them. Among others, enacting the lessons made the teachers aware of the limits of their own understanding, for example if students asked questions they were not prepared for. Changes of attitude were also reported, such as increased confidence after a second enactment of the lessons.

The data showed that the change of the classroom culture was noticeable for the students, although by varying degrees depending on the teacher. Students indicated that compared to previous physics lessons they cooperated more with others, carried out more experiments, had more opportunities to investigate things by themselves and had more opportunities to develop their own ideas. The changes of the classroom practices lasted beyond the time frame of the intervention.

The domains of the interconnected model of professional growth (Clarke & Hollingsworth, 2002) were used to describe the change process of the teachers. The changes to the lesson content and changes of the classroom culture were initiated by external sources (the external domain), but were in line with relevant concerns of the teachers about student understanding (the personal domain). Changes of teacher behavior were partly planned, and partly resulted from the teachers' responses to new situations in the classroom. Feedback, modeling, and coaching during and after the lessons took place to foster the behavior changes. However, the school timetables did not provide sufficient opportunities for individual lesson-by-lesson-feedback and evaluation in two of the three cases. It is likely that this had a negative impact on the enactment of the lessons and on the learning opportunities in these cases. In summary, cooperative lesson development, classroom enactment, coaching, reflection on the effects of the lessons, and mutual discussions helped sustain the teachers' development (domain of practice and domain of consequences) by means of a dynamic rather than a linear and sequential process. Individual differences between the teachers with respect to their learning and to the enactment of the lessons could be explained by considering their different starting points as professional educators, the different environments in which they operated, and individual differences with respect to their concerns. This dynamic process made it understandable that changes took place in different domains.

We concluded that the professional development intervention appeared effective in fostering teacher learning and changing the classroom culture towards a culture of inquiry.

The professional development was driven by the teachers' willingness to invest to change the classroom culture and in this manner improve student understanding. We inferred that the teachers were willing to invest their efforts, because the innovation agenda of the intervention matched with their concerns, and because they obtained the means to be potentially successful in the classroom, i.e. research-based ideas in the form of a workable local instruction theory. Enactment of the lessons led to a realization of the initial ideas, with visible consequences in the classroom. Coaching could take place with an eye for the individual needs of the teachers without losing the focus on the local instruction theory and agreed-upon pedagogy. Feedback and reflection were used to adapt the local instruction theory and instructional materials. The various activities complemented each other, while coaching, feedback, and the possibility to exchange experiences appeared to help the teachers persist in the light of less successful experiences.

6.2.4 Models in textbooks

In the fourth study we investigated models of electricity in a series of commonly used secondary school physics textbooks. The earlier studies indicated that students need a basic theoretical model in an inquiry context. The way such a model is presented and used should afford conceptual and experimental inquiry activities and should respect insights from NOS. In many secondary schools the main source of theoretical models for both students and teachers is the textbook. Therefore, we constructed criteria to evaluate models in physics textbooks, from an interpretation of literature on models and modeling in science and science education. These criteria were then used to evaluate the models of electricity in a set of grade 7 to 12 physics textbooks in the Netherlands.

The research question guiding the study was: 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?

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.

Models of electricity in recent editions of Dutch physics textbooks for grade 7 to 12, all from the same publisher, were evaluated using the criteria. Chapters dealing with electricity were studied in full; chapters partly dealing with electricity were studied in part. In addition to the models of electricity, some models on other topics (on matter and on mechanics) were included in the evaluation, to obtain a fair account of the different ways the textbooks paid attention to models. The applicable criteria were scored for sections of text and student (sub)tasks, and qualitative summaries were made.

Books for the lower grades described models of electricity mainly as factual knowledge, with little attention to the model nature of the explanations and to processes of knowledge development in science. Books for the higher grades addressed models of electricity in similar ways as the books for the lower grades. However, dynamic models (unrelated to electricity) and models of matter (indirectly related to electricity) were explicitly addressed as models. The latter were presented as fallible descriptions of parts of reality and attention was given to historical developments, model limitations, and idealizations.

The basic models of electricity in the books were a submicroscopic model of moving electrons, and macroscopic models relating the concepts electric current, voltage, resistance and energy. The macroscopic models used various representations (e.g. text, graphs, formulas). The microscopic model was sometimes used in the text to explain macroscopic concepts and their relations. However, the student tasks emphasized the macroscopic concepts. The large majority of student experiments were recipe-type experiments, which seldom formed part of an inquiry cycle.

We concluded 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 approach in line with NOS, 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.

However, 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. We expected that the criteria compiled in this study might be helpful for physics teachers selecting textbooks with an inquiry orientation, as well as for textbook authors and editors.

6.3 General conclusions

The four studies of this dissertation have provided insight into the design and enactment of physics education in agreement with NOS, while fostering the understanding of theoretical concepts in electricity. We have found that three tensions inherently exist in this type of education and that effective student learning requires a balanced approach to these tensions. Balance is needed in experimental work, between openness of investigations as a characteristic of inquiry and structure provided in the instructions for students to obtain meaningful results. Balance is needed between an appreciation for the development of students' own ideas and the need to inform them about accepted theories. This is supported by the notion that scientific research often starts from a theoretical basis, rather than as a purely empirical endeavor. Finally, balance is needed in the classroom culture between scientific research related norms and school related norms.

We have designed a local instruction theory and associated classroom pedagogy to create a productive balance between the three tensions mentioned earlier. In this design a basic theoretical model was offered to students as a tool for student thinking and collaborative reasoning. Students were stimulated to interpret experimental results theoretically, so that these results became more than observed regularities. Conceptual and experimental tasks were used in combination with whole class discussions. Pedagogic measures emphasized the change of the classroom norms towards norms of inquiry. Enactment of the local instruction theory took place in three classrooms and was studied in-depth in one classroom. In this classroom it appeared possible to accomplish most conceptual learning aims, to move the classroom culture towards a culture of inquiry, and to foster student engagement. The data analysis supported the conjecture that the instructional design provided a balanced approach to help students develop and understanding of electricity. It indicated that in particular the interplay between classroom norms of inquiry and an adequate local instruction theory made it rewarding for most students to actively engage.

Teachers need to learn how to successfully foster classroom norms of inquiry and enact a corresponding local instruction theory. Favorable conditions for teacher learning were created in the cooperation process of the researcher and the three teachers creating and enacting the local instruction theory, by taking into account guidelines from the literature. As could be expected, important factors found to contribute to teacher learning were the attention to teachers' concerns, the possibility to share ideas and experiences, external input in the form of research-based ideas, and feedback and reflection on lesson enactment. The teachers' classroom behaviors changed in the desired direction, and the changes lasted after the first enactment of the lessons. The extent to which the results were visible to the students varied, depending on the teachers' experience and the environment in which the teachers operated, which, among others, determined the possibilities for individual coaching. In conclusion, the cooperation process of a researcher (who was also a teacher educator) and teachers creating and enacting a local instruction theory was a viable way to help teachers develop inquiry approaches in line with NOS in their classrooms.

The textbook is likely to be one of the most important learning materials in many classrooms. It could be an effective source of theoretical models and model-oriented student tasks, if these models and tasks were presented in line with NOS, allowed for student inquiry, and fostered conceptual understanding. Among others, the textbooks should respect the tensions described earlier: theory should leave room for students to develop their ideas instead of providing final answers; tasks should provide guidance without resorting to a recipe approach. The list of criteria created to evaluate textbooks turned out to be useful when interpreted qualitatively and combined with summarizing notes. The chapters on electricity in a series of commonly used Dutch physics textbooks that were evaluated with the help of the criteria, appeared to pay attention to contexts and student conceptual understanding, but hardly showed an inquiry orientation. Models of electricity were generally presented as facts. The model concept appeared mainly in chapters unrelated to electricity (such as on dynamic modeling) or indirectly related to electricity (such as on models of matter). However, it was noticed that with relatively small modifications the use of models and tasks in the textbooks could become more in line with NOS.

6.4 Discussion and directions for future research

6.4.1 A balanced approach

The picture arises from chapters 2, 3 and 4 of this dissertation that fostering conceptual understanding using inquiry is a promising, but also a complicated process. Viennot (2008), using historical research findings, already made a case against simplistic views on student conceptual development, such as those present in early conceptual change models of learning (Vosniadou, 2013). In hindsight the instruction described in chapter 2 was perhaps based on somewhat naïve ideas. In our enthusiasm to create a culture of inquiry we overlooked the fact that scientific practice is usually guided by a structured theory and therefore the open student experiments used in this first study can be considered overly empiricist. Moreover, the instruction did not pay enough attention to the differences between learning in a school environment and the culture of scientific practice. However, the retrospective evaluation of this instruction allowed us to identify three specific tensions between requirements made by scientific inquiry and the constraints of conceptual learning processes in a secondary school environment. In chapter 3 we described a way to reduce these tensions by means of a more balanced approach. By testing this approach we contributed to the understanding of how non-simplistic ideas on student learning can work out in the classroom. In the classroom in which the approach was successful, different parts of the learning environment were coordinated to foster student learning: a local instruction theory, the classroom culture, teacher competences, and learning materials.

6.4.2 Local instruction theory

The balanced approach was incorporated into the local instruction theory by means of the support given to the students while there remained a need for student ideas and contributions. The support was given in the form of a theoretical basis, conceptual questions, and experimental instructions. In the instruction theory we anticipated possible student answers and experimental conclusions. The role of the teacher was important in orchestrating whole class discussions, to reach consensus in the classroom on the interpretation of the physics model and concepts, and to prevent student ideas from becoming increasingly idiosyncratic.

The theoretical basis in the local instruction theory gave students a language to talk about electricity. The model may have been somewhat questionable for physicists, but was in line with textbooks in the Netherlands and with educational computer simulations[10], used in many classrooms across the world. The model, the conceptual questions, and the computer simulations, in combination with the classroom discussions, helped students to start reasoning in theoretical terms. Moreover, they allowed the experimental work to become more than a hands-on activity that had to be completed: the experimental work obtained a theoretical objective.

The local instruction theory was not only important to sequence student activities during the lessons, but its development also contributed to the background knowledge of the teachers. In particular the sequence of anticipated student understanding described in the local instruction theory pointed the direction for the teachers to guide whole class discussions.

However, the analysis in chapter 3 made clear that the local instruction theory was neither perfect nor final. The same applied to the development of student understanding, which showed steps in the right direction, but was not perfect. This was expected, because developing conceptual understanding is often a process taking a considerable amount of time (Treagust & Duit, 2008).

