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Analysing teachers’ operations when teaching students: what constitutes scientific theories?

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ABSTRACT

The aim of the study is to analyse teachers’ efforts to develop secondary school students’ knowledge and argumentation skills of what constitutes scientific theories. The analysis is based on Leontiev’s three-level structure of activity (activity, action, and operation), as these levels correspond to the questions why, what, and how content is taught. The unit of analysis was a school development project in science education, where design-based interventions were conducted. Data comprised notes and minutes from eight meetings, plans, and video recordings of the lessons, and a written teacher evaluation. The teachers’ learning actions were analysed to identify (a) concept formation in science education, (b) expressions of agency, (c) discursive manifestations of contradictions, and (d) patterns of interaction during the science interventions. Three lessons on what constitutes scientific theories were implemented in three different student groups (n = 24, 23, 24), framed by planning and evaluation meetings for each lesson. The results describe (1) the ways in which teachers became more skilled at ensuring instruction met their students’ needs and (2) the ways in which teachers’ operations during instruction changed as a result of their developed knowledge of how to express the content based on theoretical assumptions.

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INTRODUCTION

According to the recent Handbook of research in science education (Lederman & Abell, 2014), the ultimate goal of science education has ‘primarily been to have a literate citizenry, to have students develop into scientifically literate individuals’ (Lederman & Abell, 2014, p. 617). Scientific teaching in school is seen as a tool to enhance scientific literacy to foster responsible citizens making wise future decisions, by developing their reasoning and argumentation skills, enhancing their future capability to draw conclusions and solve socio-scientific issues (Holbrook & Rannikmae, 2007). To achieve this, science education has focused on three areas: the products of science (knowledge in science), scientific processes (knowledge about science), and the use of and social impact of
science (Lederman & Abell, 2014; Millar, 2004; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; Osborne, Driver, & Simon, 1998). This is the case also in Sweden, where biology, chemistry, and physics syllabi share the same content in the category ‘The nature of Biology/Chemistry/Physics and its working methods’. This includes ‘Models and theories as representations of reality. Areas where models and theories can be applied, and also how they can be developed, generalized or replaced by other models and theories over time’ (Swedish National Agency for Education, 2011). Although there is still no clear definition of what the concept of the nature of science should include (see, e.g. Abd-El-Khalick, 2014; McComas, 2015; Van Dijk, 2014), there is some consensus about including the characteristics of tentativeness, empirical base, theory/law discussions, social embeddedness, and creativity (i.e. Lederman & Abell, 2014). Holbrook and Rannikmae (2007) claim that ‘education as science’ is more suitable to develop students’ socio-scientific knowledge than ‘science through education’, as the former stresses e.g. learning science for handling ‘socioscientific issues within society’ (p. 1354).

As the nature of science relates to the epistemology of science, and thus the ways that scientists evidence their claims, it is important to clarify what constitutes the nature of scientific theory and what differentiates it from scientific laws or common, everyday assumptions. There is no clear-cut definition of scientific laws, but most researchers agree with Abd-El-Khalick (2012) that scientific theories are ‘well established, highly substantiated, internally consistent systems of explanation’ (p. 358) and that ‘in general, laws are descriptive statements of relationships among observable phenomena. Theories, by contrast, are inferred explanations for observable phenomena or regularities in those phenomena’ (p. 358). Dagher, Brickhouse, Shipman, and Letts (2004) conclude that theories and laws ‘are different in nature and they serve a different function’ (p. 739) and scientific theories are especially important because they ‘constitute the backbone of scientific knowledge: They represent our best reasoned beliefs about the world around us. They are, in a word, explanations – a synthesis of facts, aims, and methods of science’ (p. 735). Suggestions about the constituents of scientific theories include such aspects as being testable, replicable, and/or leading to predictions; they are ‘fallible human constructions’ but have substantive evidence that supports them (p. 739).

