

Some Key Issues in Creating Inquiry-Based Instructional Practices that Aim at the Understanding of Simple Electric Circuits

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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 article we reflect on data collected and analyzed from a series of 12 grade 9 physics lessons 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.

Keywords Classroom culture · Design research · Inquiry-based science education · Theoretical concepts in physics · Simple electric circuits

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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 (Sjøberg and Schreiner 2005; OECD 2007). 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 and 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 et al. 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 and 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 (Wenger 1998; Roth et al. 2008; Gilbert 2006). Science education is then seen as a process in which students gradually get acquainted with scientific norms and culture (Brown et al. 1989; Duit and 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; 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 and 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 article 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 and 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 et al. 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 et al. 2001) and the topic is still receiving attention (for example Engelhardt and Beichner 2004; Hart 2008; Taber et al. 2006; Duit and Schecker 2007). 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 and Schecker 2007). We used the educational research literature on simple electric circuits to inform the design of the local instruction theory.

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 and 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?*

From theory to lessons

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 and 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 20 years of experience in an industrial research laboratory of an electronics company and 4 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.

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 and 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 and 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 (Vosniadou 2007; Sfard 1998; Leach and Scott 2008). In this study we use the interpretative framework of Cobb and Yackel (1996), based on design research studies in mathematics classes: the sociocultural and individual perspectives are complementary and classroom culture, shared classroom practices and student conceptual understanding are interactively related.

Establishing a culture of inquiry

In line with sociocultural perspectives on learning, our aim was to create a community of practice (Lave and 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 and Bowen 1995), and, in a more structured way, in mathematics classrooms with the aim to help students understand theoretical concepts of the domain (Cobb and 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 to 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 students 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 and 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).

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 and Von Rhoeneck 1998; Engelhardt and Beichner 2004; Taber et al. 2006; Shipstone 1985). 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.

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 to help students appreciate that voltage and current are different, but connected concepts.

Research setting and data

Instructional context

The lessons were enacted in a school in the south-east 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 text book 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 text book in use at the school.

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 were 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 lesson 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 1 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 and Beichner 2004).

The retrospective data analysis followed the two-step procedure described by Cobb and Whitenack (1996), based on grounded theory (Glaser and 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.¹

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.

Findings

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

¹ 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.

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 the topic of class discussions (see Table 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 1 Conceptual problems in final concept test (experimental class)

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 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.

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

Table 2 Student contributions during whole class discussions

Lesson no.	Explanations using			
	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

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.

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 students 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 et al. 1996) and most Dutch physics text books 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 text book 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 series 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.

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 and 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 text book. Among these were the ability to keep a clear focus on the scientific motive of the lesson 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 time table, 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 and Aikenhead 1998). In retrospect, this is an issue that deserved more attention in the design and enactment of the lessons.

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 and 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 et al. (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 et al. (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 and 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 (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.

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