The topic of electricity has been widely researched and various instructional approaches have been suggested (Hart, 2008; Jaakkola et al., 2011; Taber et al., 2006). Our local instruction theory was inspired by several of these approaches. It may be possible to construct more than one successful local instruction theory for this topic. In any case, having an acceptable theory at their disposal has helped teachers in their instruction and has provided teachers and researchers with a tool to systematically improve instruction. In

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[10] See https://phet.colorado.edu/

different classrooms, details of a local instruction theory may need to be adapted to comply with the local context, for example to comply with student background knowledge, student and teacher interest, and school culture.

Future research. Several areas for future research on the local instruction theory arise from the studies. First, there is a need to optimize the local instruction theory to overcome some of its present limitations and to make it more efficient. An improved local instruction theory should be tested in new rounds of design research, and eventually a program might be designed to introduce it to teachers at a larger scale (Borko, 2004). In instruction, different positions between the extremes of the three tensions can be chosen (e.g. more or less structured experiments). In a recent review study, Lazonder and Harmsen (2014) found no positive relation between the specificity of the support and the learning outcomes. However, they investigated support on the inquiry process and did not include content related support. A question for future research is how much structure is optimal for different groups of students. Varying the support within the same classroom might give rise to differentiated instruction adapted to the needs of individual students.

Second, the local instruction theory can be expanded to include the topic of electricity in higher grades than grade 9. In that case, the more quantitative topics of high school electricity need to be incorporated into the inquiry-based approach. This would be a first step in which the local instruction theory developed in this dissertation could contribute to the development of a domain-specific instruction theory.

Finally, expanding a balanced inquiry-based approach to other areas of physics, such as mechanics, provides insights into its wider viability. Then, local instruction theories for these areas need to be designed including the provision of a theoretical basis. For example, a suitable theoretical basis in the case of mechanics is unlikely to include a microscopic theoretical model. Perhaps a suitable basis can be found by studying historical developments in mechanics (Matthews, 1994).

6.4.3 Classroom culture

The successful enactment of an inquiry-based local instruction theory concerning conceptual learning is only possible when in parallel a culture of inquiry with relevant classroom norms develops in the classroom (Cobb & Yackel, 1996). The two cannot be separated: a local instruction theory does not lead to successful learning when it is not aligned with the prevailing classroom norms, and vice versa, classroom norms cannot be established and maintained if learning is not supported by a feasible local instruction theory.

In our first design study (chapter 2) too little attention was paid to the fact that classroom norms of inquiry (e.g. that students actively strive for understanding) differ from traditional school norms (e.g. that students complete their assignments; Nijland, 2011) and that new norms have to be consciously developed. Therefore it was not surprising that students acted according to the traditional school norms. In the second study (chapter 3) much more attention was paid to the development of new classroom norms. First, in the instruction design, we tried to make it worthwhile for the students to engage in the new approach by showing at an early stage that assessment would focus on the conceptual understanding reachable by active participation. Second, the classroom norms were discussed in the preparatory meetings with the teachers and were always a topic in the evaluation meetings after the lessons. Third, in the most successful classroom the teacher paid explicit attention to classroom norms important for inquiry, such as striving for understanding, interpreting data, contributing ideas to discussions and asking questions. Fourth, he not only stated the importance of these norms, but also cultivated the corresponding student behavior by modeling, leading class discussions, and interacting with the students. Subject specific norms, such as explaining phenomena in terms of the theoretical model used in the lessons, were not explicitly expressed by the teacher, but were modeled, and his example was adopted by students. Students noticed active participation and the joint responsibility to reach understanding as the most visible aspects of the new norms. A small group of students indicated they did not accept the new classroom norms.

The studies made clear that the classroom culture could not easily be changed, even though the classroom norms moved into the desired direction in the course of 12 lessons. Students and teachers have shaped their habits and mutual expectations by many years of school experience. It is difficult for a teacher to change his usual routines. Therefore, it was understandable that the teachers' behavior in our studies was not completely consistent. However, the importance of the classroom culture came to the fore during the lessons in the second study: when the instruction did not unfold in line with classroom norms of inquiry, student engagement suffered, and it is likely that the same applied to student learning. The classroom culture does not stand alone and is embedded in a wider school culture with written and unwritten norms, behaviors, and expectations for teachers and students. A culture of inquiry in the classroom is be easier to establish and maintain if it corresponds to and is supported by school culture as a whole.

Future research. In several schools student inquiry is gradually being given a more prominent place. One example is the *Nieuwste School* [Newest School] in the city of Tilburg in the Netherlands, in which students work in an inquiry-based environment built upon ideas from Dewey (1910). Future research will have to show whether theoretical concepts in physics are more easily accessible to students through inquiry-based instruction in such an environment.

Another question for future research is how the minority of students who prefer non-inquiry classroom norms (e.g. norms of direct instruction: the teacher explains and students listen) can be challenged to see benefits in the new approach.

Finally, the studies were conducted in the pre-university stream of secondary education. In the Netherlands other streams of secondary education exist, such as a higher general secondary education stream, and a pre-vocational stream. The topic of electricity features in the physics curricula of all streams, but additional research is necessary to create a local instruction theory and a culture of inquiry suited to students in other streams of secondary education.

6.4.4 Teacher competences and teacher learning

Enacting inquiry-based education requires professional development of the teacher. Therefore, our classroom studies were integrated with a professional development intervention, taking into account results from research on successful interventions (Van Veen et al., 2010): a focus on subject content and student learning, attention for teachers' concerns, involving teachers in the lesson design, and the inclusion of classroom coaching.

Taking the subject content and student learning as a starting point appeared a good choice: the teachers were well aware that electricity is an abstract and difficult topic for students. They were interested in discussing the details of a model of electricity at and above student level, to verify their own understanding and to create an instructional sequence that could successfully introduce students to the topic. Moreover, studies have shown that many teachers have a limited understanding of electricity (Gunstone et al., 2005; Gunstone et al., 2009). In our most successful classroom the teacher sometimes showed the limitations of his understanding and on a few occasions this interfered with the enactment of the local instruction theory.

The lesson-by-lesson evaluation and feedback appeared an important factor in the teacher's professional development, both for establishing classroom norms of inquiry and for enabling the enactment of the local instruction theory. The lack of evaluation and feedback on a lesson-by-lesson basis in the other classrooms appeared to have had a negative impact on the consistent enactment of the lessons according to the aims of the study.

The professional development intervention took place over a period of several months and involved a process starting with thinking about physics understanding up to and including the enactment of the local instruction theory. Each teacher started from his or her teaching experience and physics understanding. The length of the learning process gave the teachers the chance to internalize and practice with the ideas of inquiry-based instruction on electricity. The end points in this process reflected the individual starting points and learning trajectories.

Future research. It appeared useful that teachers were involved in a single difficult topic for a prolonged period of time. However, the school environment in which the teachers operated also had an impact on the opportunities for learning (Clarke & Hollingsworth, 2002; Schildwacht, 2012; Van Veen et al., 2010). This ranged from practical matters, such as the possibility of lesson-by-lesson meetings, to the (lack of) support by colleagues and the opportunity to re-enact the lessons in a subsequent school year. Future research could show if more successful teacher learning and student results could be obtained if a team of physics teachers from a single school would be involved in a similar intervention.

The professional development process in this project was relatively expensive because of the involvement of the researcher with a small group of individual teachers. The time investment was made possible by the context of a PhD research project and the teacher participation as part of a master of education course. Future research could look into logistically more efficient approaches, one of which was already suggested by the participants: after the researcher's input the participants could visit each other, and hold their evaluation meetings together. This suggestion may be particularly feasible for a team of teachers from a single school and it could more easily facilitate continued professional development after the end of the project (Schildwacht, 2012).

6.4.5 Learning materials

Coordinating physics textbooks and inquiry approaches in line with NOS might be difficult for teachers, if their textbooks are not created with that approach in mind. A textbook is likely to support student inquiry if the text describes physics theory in a model-oriented way and contains tasks that help students to explore, understand and extend the theory by conceptual and experimental activities. A textbook is unlikely to support student inquiry if physics theory is presented merely as facts and if experimental instructions focus on the completion of procedures while the theoretical intent of the experiments remains unclear. In our studies the learning materials were made for the purpose, using materials from a variety of sources (Gravemeijer & Cobb, 2006). This was in line with a tendency that teachers design their own learning materials, often cooperatively and supported by subject specialists and researchers. Designing learning materials may help teachers to professionalize as they will have to consider both subject content and student learning (Van Veen et al., 2010).

Ideally, textbooks are written with an inquiry-based and model-oriented approach in mind in order to support inquiry-based instruction. Teacher learning and professional development in this area may be fostered by the textbooks if they are written according to the guidelines of educational curriculum materials (Davis & Krajcik, 2005). However, textbook authors writing for inquiry face conflicting demands. Textbooks should allow for individual study, for instance if a student is unable to attend a lesson. Therefore the book is expected to include a reasonably complete account of the physics involved at the level of the student. At the same time, an inquiry-based approach demands physics models that can be developed and extended by means of student activities. Such conflicting demands might be solved by educational technology that allows for more flexibility than a paper textbook. Combinations of textbooks and a collection of online materials may be possible, as well as completely digital solutions. The field of design research with a focus on educational technology (Reeves, 2006) looks into design principles for these types of learning materials and environments.

From an NOS point of view an important goal of physics is to develop models of reality. Our study showed that even recent textbooks, in particular for the lower grades, treat models of electricity as factual descriptions, which corresponds to the results of earlier textbook research by Erduran (2001) and Gunstone et al. (2005). There is a need to increase the awareness of the model nature of what is presented, and to integrate the development of theoretical models with student inquiry activities. This is likely to make physics more accessible to students (see chapter 3), and may help students to develop a more realistic notion of NOS. Some researchers, such as Lederman et al. (2002), indicate that the topic of NOS should be addressed explicitly, which implies that inquiry-based instruction as such may not be enough to help students understand NOS related issues. Others, such as Duschl and Grandy (2013), claim that immersion in model-oriented scientific activities is an important prerequisite for understanding NOS related ideas.