In this study, theory-based practices of teachers’ teaching and learning were analysed, focusing on teachers’ actions and operations when teaching students about natural scientific theories, to distinguish them from common, everyday assumptions. The analytic framework used here is based on Leontiev’s (1978) three-level structure of activity: activity (why content is taught), action (what content is taught), and operation (how content is taught). We have chosen to use this model, as the later generations of activity theory is focused on a larger social context, according to Engeström (1999). In his third generation, the examination is of different systems of activity at a macro-level in relation to the micro-level with a concentration on the individual agent operating with tools. In our study, we have limited the analysis to focus on the levels of activity described by Leontiev, omitted the larger social context. The main guiding principle of activity theory is cultural–historical theory (Avis, 2007; Vygotsky, 1980; Wertsch, 1991). Bakhurst (2009) identifies two strands in the development of activity theory. The first was a philosophical strand (the cultural–historical perspective); this was followed by an organisational change model of activity theory. Bakhurst (2009) has questioned whether activity theory is really a theory; he suggests that the strength of the second strand of activity theory development
is that it constitutes an approach to the analysis of activities. He is reluctant to state whether the conceptual problems of the second strand can be answered by turning to the first strand. He writes:

My point is only that activity theorists should not have a complacent attitude to the relation of the different strands within the tradition, or blithe self-confidence that their contemporary empirical enquiries are grounded in an unproblematic, coherent, theoretical paradigm. What is vital is that there is a rich and self-critical dialogue between the different styles of thinking within the activity-theoretical tradition. (p. 209)

Leontiev’s three-level structure of activity framework has previously been used to study discourses in science education (Vieira, Bernardo, Evagorou, & Melo, 2015; Vieira, Kelly, & do Nascimento, 2012). However, instead of studying verbal dialogue or the teachers’ views of teaching or professional development, this study focuses on discourse about the handling of science content in authentic classroom practice and how it is related to differences in student learning.

Engeström (2011) sees the objective as the crucial factor that gives durable direction, purpose, and identity to an activity (p. 607), which suggests that the object is the origin of the activity. There is a triangular relation between the subject, the artefacts, and the objects. In this study, the object was to develop students’ knowledge and argumentation skills what constitutes scientific theories. In contradiction to Engeström’s view, we assume that the merged experience of the subject (learner) and object (learning objective) is the crucial factor for the activity, rather than the durable direction between the domains. This accords with the assumptions of variation theory, which is used as an artefact to design and analyse learning situations. Marton (2015) writes:

It is in this sense that subject and object are not separate. Person and world are related to begin with. There are no two worlds, a subjective one and an objective one; there is one world only, and that is both subjective and objective. The world we live in is an experienced world, a world that we are dealing with, that we try to understand, that we make sense of in many different ways. (p. 108)

Therefore, we believe that merging, instead of differentiating, the subject and the object strengthens the analysis of the activity because the subjects’ view of the object strongly influences the direction, purpose, and identity of an activity. If learning is defined as an epistemological non-dualistic activity, in which the learner (mind) and the content (world) to be learnt are seen as undivided, then each learner experiences the object differently and has a unique understanding and interpretation of it. This demonstrates individual differences in action, even if the object the action is directed towards is the same. Therefore, the focus of our analysis is not on the durable directions between two separate domains, such as action and mind, or object and mind. Our focus is on how aspects of the actions are discerned and affect the teachers’ actions in the activity, given that the experience is unique for each participant (although it is shared by the community).

In this study, learning is analysed through the teachers’ developed operations; that is, how they enact learning situations during classroom instruction. The results of the students’ learning outcomes have been used as outcome indicators for the teachers’ operations. The analysis of the learning was conducted at the third level (operation), in which actions to develop students’ learning were operationalised using theoretical conjectures, and the teachers’ operations were studied from the perspective of the students’ learning outcomes.
In accordance with the discussion above, we raise the following questions:

**RQ1.** How do teachers justify why the content should be taught? (Why)

**RQ2.** What actions constitute teachers’ formation of what content should be taught? (What)

**RQ3.** How do teachers enact the content during the interventions? (How)

### The current study

The professional development project in this study was conducted in a secondary school during 12 weeks of one semester. A group of seven teachers and one researcher worked together in eight meetings. Data for the analysis were notes from the researcher; minutes from the meetings written by the teachers; three lesson designs; three video-recorded lessons; and pre-, post-, and delayed post-test results from 71 students in three different groups. The tests featured the same open-ended question asking the students what constitutes scientific theories. The students received four different examples (gravitation, telepathy, astrology, and astronomy) and were asked to provide arguments and reasons for why each example was (or was not) a scientific theory. Analysis of the test results was based on the arguments, rather than on whether the answer was correct. During the meetings, the teachers decided that four different criteria should be mentioned to obtain the maximum of 4 points; the criteria expressed four characteristics of scientific theories: (1) the theory is possible to investigate/test and/or falsify; (2) the theory is supported by previous findings; (3) the theory may be used to make predictions; and (4) the theory may be modified and developed and/or the formulation is a human construct. The students’ test scores increased between the pre- and post-tests in all three groups: +0.17 (group A), +0.87 (group B), and 1.54 (group C), which indicates that the students in group C used more criteria than those in groups A (first lesson) and B (second lesson) (Holmqvist Olander & Olander, 2014).