Tools to support student conceptual inquiry and modeling activities, such as computer simulations and apps are readily available on the internet. They can help visualize concepts and models in ways that are impossible in real experiments, and thus foster conceptual discussions and understanding. Moreover, students can easily manipulate variables in runnable simulations. Therefore, computer simulations as part of inquiry-based instruction had a place in the studies of this dissertation (chapters 3 and 4). Using computer simulations in a meaningful way may be a challenge for teachers. Textbooks could be of help by providing research-based student activities (Smetana & Bell, 2012), but in the textbooks studied only a few references were made to runnable simulations.

Future research. The importance of models and model-based reasoning gradually receives more recognition also for the lower grades. Among others, this is reflected in the lower grades Physics Knowledge Base recently published in the Netherlands (SLO, 2014). It is not yet clear how this increased awareness will eventually appear in the treatment of physics theory in textbooks. A consistent series of models of electricity, suitable for inquiry activities, for students to encounter in the course of their secondary school years is not yet available. Research is needed to develop this series of models based on a sequence of interconnected local instruction theories at different grade levels.

Physics textbooks are understandably a compromise between demands from various origins: national curricula, physics teachers working at schools, pedagogic, and commercial considerations. At present, instruction in line with NOS (inquiry-based and model-oriented) does not seem to be high on the agenda of textbook authors in the Netherlands. However, there are indications that this may change in the foreseeable future and continued textbook research using the criteria developed in this dissertation (chapter 5) will help monitor the development of learning materials in which NOS plays a more prominent role.

6.5 Strengths and limitations

The studies in this dissertation have taken into account the complications of coming to understand the topic of dc electricity: the demands of school physics and the demands of physics as a scientific discipline, the need to attend to individual student understanding and the need for relevant classroom social norms, the required teacher professional development, and finally the learning materials and the ways in which physics models are used in the textbooks. This comprehensive approach was reflected in the different theoretical perspectives used to inform the research. The studies contributed to the understanding of physics education in agreement with NOS, while fostering the understanding of theoretical concepts in electricity. In the first design study three inherent tensions were identified. In the second design study, a local instruction theory and classroom pedagogy were designed and enacted to create a productive balance between these tensions. The results of the study provided support for this balanced approach and insights into the ways it may be used to innovate classroom practice. Methodologically, the two design studies were good examples of design research with the aim to understand learning processes (Gravemeijer & Cobb, 2006), originating in the domain of mathematics education and now applied to physics education.

The study on teacher learning was closely related to the design studies. The qualitative research methods, chosen to obtain rich accounts of the learning that took place, were not limited to teacher self-evaluation, but extended to teacher behavior and students' accounts of changes in the classroom. The study showed that the cooperation process of a researcher and teachers creating and enacting a local instruction theory, was a viable way to help teachers develop inquiry approaches in line with NOS in their classrooms.

Finally, the textbook study provided tested criteria that may be used by educational practitioners and researchers to evaluate the use and presentation of models in physics textbooks, and by authors as well as editors to obtain a focus on learning materials suitable for inquiry-based physics education.

Limitations of the studies can also be identified. The qualitative approach in the classroom studies allowed for a thorough understanding, but the research questions were explored only for a relatively small group of students and their teacher. Therefore, it is possible to learn from the studies, but the results cannot easily be generalized. The design should be considered a prototype rather than a final version suitable for large scale use. More research is still needed to understand how the design can be scaled up and used in more classrooms, and how more teachers can become involved effectively. It is clear that this involvement should include a further development of the design by teachers, and teacher professional learning, because a mere distribution of new learning materials will not lead to innovative education (Fullan, 2001).

A second limitation can be found in the study on teacher learning. In this study it is also the limited number of subjects that reduces the generalizability of the results. To involve larger numbers of teachers in a professional development intervention, a more cost-effective organization is needed, even though it will need to contain elements of the intervention described in our study and will aim at similar results.

Finally, the textbook study was limited to two textbook series of a single publisher. The findings cannot be extended to the whole range of physics textbooks used in secondary schools in the Netherlands, even though the selected textbooks were, and are, commonly used in schools. Moreover, a limitation of a textbook study is that it did not consider how physics teachers used the textbooks in their classrooms. The support from the textbooks in the study appeared limited for instruction in line with NOS. However, one may expect that this support will be even less in practice, due to the various constraints faced by the teachers.

6.6 Implications for practice

Physics education in line with NOS is a promising way to foster student understanding. Teachers and teacher educators need to develop a balanced perspective on conceptual understanding in relation to inquiry (Viennot, 2008) and move beyond naive ideas. This balanced perspective includes awareness of the tensions inherent in inquiry-based education at secondary school level, and of ways to deal with these tensions in the classroom. It also includes awareness of the importance of working with a feasible local instruction theory and developing a suitable classroom culture. For the topic of electricity, teachers may be informed by the local instruction theory and pedagogy developed in this dissertation.

A balanced approach to instruction in line with NOS is demanding for teachers to understand, to design, and to enact. Therefore, teacher education institutes need to prepare teachers for this type of instruction in their pre-service curricula. Once in-service, teachers will become better equipped to meet the demands with increasing experience, and their professionalization can be fostered by continued in-service interventions.

Teachers and teacher educators need to develop an understanding of NOS in order to develop a balanced approach to instruction in line with NOS. Aspects of NOS can be studied theoretically, but first-hand experiences with physics as a scientific discipline, and reflection on those experiences will be relevant as they may support the teacher's role modeling and enactment of science norms. Awareness of the importance of first-hand experiences is growing in society in general and in institutions of teacher education, which manifests itself in initiatives to let student teachers gain practical work experience in cooperation with industry and research institutions (Techniekpact, 2013). These initiatives also stress the connection between physics and technology and in this way emphasize the relevance of the subject.

Teacher learning effectively takes place in a collaborative setting, such as in professional learning communities or in collaborative teams (Voogt et al., 2011), which often exist for several years and strive for educational innovation. There seems to be a variety of approaches to such initiatives. Our studies confirmed the review findings of Van Veen et al. (2010) that a noticeable classroom impact of teacher learning may be expected if the teachers work cooperatively on the same issue, related to a concern about student learning, if expertise is available on the content and pedagogy, and if classroom coaching and feedback is part of the project.

There is increasing attention for the importance of models in physics education, also in lower grades (SLO, 2014). The criteria developed in this dissertation to evaluate textbooks may be helpful for several stakeholders: teachers, departments, and schools may find the criteria helpful in the selection of textbook series. In teacher education they may be used to prepare teachers for a systematic evaluation of physics textbook series, or a comparison of different series. Designers and authors of learning materials, be it textbooks, educational websites or runnable simulations, are advised to take the criteria into account if they intend to foster model-oriented activities and inquiry.

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APPENDIX. LESSON EXCERPTS FROM CHAPTER 3.

The materials presented here consist of lesson excerpts to illustrate and substantiate the conjectures in the Findings section of Chapter 3. The lesson excerpts are organized per conjecture and were translated from Dutch by the first author.

Conjecture 1. Classroom norms and expectations were explicitly cultivated by Mr. Adler in interactions with the students.

The following excerpts illustrate that Mr. Adler regularly referred to the classroom norms and expectations mentioned in the conjecture. The examples are taken from the first lessons:

<u>Introductory Lesson</u>. Teacher: In other words, making mistakes is allowed.
<u>Lesson 1</u>. Teacher: Everybody is asking me, is it right, is it right … but in the end, the question is what do you think?
<u>Lesson 2</u>. Teacher: When I have answered the questions, everything is ok, isn't it?...
Student: Well, then you have the answers, but you don't understand.
Teacher: Yes, and for me that is more important than saying, 'well, we found the answers'.

The following excerpts are taken from lessons 5 and 10. In lessons 5, 8, and 10, brief discussions took place with students who said they preferred listening to teacher explanations rather than finding answers by inquiry. In his reply, Mr. Adler referred to the effectiveness of the approach:

<u>Lesson 5.</u> The very simple reason … we have to listen to each other is, I think … that if you have a certain idea in your head … you can't get rid of it by me giving you a new rule and saying memorize it.
<u>Lesson 10.</u> In [the other class] I stuck to the textbook.… But you are beginning to think more critically.… They still think current is used up.… We found out, three times, because we measured it.… No, that's not right.

Conjecture 3. Students used the model of charged particles while they developed an understanding of electric circuits.

The following excerpts illustrate how different students talked about electric current in the course of the lessons (temporal position within the lesson recording indicated in parentheses):

Lesson 1. The electric energy or current has to flow in a closed circuit from the battery to the light bulb and back and because of this the bulb will light. (41:55)
Lesson 3. Ehr, nature tries to find equilibrium. So the minus terminal goes, no, from the minus terminal energy moves to the plus terminal, because the plus attracts the electrons (07:11). Well, … in any case we agree student 2 was wrong, because the electrons are not used up, but the energy in the electrons. (37:31)
Lesson 4. Well, that with this other light bulb … that the number of amperes before and after the light bulb remains almost the same [after experiment]. (42:15)
Lesson 5. The filament is thinner … so it takes effort for the electrons to go through, so they take the easiest way and go through the ammeter and not through the light bulb [discussion on simulation of short circuit]. (13:08)
Lesson 10. At point 1, all electrons pass through all bulbs, because the mA does not change, because there is no junction. You don't measure a difference. In situation 2, there is [a junction] and electrons go one by one to a and b [explaining the difference between current in series and parallel circuit]. (26:55)
Lesson 13. Sir, if the voltage gets higher, means that the attractive force here increases, which makes it flow faster.… So you get a higher amperage. (26:24)
Interview: At the negative side of the battery there is a surplus of electrons, at the positive side there is a shortage.… The higher the difference, the higher the voltage.… Because, the surplus of electrons at the minus side repels the electrons, and the electrons are attracted by the protons at the positive side. So the electrons start to flow and the higher the pushing and pulling forces, the more they start to flow … the higher the amperage. The number of amperes is the current.

Conjecture 5. Classroom norms of inquiry and the enactment of an adequate local instruction theory were instrumental in establishing student engagement and conceptual understanding.

The following vignette from lesson 7 illustrates students' active participation in response to teacher questions and the tasks set in the worksheets and how engagement and development of understanding went together. The teacher showed a computer simulation of a short circuit: an ammeter in parallel with a light bulb. A large current (shown by blue balls indicating charge) passed through the ammeter and the battery was overheating (shown by flames). The students were looking for an explanation of the phenomenon (temporal position within 50-minute lesson indicated in brackets).

Student 1: Yes, I have that the electrons, [move] as fast as possible to the plus … by the shortest route. (11:52)
Teacher: But that one is much longer [pointing at the ammeter]. (11:55)
Student 1: No, but then I mean through the bulb, through the first one, I mean where the bulb is there it does the shortest route.… (12:05)
Teacher: It is looking for the shortest route, but according to me this is the shortest route.
Student 1: Yes, but then it doesn't pass through the ammeter. (12:10)
Teacher: So it doesn't pass through the ammeter?
Student 1: Yes. (12:12)
Teacher: Oh? Because, so, the ammeter doesn't measure anything in this case? (12:18)
Student 2: Well, I think it does. (12:19)
Teacher: You think it does? [several students talking at the same time; a student mentions the resistance of the light bulb and is asked by the teacher to explain.]
Student 2: That ehr, the bulb, the filament is thinner than where you hold it, so it takes effort for the electrons to pass through. So they look for the easiest way and they pass through the ammeter and not through the bulb…. (13:22)
Student 3: But you don't know that in advance [the discussion continues]. (13:23)

This short vignette illustrates how the teacher led the discussion in which the students tried to make sense of what they saw in the simulation. The first student suggested charge takes the shortest route; the teacher asked her to clarify what she meant by shortest. The discussion continued until Student 2 mentioned that it is easier for charge to pass through the ammeter than through the light bulb, showing her disagreement with Student 1's idea that current did not pass through the ammeter. Student 3 then responded to Student 2 by bringing up that current doesn't know in advance which of the two branches of the circuit poses the least resistance. The discussion continued by exploring the issue brought up by Student 3.

SUMMARY

Toward physics education in agreement with the nature of science:
Grade 9 electricity as a case.

In the Netherlands the number of people choosing a science or technology related career is below the expected future demand, which, so is argued, might jeopardize the country's innovative and competitive power. Having an understanding of science is potentially of economic value, but also of cultural importance for an individual in a scientifically and technologically oriented world. However, in secondary education physics is particularly unpopular as compared to other school subjects, and students often associate terms such as "difficult" and "unpleasant" with it. The understandings of specific theoretical concepts in physics (e.g. electric current, potential difference, and resistance) are problematic for many students and not in line with the scientifically accepted conceptions. It has been hypothesized that understanding concepts in the sciences requires the learner to think in terms of a scientific world view. In this enculturating perspective the focus is on the processes by which students become familiar with relevant scientific norms, values, motives, epistemology and other characteristics of the Nature of Science (NOS), while theoretical concepts are seen as cognitive tools used by students in scientific activities.

It is not self-evident that physics education in line with NOS leads to student understanding of theoretical concepts. Therefore, it is relevant to investigate how such education can be appropriately designed and enacted, and how student learning may then take place. This dissertation describes research in physics education designed in line with NOS and aimed at helping students understand theoretical concepts. The overall research question of the dissertation was:

How can physics education be designed and enacted in such a way that it is in agreement with the Nature of Science (NOS) and fosters conceptual understanding in electricity?

We have followed the design research approach described by Gravemeijer and Cobb (2006) to answer the overall research question. This is a cyclic research approach that uses macro-cycles consisting of a preparation phase, a classroom experiment, and a retrospective evaluation. The instruction has provided an experimental setting enabling us to study aspects of learning and their relation with instruction. A potentially effective way to innovate in education is to involve practicing teachers in educational design and to relate the innovation to teachers' concerns about student learning. Therefore, physics teachers and the author of the dissertation, who is a teacher educator, partly assisted by a second teacher educator, collaboratively designed the instruction. The instruction was enacted in grade 9 (age 14) classrooms of the pre-university stream of secondary schooling in the southeastern part of the Netherlands. Two cycles of design research were carried out (described in Chapters 2 and 3), with the second cycle building on the results of the first. The participation of teachers in the second cycle was further studied from the perspective of teacher learning and professionalization (Chapter 4).

The design cycles gave rise to questions about the support given to students by the learning materials in the form of a basic model as a theoretical starting point for inquiry activities. Generally, the textbook is the main learning material and source of scientific models in the classroom. Hence, the last study of the dissertation was a textbook study on the use of models (Chapter 5). Criteria were derived from the literature and applied to pre-university physics textbook series commonly used in schools in the Netherlands.

The different studies of the dissertation were guided by specific research questions. In the first design cycle the research question was:

1. Which inherent characteristics of inquiry-based instruction complicate the process of constructing conceptual understanding?

The second design cycle incorporated what had been learnt during the first. The research questions were:

2. How effective was the enacted instructional design in terms of the conceptual learning aims of the Grade 9 lessons about electric circuits?
3. How do the learning arrangement characteristics help explain the development of Grade 9 students' conceptual understanding in the inquiry classroom?

To understand the professionalization and learning of the participating teachers, we posed the research questions:

4. What learning did the teachers report after participation in the collaborative lesson design and enactment?
5. To what extent did the teachers change their classroom practice?
6. How can the reported learning and the teachers' classroom practice be related to participation in the professional development process?

Finally, the textbook study was guided by the following research question:

7. 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 the literature?

First design research cycle: key issues in creating inquiry-based instruction

Chapter 2 describes the first cycle of design research, which started with the intention to develop a local instruction theory for learning about direct current (dc) electric circuits in the context of scientific inquiry. A local instruction theory consists of conjectured student learning processes related to a selected topic and possible means of support for those learning processes, encompassing among others the instructional activities, classroom culture, and learning materials (Gravemeijer & Cobb, 2006). Drawing on a theoretical framework based on individual conceptual change and socio-cultural views on learning, instruction was designed addressing well-known and common conceptual problems and attempting to create a physics (research) culture in the classroom. Twelve lessons were designed in cooperation with a physics teacher and enacted in the teacher's pre-university stream grade 9 classroom (age 14). The core elements of the lessons were formed by investigative tasks for groups of students, and whole class discussions led by the teacher, focusing on discussion of the results and the formulation of new questions. During the enactment of the lessons an iterative process took place of testing and adapting instruction. However, it became clear that the conjectured local instruction theory was not successful. Therefore, during the retrospective evaluation the focus of the study shifted to identifying the characteristics of inquiry-based instruction that complicated the process of constructing conceptual understanding.

Data were collected in the forms of pretests and posttests, video and audio recordings, field notes, and students' written work. Retrospective analysis of the data took place following the two-step procedure described by Cobb and Whitenack (1996), based on grounded theory. The first step consisted of identifying patterns in the data guided by sensitizing concepts based on the theoretical framework. Patterns became apparent from the lesson observations and a first examination of the data; they were described as conjectures about the dataset. Subsequently the data were examined using the constant comparison approach, looking for confirmations or refutations of the previously identified conjectures. The first step resulted in a number of conjectures supported and refined by evidence from the data. The second step was directed at identifying possible causal mechanisms and processes to account for the patterns found in the first step.

From the analysis of the data three tensions have emerged: (a) the tension between open inquiry as a characteristic of scientific practice, and the need to guide and structure the student investigations to help students obtain empirical results that can be built upon; (b) the tension between the need to allow students to invent and adjust their own ideas on the basis of inquiry activities and the need to inform them about accepted theories that were deemed to be too sophisticated to be reinvented; and (c) the tension between fostering scientific interest as part of a scientific research culture in the classroom and the existing task-oriented school culture.

Based on the results of the study we formulated three recommendations for physics instruction in which understanding theoretical concepts and processes of inquiry are important:

1. Open student investigations have to be sufficiently structured to enable students to find experimental results, which they can productively build upon.
2. Students have to be offered an initial theoretical starting point for constructing scientifically sound theories from empirical data.
3. Teachers have to offer the students considerable support to help them shift from school-oriented motives to scientifically oriented motives.

Second design research cycle: a balanced approach

Chapter 3 describes the second cycle of design research, in which a conjectured local instruction theory was created in cooperation with three physics teachers for the grade 9 topic of electricity, taking into account the findings of the first study. The lessons emphasized establishing classroom norms of inquiry using, among others, a theoretical starting point, targeted experiments guided by conceptual questions, and theory-oriented, whole-class discussions. The goal of the study was to understand how the learning arrangement characteristics might support learning in the classroom.

The data collection and the retrospective analysis took place following the same method as during the first study. The retrospective analysis focused on one teacher's class, because lesson-by-lesson meetings to evaluate and redesign instruction had only been possible with this teacher, and his enactment of the instruction most closely approximated the design intention.

The analysis of the pretest and posttest results showed that the conceptual learning aims of the lesson series had to a large extent been accomplished in this classroom. Student conceptual understanding had increased: many students had developed the ability to interpret circuit diagrams, to distinguish the concepts electric current, voltage and resistance, and to explain the role of the battery or power supply. Selected topics, such as the electric circuit as a system, the battery as a source of constant potential difference, and some aspects of parallel circuits, were still difficult for the students. Moreover, we found that the new classroom norms were consciously enacted by the teacher and by most, though not all, of the students. The teacher appreciated and used student contributions and generally, the students were engaged during the lessons. The students made use of the theoretical starting point, a charged particle model of electricity, while they developed an understanding of electric circuits. It appeared more difficult for the students and the teacher to refer to the model in their reasoning when circuits became more complicated. The experiments carried out by the students were characterized both by structure and by inquiry. During the experiments there was additional teacher support, which sometimes interfered with the inquiry, but allowed students to obtain meaningful results. Whole class discussions linked the experiments to the development of theoretical ideas.

In the data analysis we paid attention to the ways in which student ideas on physics concepts developed in the classroom when the norms of inquiry were present or absent, and when the local instruction theory was adequate or inadequate. We found that the classroom norms of inquiry and the enactment of an adequate local instruction theory fostered the engagement and the conceptual understanding of most students. We concluded that the enacted local instruction theory involved a combination of conceptual tools, challenges, and supports that made engagement rewarding for students. The balance created in the three tensions identified in the first study worked out successfully in this class and the elements emphasized in the design reinforced each other. As a result, the students saw the experimental lessons as a way to understand physics not available to them in the teacher's traditional instruction. The study thus yielded a local instruction theory for electric circuits and insights into the ways the guidelines formulated after the first study played out in practice.

Teacher professionalization

Chapter 4 describes the second design research cycle with the three teachers from the perspective of a professional development intervention. The intervention focused on establishing a culture of inquiry in the classroom and on helping students understand the basic concepts of electricity. It was designed to include characteristics that, according to literature, foster a successful change of classroom practice: subject content and student learning were important starting points, teachers' concerns and experiences were integrated in the process, teachers shared experiences and collaborated, classroom coaching was included, and the intervention took a substantial amount of time.