To deepen the knowledge about what was important for increasing student learning outcomes, the teachers’ actions were analysed to identify (a) concept formation in science education, (b) expressions of agency, (c) discursive manifestations of contradictions, and (d) patterns of interaction during the science education interventions. Three lessons on the same topic were implemented in three different student groups (n = 24, 23, 24), framed by planning and evaluation meetings for each lesson. The design of the teachers’ school development project was based on the learning study model and framed by variation theory, which is described below. The first step in a learning study is to study the students’ previous knowledge about the content to be taught. The findings from this first investigation by the teachers formed the basis of the design of the first lesson. Guided by theoretical assumptions about learning, the content was offered to the students in a way that made them discern what they previously had not discerned. The content taught was what constitutes scientific theories. Teachers aimed to help students develop an ability to see the difference between a scientific theory and common, everyday assumptions and to develop their scientific argumentation skills.

### The theoretical framework as a guiding principle in the school development project

The theoretical tool used by the researcher and teachers during the school development project was variation theory, which is based on a non-dualistic, epistemological
assumption that what is to be learnt and the learning itself are inseparable (Marton, 2015; Marton & Booth, 1997). The theoretical framework was used in the school development project to predict which changes to the instruction would better meet the students’ needs. A non-dualistic perspective was used to ensure that the teachers focused on the students’ perspective of the content to be taught, avoiding a solely content-based perspective on how to teach. This was intended to guide the teachers to teach the aspects of the content the students did not yet know, rather than content they already knew. According to this framework, a necessary condition for learning is the ability to discern what is to be learnt, to pick out critical aspects of the learning content from the patterns of variation and invariance within the material (Marton, 2015). Lo and Marton (2011) explain how to vary aspects to be discerned using patterns of variation:

… the teacher should enable the learner to discern and separate aspects by letting them vary one at a time, and finally allow simultaneous variation in all aspects, which is referred to as fusion. … fusion (the undivided whole) – contrast (leading to separation of dimension of variations, so that critical aspects and features will be separated out from the whole) – generalization (differentiating the critical aspects from those that are not) – fusion (seeing all the critical aspects in relation to each other and to the whole). (p. 11)

An example of how the assumptions of variation theory are used to analyse learning is the way very young children acquire knowledge using patterns of variation to develop general insights about an object. A child aged 2 or 3 years can learn what a dog is by someone pointing out all animals that are dogs. However, it is unlikely that a child could differentiate between, for example, a dog and a horse using this kind of information. An alternative would be to use a pattern of contrast to point out critical features that differentiated dogs from horses to enable the child to develop another kind of seeing that would allow her or him to learn more about what a dog is in future encounters. A critical feature in this example is the difference between a dog’s paws and a horse’s hooves. Pointing out this difference by isolating one aspect of the object and making it discernible helps the child become aware of one aspect of what a dog is without requiring someone to confirm that it is a dog. Otherwise, the child may wrongly assume that another feature, such as size or colour, is the critical identifier. The child may then mistakenly identify a big dog as a horse if the two animals were different sizes and if the child had not previously seen any big dogs. By pointing out critical features, the learning situation is supposed to be more powerful; instead of learning, the child is expected to identify such features by her/himself through trial and error. Teachers can use theoretical assumptions as conjectures to create powerful learning situations (Holmqvist, 2011).