The intervention consisted of preparatory meetings and feedback/evaluation meetings. In the preparatory meetings the topics were: the physics concepts and student conceptual problems, a model of moving charged particles as a theoretical starting point, a pedagogy to create a culture of inquiry in the classroom, design of a conjectured local instruction theory, assessment, and practical issues. Feedback and evaluation took place during the lesson enactment, partly individually, partly as group meetings.

The research aim of the study was to understand how the participating teachers developed professionally in terms of reported learning and changes in the classroom.

The collected data included video and audio recordings of meetings and lessons, agendas, notes, e-mails, interviews, and a student pre/post questionnaire. In the qualitative data analysis the various sources were organized so that the professional development of each teacher could be described as a separate case and common themes between the three cases could be identified.

The teachers reported changes with respect to pedagogical content knowledge (PCK), classroom pedagogy and attitude. These changes consisted of a deeper understanding of the physics content in relation to student learning; an awareness of the extent of their own understanding; and increased confidence after a second lesson enactment.

The data showed that the change of the classroom culture had been noticeable for the students, although by varying degrees depending on the teacher. Students indicated that they cooperated more with others, carried out more experiments, had more opportunities to investigate things by themselves and had more opportunities to develop their own ideas. The changes of the classroom practices lasted beyond the time frame of the intervention.

The dynamic change process of the teachers could be understood from the perspective of the interconnected model of professional growth (Clarke & Hollingsworth, 2002). Changes were initiated by external sources, but were in line with relevant concerns of the teachers about student understanding. Behavior changes were partly planned, and partly resulted from the teachers' responses to new classroom situations. Feedback, modeling, and coaching were planned to foster the behavior changes. However, the school timetables did not sufficiently allow for individual lesson-by-lesson feedback in two of the three cases, which may have had a negative impact on the lesson enactment and the learning opportunities. Cooperative lesson development, classroom enactment, coaching, reflection, and mutual discussions helped sustain the teachers' development by means of a dynamic rather than a strictly sequential process. Differences between the individual teachers could be explained by considering their different starting points as professional educators, the environments in which they operated, and differences with respect to their concerns.

The teachers' willingness to invest to change the classroom culture and in this manner improve student understanding was important for their professional development. We inferred that the teachers were motivated, because the innovation agenda matched with their concerns, and because they obtained the means to be potentially successful in the classroom, that is, a workable local instruction theory. Enactment of the lessons led to a realization of the initial ideas, with visible consequences in the classroom. Coaching could take place with an eye for the individual needs of the teachers without losing the focus on the local instruction theory and agreed-upon pedagogy. Feedback and reflection were used to adapt the local instruction theory and instructional materials. We concluded that the professional development intervention appeared effective in fostering teacher learning and changing the classroom culture, because the various activities complemented each other, while coaching, feedback, and the possibility to exchange experiences appeared to help the teachers persist in the light of less successful experiences.

Models in textbooks

Chapter 5 describes an investigation of models of electricity in a series of commonly used secondary school physics textbooks. In an inquiry context, theoretical models offered to students should afford conceptual and experimental inquiry activities and should respects insights from NOS. In many secondary schools the main source of theoretical models for both students and teachers is the textbook. 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 applied to student tasks. The criteria needed to be interpreted and evaluated qualitatively.

Models of electricity were evaluated using the criteria in recent editions of commonly used Dutch physics textbooks for grade 7 to 12, all from the same publisher. Six books were studied from two series. Chapters dealing with electricity were studied in full; chapters partly dealing with electricity were studied in part. Some models on other topics were included in the evaluation, to obtain a fair account of the different ways the textbooks paid attention to models. The criteria were scored for sections of text and student tasks, and qualitative summaries were made.

Books for the lower grades described models of electricity mainly as factual knowledge, with little attention to the model nature of the explanations and to processes of knowledge development in science. Books for the higher grades addressed models of electricity in similar ways as the books for the lower grades. However, dynamic models (unrelated to electricity) and models of matter (indirectly related to electricity) were explicitly addressed as models. The latter were presented as fallible descriptions of parts of reality and attention was given to historical developments, limitations, and idealizations.

The basic models of electricity in the books were a submicroscopic model of moving electrons, and macroscopic models relating the concepts electric current, voltage, resistance and energy. In the descriptive text both types of models were sometimes related. However, the student tasks emphasized the macroscopic concepts. Most student experiments were recipe-type experiments, which seldom formed part of an inquiry cycle.

We concluded 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 approach in line with NOS, because little was left for students to find out. Student activities that would fit such an approach appeared only to a limited extent.

However, the textbooks paid considerable attention to conceptual understanding, both in the descriptive text and the student tasks. This 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. We expected that the criteria compiled in this study might be helpful for physics teachers selecting textbooks with an inquiry orientation, as well as for textbook authors and editors.

Conclusions and discussion

In chapter 6 the findings and conclusions of the studies are summarized and discussed in order to answer the main research question. Directions for future research are suggested, and selected strengths and limitations of the studies are provided. The chapter ends with implications for educational practice.

In the design studies we have found that three tensions inherently exist in physics education in agreement with NOS, aiming at fostering the understanding of theoretical concepts in electricity. Effective student learning requires a balanced approach: balance between openness of investigations and structure; balance between the development of students' own ideas and the need to inform them about accepted theories; balance between scientific research related norms and school related norms. With this balance in mind, a local instruction theory and classroom pedagogy were designed. In one classroom, in which the local instruction theory was enacted, it appeared possible to accomplish most conceptual learning aims, to move the classroom culture towards a culture of inquiry, and to foster student engagement. The data analysis indicated that in particular the interplay between classroom norms of inquiry and an adequate local instruction theory made it rewarding for most students to actively engage.

Conditions for teacher learning were created in the cooperation process of the researcher and the three participating teachers, by taking into account guidelines from the literature. Factors that contributed to teacher learning were the attention to teachers' concerns, the possibility to share ideas and experiences, external input in the form of research-based ideas, and feedback and reflection on lesson enactment. The teachers' classroom behaviors changed in the desired direction, and the changes lasted after the first enactment of the lessons. The extent to which the results were visible to the students varied, depending on the teachers' experience and the environment in which the teachers operated, which, among others, determined the possibilities for individual coaching. In conclusion, the cooperation process has been a viable way to help teachers develop inquiry approaches in line with NOS in their classrooms.

The textbook could be an effective source of theoretical models and model-oriented student tasks, if the ways in which textbooks presented and used models were in line with NOS, allowed for student inquiry, and fostered conceptual understanding. Qualitative criteria were identified in the literature to evaluate textbooks in this respect. The chapters on electricity in a series of commonly used Dutch physics textbooks that were evaluated with the help of the criteria, appeared to pay attention to contexts and student conceptual understanding, but hardly showed an inquiry orientation. Models of electricity were generally presented as facts. The model concept appeared mainly in in topics unrelated (such as dynamic modeling) or indirectly related to electricity (such as models of matter). However, it was noticed that with relatively small modifications the use of models and tasks in the textbooks could become more in line with NOS.

Fostering conceptual understanding using inquiry turned out to be a promising, but complex process. In the classroom in which the approach was successful, selected elements of the learning environment were coordinated to foster student learning. Chapter 6 discusses the role of these elements: a local instruction theory and classroom culture, teacher competences, and learning materials. Areas for further research are also indicated: among others they include the investigation of optimized or extended versions of the local instruction theory, of fostering conceptual understanding in schools in which a culture of inquiry is commonplace, of teacher learning in similar interventions with a team of teachers from a single school, and of the role of models in a more extended range of textbooks.

As strengths of the studies we identified the comprehensive approach that took into account the complications of coming to understand the topic of dc electricity by means of inquiry. Moreover, the results of the design studies provided support for a balanced approach and insights into the ways it may be used to innovate classroom practice. Methodologically, the two design studies were good examples of design research with the aim to understand learning processes. The study on teacher learning showed that a cooperation process of a researcher and teachers creating and enacting a local instruction theory, was a viable way to help teachers develop inquiry approaches in line with NOS in their classrooms. Finally, the textbook study provided tested criteria that may be used by educational practitioners, researchers and textbook authors or editors.

Limitations of the studies can be found in the relatively small numbers of students and teachers involved in the project, which means that the instructional design should be considered as a prototype. The textbook study also involved a limited range of textbooks, so that no claims can be made about the whole range of physics textbook in use in secondary schools in The Netherlands. Moreover, the textbook study did not include the actual use made of the textbooks by teachers in their classrooms.

The results of the studies may have implications for practice. Teachers and teacher educators need to develop a balanced perspective on conceptual understanding in relation to inquiry and take into account the tensions that were identified. For the topic of electricity, teachers may learn from the local instruction theory and pedagogy developed in this dissertation. Both teacher education institutes and professionalization efforts need to prepare teachers for this type of instruction. This will be fostered if teachers and teacher educators develop an understanding of NOS. A noticeable classroom impact of teacher learning may be expected if teachers work cooperatively on the same issue, related to a concern about student learning, if expertise is available on the content and pedagogy, and if classroom coaching and feedback are part of the project. The criteria to evaluate textbooks may be helpful for authors of learning materials if they intend to foster model-oriented activities and inquiry, but also for practitioners for the selection of these materials and in teacher education to prepare for a systematic evaluation of learning materials for physics.

SAMENVATTING

Naar natuurkundeonderwijs in overeenstemming met de aard van de natuurwetenschappen: Elektriciteitsleer in 3 VWO als voorbeeld.

In Nederland kiezen minder mensen voor een carrière in de exacte wetenschappen of techniek dan nodig is op basis van de verwachte toekomstige vraag vanuit de arbeidsmarkt. Dit vormt een mogelijke bedreiging voor het innovatievermogen en de concurrentiekracht van het land. Verstand hebben van exacte vakken heeft niet alleen economische waarde, maar heeft ook een culturele waarde in een wereld die is gericht op wetenschap en techniek. In het voortgezet onderwijs is echter met name natuurkunde onpopulair vergeleken met andere schoolvakken. Dit vak wordt relatief vaak geassocieerd met termen als “moeilijk” en “onprettig”. Het begrijpen van bepaalde theoretische natuurkundige concepten (zoals elektrische stroom, spanning en weerstand) is voor veel leerlingen lastig en hun begrip van die concepten is vaak niet in overeenstemming met de wetenschap. Er wordt geopperd dat het begrijpen van concepten in de exacte vakken van de leerling vraagt om te denken volgens een wetenschappelijk wereldbeeld. In dit enculturatieperspectief ligt bij het leren de nadruk op wetenschappelijke processen die de leerlingen vertrouwd maken met normen, waarden, motieven, epistemologie, en andere kenmerken van de aard van de natuurwetenschappen (Nature of Science; NOS). Theoretische concepten vervullen daarbij de rol van gereedschappen gebruikt door leerlingen in hun natuurwetenschappelijke activiteiten.