The learning study as a model for the school development project

In this study, collaborative learning was analysed in the activity and actions (Leontiev’s Levels 1 and 2) as both partners (teachers and researcher) worked together towards the same goal of increased knowledge. At the third level, operation, instructed learning was analysed, because there is a deliberate intent from the agent to communicate a specific view of the content during the interventions. A learning study approach (Marton, Tsui, Chik, Ko, & Lo, 2004) was used, that is an iterative and cyclic process, where teachers study, plan, enact, analyse their own video-recorded lessons, and revise instruction of the same content based on a theoretical learning framework. The differently designed instruction is tried out on
different groups of students, video recorded, and then compared and analysed to develop the teachers’ knowledge of what it takes to learn the content taught for this particular group of learners. In a learning study, teachers and researchers in collaboration scrutinise what it takes to learn a specific content and systematically, through iterative cycles of video-recorded research lessons, seek out ‘critical aspects’ (i.e. aspects of the object of learning that are important for understanding, but are not yet discerned by the students). The learning study in this case was part of a school development project involving an entire upper secondary school, in which different subject groups chose different objects of learning.

In a learning study, the students’ learning is measured before and after the instruction to capture the difference in knowledge. The learning study model can be defined either as an action research approach, as described in an education working paper from the Organisation for Economic Co-operation and Development (Cheng & Lo, 2013), or as design-based research (Holmqvist, Gustavsson, & Wernberg, 2008). In this study, the learning study approach was inspired by the design-based research approach of McKenney and Reeves (2012), which we redesigned in accordance with Engeström’s criticism of design-based research. Engeström (2011) suggested a shift from design experiments to formative interventions. A learning study is design-based and addresses Engeström’s criticism. Engeström’s criticism of design experiments refers to units of analyses that are too complex. This problem arises from a process initiated and implemented by researchers who set their goals largely ignoring the agency of the other participants. He claims that design research is often a linear progression through six steps (from implementing the design to reporting on it), which emphasises completeness, closure, and control of aims. Contradiction is identified as one source of change and Engeström (2011) claims that such contradictions are avoided if a linear model is used. To be formative, the researchers and teachers must take the learners’ perspective of the targeted content to be taught. If the focus is on the students’ learning of the content, instead of the content, the design has to take into account differences in how the same content can be understood and experienced by the students.

Learning study as intervention is based on the idea of lessons as a narrow unit of analysis. The learning process and goals are initiated by the teachers. Instead of being linear, the process is iterative and cyclic. This approach takes a snapshot of part of an ongoing open learning process, in which student learning has decreased and changes are needed to increase learning. The design, analysis, and revision are based a theoretical framework, in this case; variation theory (Marton, 2015). Therefore, learning study results are not products such as lessons or instructional material designs. Instead, they aim to increase our understanding of what it takes to learn a specific content or develop a defined ability based on theoretical standpoints. In this study, the aim is to analyse teachers’ efforts to develop secondary school students’ knowledge and argumentation skills of what constitutes natural scientific theories, and how they differ from common, everyday assumptions. In other words, in the school-project the search was to find conjectures to make the students develop their skills as much as possible, while the research aims to describe the teachers’ efforts and ways to find such conjectures and their impact on student learning.

**Methodology and participants**

This study was based on a school development project involving an entire school. This began with two teachers who wanted to participate in a study with researchers from the
university (Olander & Holmqvist Olander, 2013). The teachers were inspired by the students’ increased outcomes during the study and shared their findings with the other teachers. This led to interest from all the teachers and the management, resulting in a larger project. Unlike in the initial study, all teachers were required to participate in the larger teacher development project; however, participating in this research project was optional for the teachers and students. Participants in the research project reported on here were seven teachers (six females and one male) from one of the teams at a secondary school established in the early 1900s in Sweden; the school has approximately 1300 students. Both teachers and students were informed about the research project and verbal informed consent of participants were collected. The teachers were aged between 30 and 50 years old, and all were formally qualified with a 4-year university-level teaching degree to teach the topic to this age group. Their teaching experience ranged from 3 to 21 years. Students from three classes (n = 24, 23, 24) followed the science programme, which attracts approximately 10–15% of the annual cohort of students. The science programme is for students at secondary school (grades 10–12) who wish to work in the natural sciences, and lays the foundations for further studies at the university level or higher education in natural sciences, mathematics, technology, and social sciences. The science programme is considered to be rather challenging compared with other programmes.

We focused on how participating teachers’ operationalisation of the content was related to students’ learnt knowledge. However, we needed to examine which actions and operations were enacted and how they affected the students’ enhanced knowledge during the activity. In this study, there was a strong focus on actions and the operation of theoretical conjectures to develop students’ knowledge. In accordance with the learning study approach, this methodology gives teachers a unique opportunity to influence the content they wish to focus in the project.