Het spreekt niet vanzelf dat natuurkundeonderwijs in overeenstemming met NOS leidt tot begrip van theoretische concepten. Daarom is het relevant om te onderzoeken hoe dit soort onderwijs met succes kan worden ontworpen en uitgevoerd, en hoe leerprocessen dan plaatsvinden. Dit proefschrift beschrijft onderzoek naar natuurkundeonderwijs, ontworpen in lijn met NOS en gericht op bevorderen van het begrip van theoretische concepten. De hoofdvraag van het proefschrift was:

Hoe kan natuurkundeonderwijs zo worden ontworpen en uitgevoerd dat het in overeenstemming is met de aard van de natuurwetenschappen, en het begrip van theoretische concepten op het gebied van elektriciteit bevordert?

Om de hoofdvraag te beantwoorden is de methode van ontwerponderzoek gevolgd, zoals beschreven door Gravemeijer en Cobb (2006). Dit is een cyclische onderzoeksmethode waarin macro-cycli worden gebruikt die bestaan uit een voorbereidingsfase, een experiment in de klas, en een retrospectieve analyse. De lessen vormen een experimentele setting waarin relevante aspecten van het leren en de relatie tussen het leren en het uitgevoerde onderwijs bestudeerd kunnen worden. Voor kansrijke onderwijsinnovatie is het van belang om docenten uit het werkveld bij het onderwijsontwerp te betrekken en de innovatie te relateren aan docentvragen rond het leren van leerlingen. Het onderwijs in dit onderzoek is dan ook gezamenlijk ontwikkeld door de onderzoeker, die ook lerarenopleider is, en natuurkundedocenten, deels met medewerking van een tweede lerarenopleider. De lessen zijn uitgevoerd in 3 VWO klassen in Zuidoost Brabant. Twee ontwerponderzoekscycli zijn uitgevoerd (beschreven in hoofdstukken 2 en 3), waarbij de tweede cyclus voortbouwde op de resultaten van de eerste. De deelname van de docenten uit de tweede cyclus is daarnaast bestudeerd vanuit het perspectief van professionalisering en leren van deze docenten (hoofdstuk 4).

In de ontwerponderzoekscycli werd experimenteel lesmateriaal gebruikt. Dit materiaal bood bijvoorbeeld een eenvoudig model van elektriciteit als theoretisch startpunt voor de leerlingactiviteiten. Over het algemeen vormt het natuurkundeboek het belangrijkste leermateriaal in de klas en is het de bron voor de natuurwetenschappelijke modellen die worden gebruikt. De vraag is in hoeverre de aangeboden modellen ondersteuning bieden voor onderwijs in overeenstemming met NOS. Vandaar dat de laatste studie van het proefschrift bestond uit een studie naar natuurkundeboeken over het gebruik van modellen (hoofdstuk 5). Met behulp van de literatuur zijn criteria bepaald en deze zijn toegepast op een aantal VWO natuurkundeboeken die algemeen in Nederland worden gebruikt.

Voor de verschillende studies in het proefschrift zijn specifieke onderzoeksvragen geformuleerd. De onderzoeksvraag in de eerste ontwerponderzoekscyclus was:

1. Welke kenmerken van onderzoekend leren compliceren het proces van begripsontwikkeling?

De tweede ontwerponderzoekscyclus maakte gebruik van wat tijdens de eerste was geleerd. De onderzoeksvragen waren:

2. Hoe effectief was het uitgevoerde lesontwerp ten aanzien van de conceptuele leerdoelen van de VWO 3 lessen over elektrische stroomkringen?
3. Hoe kunnen de kenmerken van de leeromgeving de begripsontwikkeling van de 3 VWO leerlingen in de experimentele klas helpen verklaren?

Als leidraad bij het begrijpen van het leren en de professionalisering van de deelnemende docenten, zijn de volgende onderzoeksvragen gebruikt:

4. Welke leeropbrengsten rapporteerden de docenten na deelname aan het gemeenschappelijk lesontwerp en de uitvoering van de lessen?
5. In welke mate hebben de docenten hun lespraktijk veranderd?
6. Hoe kunnen de gerapporteerde leeropbrengsten en lespraktijk van de docenten gerelateerd worden aan hun deelname aan een professioneel ontwikkelingsproces?

Bij de leerboekstudie is tenslotte de volgende onderzoeksvraag gebruikt:

7. In welke mate wordt onderzoekend leren bevorderd of belemmerd door de manier waarop modellen van elektriciteit worden aangeboden, uitgewerkt en gebruikt in een serie natuurkundeboeken in het Nederlandse voortgezet onderwijs?

Eerste ontwerponderzoekscyclus: kenmerken van onderzoekend leren

Hoofdstuk 2 beschrijft de eerste ontwerponderzoekscyclus. Aanvankelijk was deze gericht op het ontwerp van een lokale instructietheorie voor het leren begrijpen van elektrische gelijkstroomkringen middels een onderzoekende aanpak. Een lokale instructietheorie beschrijft hypothetische leerprocessen in relatie tot een bepaald onderwerp en mogelijke manieren om die leerprocessen te ondersteunen met behulp van onder andere de instructie, de cultuur in de klas, en de leermaterialen (Gravemeijer & Cobb, 2006). Voor het theoretisch kader is gebruik gemaakt van zowel het individuele *conceptual change* perspectief op leren, als van socioculturele perspectieven. Op basis hiervan zijn lessen ontworpen om bekende en veel voorkomende begripsproblemen aan te pakken, en om een natuurwetenschappelijke (onderzoeks)cultuur in de klas tot stand te brengen. Twaalf lessen zijn ontworpen in samenwerking met een natuurkundedocent, en uitgevoerd in de VWO 3 klas van de docent. De belangrijkste elementen van de lessen waren korte onderzoekjes door groepjes leerlingen en klassendiscussies geleid door de docent, gericht op de resultaten van de onderzoekjes en op het formuleren van nieuwe vragen. In de lessen werd het onderwijsontwerp iteratief uitgeprobeerd en aangepast. Het werd echter snel duidelijk dat de hypothetische lokale instructietheorie niet succesvol was. Daarom verschoof de focus tijdens de retrospectieve analyse naar het identificeren van de specifieke kenmerken van onderzoekend leren die begripsvorming bemoeilijken.

Gegevens zijn verzameld in de vorm van pre- en posttoetsen, video- en audio-opnamen, aantekeningen en geschreven werk van de leerlingen. Bij de retrospectieve analyse werd de procedure gevolgd van Cobb en Whitenack (1996), op basis van *grounded theory*. De eerste stap van deze procedure bestond uit het bepalen van patronen in de data, geleid door *sensitizing concepts* uit het theoretisch kader. Deze patronen werden zichtbaar tijdens de lesobservaties en het doornemen van de data; ze werden geformuleerd als hypotheses over de totale dataset. Vervolgens werd de dataset doorgenomen volgens de methode van *constant comparison*, waarbij gezocht werd naar bevestiging en ontkrachting van de eerder geformuleerde hypotheses. De eerste stap resulteerde zo in een aantal hypotheses die werden ondersteund en waar nodig verfijnd door bewijsmateriaal uit de data. De tweede stap bestond eruit mogelijke causale mechanismen en processen te identificeren om de patronen uit de eerste stap te kunnen verklaren.

Uit de analyse kwamen drie spanningsvelden naar voren: (a) tussen enerzijds open onderzoek als kenmerk van de wetenschappelijke praktijk en anderzijds de noodzaak de leerlingonderzoekjes te begeleiden en structureren, zodat leerlingen bruikbare resultaten kunnen verkrijgen; (b) tussen enerzijds de noodzaak om leerlingen hun eigen ideeën te laten vormen op basis van de onderzoekjes en anderzijds hen te informeren over geaccepteerde theorie die te moeilijk is om zelf te bedenken; en (c) tussen enerzijds het bevorderen van wetenschappelijke nieuwsgierigheid als onderdeel van een onderzoekscultuur in de klas en anderzijds de bestaande taakgeoriënteerde schoolcultuur.

Op grond van de resultaten van deze studie hebben we drie aanbevelingen geformuleerd voor natuurkundeonderwijs waarin het begrijpen van concepten en onderzoeksprocessen belangrijk zijn:

1. Zorg dat open leerlingonderzoek voldoende gestructureerd is om leerlingen te helpen experimentele resultaten te vinden die tot verder begrip kunnen leiden.
2. Reik leerlingen een theoretisch startpunt aan om hen te helpen zinvolle theorie te construeren op basis van empirische gegevens.
3. Ondersteun de leerlingen om vanuit een school georiënteerde motivatie een meer natuurwetenschappelijk georiënteerde motivatie te ontwikkelen.

Tweede ontwerponderzoekscyclus: een gebalanceerde aanpak

Hoofdstuk 3 beschrijft de tweede ontwerponderzoekscyclus. Hierin is een hypothetische lokale instructietheorie ontworpen in samenwerking met drie natuurkundedocenten voor het onderwerp elektriciteit in klas 3 VWO. De bevindingen uit de eerste studie zijn daarbij in acht genomen. De nadruk in de lessen lag op het tot stand brengen van onderzoeksnormen in de klas met behulp van onder meer een theoretisch startpunt voor de leerlingen, gerichte experimenten geleid door conceptuele vragen, en theoriegeoriënteerde klassendiscussies. Het doel van de studie was om te begrijpen op welke manier de kenmerken van de leeromgeving konden leiden tot leren in de klas.

Bij de dataverzameling en –analyse werd dezelfde aanpak gevolgd als tijdens de eerste studie. De retrospectieve analyse richtte zich op de klas van één van de docenten, omdat alleen bij deze docent na elke les een evaluatiebespreking en herontwerp mogelijk waren, en omdat zijn aanpak het dichtst in de buurt kwam van de ontwerpintentie.

De analyse van de pre- en posttoets liet zien dat de conceptuele leerdoelen van de lessenserie voor een groot deel gerealiseerd waren in deze klas. Het conceptuele begrip van de leerlingen was vooruit gegaan: veel leerlingen waren nu in staat schema's van schakelingen te interpreteren, de begrippen elektrische stroom, spanning en weerstand van elkaar te onderscheiden, en de rol van de batterij of spanningsbron uit te leggen. Sommige onderwerpen bleven lastig voor de leerlingen, zoals het beschouwen van de schakeling als een systeem, de batterij als spanningsbron, en aspecten van parallelschakelingen. Verder vonden we dat de nieuwe klassennormen bewust werden uitgedragen door de docent en zichtbaar waren bij de meeste, maar niet alle, leerlingen. De docent gaf blijk van waardering voor discussiebijdragen van de leerlingen en in het algemeen namen de leerlingen actief deel aan de lessen. Ze maakten gebruik van het theoretische startpunt, een model van elektrisch geladen deeltjes, terwijl zij hun begrip ontwikkelden van elektrische stroomkringen. Lastiger bleek het voor de leerlingen en de docent om ook bij het redeneren over ingewikkelder schakelingen gebruik te blijven maken van het model. De leerlingexperimenten waren zowel gestructureerd als onderzoeksgericht. Tijdens de experimenten gaf de docent extra hulp, die soms van invloed was op de onderzoekjes, maar de leerlingen wel de mogelijkheid gaf zinvolle resultaten te behalen. Klassendiscussies verbonden de experimenten met de ontwikkeling van theoretische ideeën.

In de data-analyse hebben we aandacht besteed aan de manier waarop het conceptuele begrip van de leerlingen zich ontwikkelde in verschillende situaties: in aanwezigheid of in afwezigheid van onderzoeksnormen, en wanneer de lokale instructietheorie geschikt of ongeschikt bleek. We vonden dat de actieve deelname en begripsontwikkeling van de meeste leerlingen bevorderd werden wanneer onderzoeksnormen in de klas aanwezig waren en wanneer de docent de lokale instructietheorie volgde. We concludeerden dat de uitgevoerde lokale instructietheorie een combinatie bevatte van conceptueel gereedschap, uitdagingen en ondersteuning, die het voor de leerlingen de moeite waard maakte om actief deel te nemen. De balans in de drie spanningsvelden uit de eerste studie werkte succesvol in deze klas en de elementen die in het lesontwerp de nadruk hadden gekregen versterkten elkaar. Als gevolg hiervan zagen de leerlingen de experimentele lessen als een manier om natuurkunde te begrijpen die ze niet hadden in de traditionele lessen van de docent. De studie resulteerde dus in een lokale instructietheorie voor gelijkstroomkringen en inzicht in de manier waarop de richtlijnen uit de eerste studie in de praktijk kunnen werken.

Professionalisering van de docenten

Hoofdstuk 4 beschrijft de tweede ronde ontwerponderzoek als een interventie gericht op de professionele ontwikkeling van de drie deelnemende docenten. Doel van de interventie was om een onderzoekscultuur in de klas te bereiken en de leerlingen te helpen de basisconcepten van elektriciteit te begrijpen. De interventie was ontworpen om te voldoen aan richtlijnen die volgens de literatuur leiden tot een succesvolle verandering van de lespraktijk: belangrijke uitgangspunten waren de vakinhoud en het leren van leerlingen, de behoeften van de docenten werden in het proces meegenomen, de docenten deelden hun ervaringen en werkten samen, er vond coaching plaats in de klas en de interventie duurde enige tijd.

De interventie bestond uit voorbereidingsbijeenkomsten en bijeenkomsten voor feedback en evaluatie. In de voorbereidingsbijeenkomsten werd het volgende besproken: de natuurkundige concepten en begripsproblemen bij de leerlingen, een model van bewegende geladen deeltjes als theoretisch startpunt, een didactiek waarmee een onderzoekscultuur in de klas kan worden bevorderd, ontwerp van een hypothetische lokale instructietheorie, toetsing, en praktische zaken. Evaluatie en feedback vond plaats in de periode waarin de lessen werden uitgevoerd, deels individueel, deels tijdens groepsbijeenkomsten.

Het onderzoeksdoel van deze studie was om te begrijpen hoe de deelnemende docenten zich professioneel ontwikkelden, in termen van zelfrapportage en van zichtbare veranderingen in de klas.

De dataverzameling bestond uit video- en audio-opnamen van bijeenkomsten en lessen, agenda's, aantekeningen, e-mails, interviews en een pre-/post- leerlingenvragenlijst. Bij de kwalitatieve data-analyse zijn de verschillende bronnen zo georganiseerd dat de professionele ontwikkeling van elk docent als een apart geval kon worden beschreven en dat gemeenschappelijke thema's tussen de drie gevallen zichtbaar werden.

De docenten rapporteerden veranderingen met betrekking tot hun vakdidactische kennis (*pedagogical content knowledge*), vakdidactische aanpak en attitude. Veranderingen bestonden onder andere uit een beter begrip van de natuurkundeconcepten in relatie tot het leren van de leerlingen, een bewustzijn van de grenzen van hun eigen begrip, en een toegenomen zelfvertrouwen na een tweede uitvoering van de lessen.

De data lieten zien dat de verandering van de cultuur in de klas merkbaar was voor de leerlingen, hoewel verschillend per docent. De leerlingen gaven aan dat ze meer samenwerkten met anderen, meer experimenten uitvoerden, meer gelegenheid hadden zelf zaken te onderzoeken en meer mogelijkheden hadden om hun eigen ideeën te ontwikkelen. Veranderingen in de uitvoering van de lessen bleven niet beperkt tot de duur van de interventie.

Het dynamische veranderingsproces van de docenten kon worden begrepen met het *interconnected model of professional growth* (Clarke & Hollingsworth, 2002).

Veranderingen werden geïnitieerd door kennis uit externe bronnen, maar deze paste bij begripsproblemen van leerlingen die de docenten hadden ervaren. Gedragsveranderingen waren deels gepland in het ontwerp, en kwamen deels tot stand door de reacties van de docenten op nieuwe situaties in de klas. Feedback, modelleren, en coachen werden ingezet om de gedragsveranderingen te stimuleren. In twee van de drie gevallen was het gezien de lesroosters echter niet mogelijk om elke les na te bespreken. Dit heeft waarschijnlijk de mogelijkheden tot leren van deze docenten negatief beïnvloed. De ontwikkeling van de docenten werd in stand gehouden door de gezamenlijke lesontwikkeling, het uitproberen in de klas, het coachen, de reflectie en de gezamenlijke discussies. Dit was meer een dynamisch dan een strikt sequentieel proces. Verschillen tussen de individuele docenten konden verklaard worden door rekening te houden met hun verschillende beginsituaties als onderwijsprofessionals, de verschillende omgevingen waarin zij werkten, en de verschillende aandachtspunten die zij hadden ten aanzien van het leren van hun leerlingen.

De bereidheid van de docenten om de klassencultuur te veranderen en op deze manier het conceptuele begrip van de leerlingen te verbeteren, was belangrijk voor hun professionele ontwikkeling. We concludeerden dat de docenten gemotiveerd waren, omdat de innovatie-agenda van de interventie overeen kwam met hun eigen behoeften, en omdat zij een bruikbare lokale instructietheorie in handen kregen die het mogelijk maakte om in beginsel succesvol te zijn in de klas. De uitvoering van de lessen leidde tot een realisatie van de aanvankelijke ideeën, met zichtbaar resultaat. Coachen vond plaats met oog voor de individuele behoeften van de docenten, zonder de lokale instructietheorie en de afgesproken aanpak uit het oog te verliezen. Evaluatie en reflectie hielp bij het aanpassen van de lokale instructietheorie en de leermaterialen. We concludeerden dat het professionele ontwikkelingstraject effectief was in het bevorderen van het leren van de docenten en het veranderen van de klassencultuur, doordat de verschillende activiteiten elkaar aanvulden. Coaching, feedback en de mogelijkheid ervaringen uit te wisselen hielpen de docenten om te volharden, ook in minder succesvolle situaties.

Modellen in natuurkundeboeken

Hoofdstuk 5 beschrijft een onderzoek naar modellen van elektriciteit zoals die voorkomen in een serie veelgebruikte VWO natuurkundeboeken. In een context van onderzoekend leren wordt van theoretische modellen voor leerlingen verwacht dat ze conceptuele en experimentele onderzoeksactiviteiten mogelijk maken en niet strijdig zijn met NOS inzichten. In veel scholen voor voortgezet onderwijs is het leerboek de belangrijkste bron van theoretische modellen voor zowel leerling als docent. In deze studie is een lijst met 16 criteria opgesteld om modellen in natuurkundeboeken te kunnen evalueren ten aanzien van de mate waarin ze in overeenstemming zijn met NOS. De criteria zijn opgesteld op basis van geselecteerde artikelen over modellen in de wetenschap, in het natuurkundeonderwijs en in leerboeken. Acht criteria hebben betrekking op de beschrijvende tekst, en acht criteria op de leerlingopdrachten. De criteria zijn bedoeld om kwalitatief te worden geïnterpreteerd.

De criteria zijn gebruikt om modellen van elektriciteit te evalueren in recente edities van veelgebruikte Nederlandse natuurkundeboeken voor het VWO. Zes boeken uit twee series zijn in de studie opgenomen, alle van dezelfde uitgever. De hoofdstukken over elektriciteit zijn geheel bestudeerd; delen van hoofdstukken over elektriciteit zijn ook bestudeerd. In de studie zijn enkele modellen over andere onderwerpen opgenomen, om een representatief beeld te krijgen van de verschillende manieren waarop modellen in de boeken behandeld worden. Secties van de tekst en opdrachten zijn gescoord op de criteria en daarnaast zijn korte kwalitatieve samenvattingen opgesteld.

De boeken voor de onderbouw behandelden modellen over elektriciteit vooral als feitelijke kennis en besteedden nauwelijks aandacht aan het modelmatige karakter van de uitleg en aan processen van wetenschappelijke kennisontwikkeling. De boeken voor de bovenbouw behandelden modellen over elektriciteit op een vergelijkbare manier als de boeken voor de onderbouw. Echter, dynamische modellen (niet gerelateerd aan elektriciteit) en materiemodellen (indirect gerelateerd aan elektriciteit) werden expliciet als modellen besproken. Deze laatste werden gepresenteerd als feilbare beschrijvingen van gedeelten van de werkelijkheid en er was enige aandacht voor historische ontwikkelingen, beperkingen en idealisaties.

De modellen over elektriciteit in de boeken bestonden uit een submicroscopisch model van bewegende geladen deeltjes (elektronen), en macroscopische modellen met daarin de concepten elektrische stroom, spanning, weerstand, en energie. In de beschrijvingen werden beide soorten modellen soms aan elkaar gerelateerd, maar in de opdrachten lag de nadruk op macroscopische concepten. De meeste leerlingexperimenten hadden een receptmatig karakter en maakten zelden deel uit van een onderzoekscyclus.

We concludeerden dat de manier waarop de theorie werd gepresenteerd en uitgewerkt in de onderbouwboeken en in delen van de bovenbouwboeken moeilijk te verenigen was met een op NOS gebaseerde aanpak. Er bleef namelijk weinig over voor de leerlingen om zelf te onderzoeken en bedenken. Ook waren er maar weinig leerlingopdrachten die pasten bij een dergelijke aanpak.

Wel besteedden de boeken aandacht aan conceptueel begrip, zowel in de tekst als in de opdrachten. Dit zou een startpunt kunnen zijn voor een aanpak in de toekomstige edities die meer op onderzoekend leren gericht is. De auteurs zouden het modelmatige karakter van de theorie in een eerder stadium dan de $5^e/6^e$ klas kunnen introduceren in combinatie met meer theoretische en experimentele onderzoeksactiviteiten. We verwachten dat de criteria uit deze studie van nut kunnen zijn voor docenten die een leerboek zoeken met een onderzoeksoriëntatie, en ook voor auteurs en redacteurs van deze boeken.

Conclusies en discussie

In hoofdstuk 6 zijn de bevindingen en conclusies van de studies samengevat en besproken om de hoofdvraag van het proefschrift te beantwoorden. Er worden suggesties voor verder onderzoek gedaan en de sterke punten en beperkingen van het onderzoek worden vermeld. Het hoofdstuk eindigt met een aantal implicaties voor de onderwijspraktijk.

In de ontwerponderzoekscycli hebben we gevonden dat drie inherente spanningsvelden bestaan in natuurkundeonderwijs in overeenstemming met NOS, waarin conceptuele begripsvorming van elektriciteit wordt bevorderd. Effectief leren vraagt om een gebalanceerde aanpak: balans tussen de openheid en structuur van leerlingonderzoekjes; balans tussen de ontwikkeling van de eigen ideeën van leerlingen en de noodzaak hen te informeren over geaccepteerde theorieën; balans tussen normen uit een wetenschappelijke onderzoekscultuur en schoolgerelateerde normen. Met deze balans in gedachten is een lokale instructietheorie ontworpen. In één klas, waarin de lokale instructietheorie is uitgevoerd, bleek het mogelijk om de meeste conceptuele leerdoelen te verwezenlijken, om de cultuur in de klas te ontwikkelen in de richting van een onderzoekscultuur, en om de leerlingen actiever bij de lessen te betrekken. Uit de data-analyse werd duidelijk dat in het bijzonder het samenspel tussen onderzoeksnormen in de klas en een lokale instructietheorie het voor de meeste leerlingen de moeite waard maakte om zich voor de leeractiviteiten in te zetten.

Op basis van richtlijnen uit de literatuur werden voorwaarden gecreëerd om het leren van de docenten te bevorderen in de samenwerking tussen de onderzoeker en de drie deelnemende docenten. Factoren die bijdroegen tot het leren van de docenten waren de aandacht voor de behoeften van de docenten, de mogelijkheid om ideeën en ervaringen uit te wisselen, input van buiten in de vorm van op onderzoek gebaseerde ideeën, en feedback en reflectie ten aanzien van de uitgevoerde lessen. Het gedrag van de docenten in de klas veranderde in de beoogde richting en veranderingen bleven na een eerste uitvoering van de lessen in stand. De mate waarin resultaten van de professionalisering zichtbaar waren wisselde, afhankelijk van de ervaring van elke docent en van de omgeving waarin hij/zij werkzaam was. Hierbij speelde onder andere de mogelijkheden tot individuele coaching een rol. We concludeerden dat deze samenwerking een zinvolle manier was om docenten te helpen onderzoekend leren in de klas te ontwikkelen, in overeenstemming met NOS.

Het leerboek kan een effectieve bron zijn van theoretische modellen en model-georiënteerde leerlingopdrachten, als de manier waarop deze in leerboeken voorkomen tenminste in overeenstemming zijn met NOS, als ze onderzoekend leren mogelijk maken en conceptueel begrip bevorderen. Uit de literatuur hebben we kwalitatieve criteria afgeleid om leerboeken in dit opzicht te evalueren en de hoofdstukken over elektriciteit in een serie veelgebruikte Nederlandse natuurkundeboeken zijn met behulp van de criteria geëvalueerd. Deze hoofdstukken besteedden aandacht aan contexten en aan conceptueel begrip, maar hadden nauwelijks een onderzoeksgerelateerde oriëntatie. Modellen over elektriciteit werden over het algemeen gepresenteerd als vaststaande feiten. Het modelbegrip kwam vooral naar voren bij onderwerpen die niet gerelateerd waren aan elektriciteit (zoals dynamisch modelleren) of slechts indirect gerelateerd waren aan elektriciteit (zoals modellen van de materie). We merkten echter op dat met een aantal relatief kleine aanpassingen de modellen en taken in de leerboeken meer in overeenstemming gebracht zouden kunnen worden met NOS.

Het bevorderen van conceptueel begrip middels een onderzoekende aanpak bleek een veelbelovend, maar complex proces. In de klas waarin de aanpak succesvol was werden relevante elementen van de leeromgeving in samenhang gebruikt om het leren te bevorderen. In hoofdstuk 6 zijn deze elementen nader besproken: een lokale instructietheorie en klassencultuur, docentcompetenties en leermaterialen. Ook zijn onderwerpen voor verder onderzoek geïdentificeerd: hierbij gaat het onder andere om geoptimaliseerde of uitgebreide versies van de lokale instructietheorie, het bevorderen van conceptueel begrip in scholen waarin men al gewend is aan een onderzoekende aanpak, het leren van docenten in vergelijkbare interventies waarbij een team van docenten van dezelfde school is betrokken, en de rol van modellen in een uitgebreidere selectie natuurkundeboeken.

Als sterke punten van de studies beschouwen we de holistische opzet die rekening hield met het complexe karakter van begripsontwikkeling op het gebied van elektriciteit middels onderzoekend leren. De resultaten ondersteunden het idee van een gebalanceerde aanpak en gaf inzicht in een manier waarop deze gebruikt kan worden voor vernieuwing in de onderwijspraktijk. Methodologisch waren de twee ontwerpstudies goede voorbeelden van ontwerponderzoek met het doel om leerprocessen te begrijpen. De studie over docentprofessionalisering liet zien dat samenwerking tussen een onderzoeker en docenten, waarin een lokale instructietheorie werd ontwikkeld en uitgevoerd een haalbare manier was om docenten te helpen onderzoekend leren in hun klas te ontwikkelen. Tenslotte heeft de leerboekstudie geteste criteria opgeleverd die van nut kunnen zijn voor docenten, onderzoekers en leerboek auteurs of redacteurs.

Beperkingen van de studies zijn te vinden in het relatief kleine aantal leerlingen en docenten dat bij het project betrokken was. Dit heeft tot gevolg dat het ontworpen onderwijs als prototype gezien moet worden. De leerboekstudie omvatte ook een beperkt aantal leerboeken, zodat geen uitspraken mogelijk zijn over de hele range aan natuurkundeboeken voor het voortgezet onderwijs in Nederland. Bovendien is in de leerboekstudie geen rekening gehouden met de manier waarop daadwerkelijke gebruik gemaakt wordt van de boeken in de klas.

De resultaten van de studies leiden tot mogelijke implicaties voor de onderwijspraktijk. Voor docenten en lerarenopleiders is het aan te bevelen dat zij een gebalanceerd perspectief ontwikkelen op conceptueel begrip in relatie tot onderzoekend leren en dat zij rekening houden met de spanningsvelden die zijn gevonden. Voor het onderwerp elektriciteit kunnen docenten leren van de lokale instructietheorie die in dit proefschrift is ontwikkeld. Het zou goed zijn als docenten werden voorbereid op het ontwerpen en uitvoeren van dit soort onderwijs, op de lerarenopleiding, of via professionaliseringsinitiatieven. Dit zou nog meer worden gestimuleerd als docenten ook zelf een goed begrip van NOS ontwikkelen. Merkbaar effect van professionalisering op de praktijk in de klas kan worden verwacht als docenten gezamenlijk werken aan eenzelfde probleemstelling gerelateerd aan het leren van leerlingen, als vakdidactische expertise wordt ingebracht, en als coaching en feedback zijn inbegrepen. De criteria om leerboeken te evalueren kunnen van nut zijn voor auteurs van leermaterialen wanneer zij modelgeoriënteerde activiteiten en onderzoek willen bevorderen, maar ook voor docenten die leermaterialen selecteren en in lerarenopleidingen om docenten voor te bereiden op een systematische evaluatie van leermaterialen voor natuurkunde.

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CURRICULUM VITAE

Zeger-Jan Kock was born on 20 August 1963 in Maassluis, the Netherlands. He finished pre-university education (VWO) in 1981 and studied mechanical engineering at the Technical University Delft, graduating in 1988 in the department of measurement and control. His master thesis reported on the digital control of an experimental wind turbine. From 1989 to 1993 he was employed as an instrument engineer with an engineering company in the (petro-)chemical industry. In 1994 he moved to Zimbabwe to work as a physics and mathematics teacher at Gutu High School until 1997, simultaneously studying at the University of South Africa (UNISA) for a Higher Education Diploma (HED) in physics and mathematics. Returning to the Netherlands in 1998 he worked respectively as a SAP-HR consultant and as a product specialist for computer equipment and software for visually impaired people, before returning to education in 2003. In 2003 he became a physics and technology teacher at the International Secondary School Eindhoven and studied for an MEd in physics education at Fontys University of Applied Sciences in Tilburg. In 2007 he started his PhD project at Fontys University of Applied Sciences and the Eindhoven School of Education (Eindhoven University of Technology). As an employee of Fontys University of Applied Sciences since 2007, he has been working as a physics teacher and teacher educator, and since 2013 as coordinator of the Fontys MEd programme in physics.

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