At the third level (operation), we studied the operationalisation of the instruction in a multiple-case study (Stake, 2006) using three cases; these were analysed in terms of the lesson designs, the teachers’ actions during instruction, and the students’ knowledge as expressed in tests. Drawing on the learning study model, each case was characterised by seven steps: pre-interviews, screening, design of one lesson, pre-test, intervention, post-test, and post-test session. A delayed post-test was given 7 weeks after the intervention. The team’s analysis of students’ previous knowledge was based on data from interviews and screening. The teachers’ reflections of student knowledge were used to design tests and lessons afterwards.

Analysis

The unit of analysis was the school development project, and the analyses presented in Table 1 follow the three-level structure of activity proposed by Leontiev (1977) to organise the structure of the activity (Vieira et al., 2012).

We used a method that produces a more detailed analysis of the levels. The first level, activity (why), is the broadest and describes the activities that the teachers and researcher’s team conducted during the study. At the second level, analyses were conducted of the teachers’ learning actions (what) and steps in concept formation, expressions of agency, and discursive manifestations of contradictions (as reported by e.g. Engeström & Sannino, 2011; Sannino, 2008a, 2008b, 2010). This level was more detailed and focused on those
teachers’ actions and affordances that had an impact on teachers’ developed knowledge of how to use the theoretical conjectures.

Finally, the operations (how) at the third level were analysed and reported within the framework of the learning study model and students’ learning outcomes were also reported to indicate and strengthen the analysis of the teachers’ operationalisation at Level 2. At the third level, quantitative and qualitative analyses were performed of students’ learning processes and learning outcomes to indicate teachers’ developed knowledge about how to design instruction to enhance student learning. The operations in the learning study (Figure 1) are a means to achieve higher order goals at Levels 1 and 2, and patterns of interaction during the interventions were examined.

The analysis aimed to answer three questions. The first was ‘How do teachers justify why the content should be taught?’ and describes the teachers’ use of variation theory as a guiding principle. The relevant data were notes, minutes, three video recorded and transcribed lessons, and three lesson plans. The learning activity was permeated by the ontological perspective the teachers were introduced to during the school development project. The analysis of the level of operation focused on teachers’ expressed non-dualistic theoretical perspective when enacting the content during instruction (i.e. the teachers’ abilities to take into account the students’ knowledge when designing instruction): the ways in which the teachers handled the content arose from the merged expression of the content and the students’ previous experiences of the content. By trying to make the students discern aspects needed to enhance their learning, teachers must consider both the structure of the content and the structure of the students’ knowledge. The action that takes place is a fusion of the teachers’ experiences of the content and the students’ experiences of the content, and the actions start in this merged experience.

The analysis of actions that constituted the teachers’ concept formation answered the second question: ‘What actions constitute teachers’ formation of what content should
be taught? The analysis focused on (a) concept formation, (b) expressions of agency, and (c) discursive manifestations of contradictions (after e.g. Engeström & Sannino, 2011; Sannino, 2008a, 2008b, 2010). The differences between the expressed agencies for the theoretical framework and the content taught challenge the teachers’ everyday assumptions about how content should be taught. The theoretical perspective favours contrasts and simultaneous presentation of different, and sometimes contradictory, aspects of the content, rather than a sequential presentation (i.e. small parts one at a time). The data analysed were lesson plans, researchers’ notes from the meetings, and the teachers’ minutes. The focus was the teachers’ mastery of the theoretical framework. The third question was ‘How do teachers enact the content during the interventions?’ This was answered by analysing the operations performed to reveal which contradictions affected the operation of the conjectures used in the classroom. This analysis level examined the teachers’ appropriation of the theoretical framework. The students’ learning outcomes were contradictions used to test the teachers’ beliefs of what constitutes a fruitful learning situation. Teachers’ views of what is successful in a teaching situation do not always reflect what actually enhances students’ learning outcomes. Such contradictions can make teachers rethink and revise their instruction and adapt it to students’ experiences. Contradictions can also reduce teachers’ reliance on presumed beliefs, and help them redesign lessons from the learners’ perspectives and carefully explore their students’ experience of the taught content. This process is in accordance with the non-dualistic assumption that learning is based on the merged, indivisible experience of how the object is understood and what can be seen of the object.

The analysis was iterative and the analysis at each level formed the basis for understanding the data at the next level. For example, when assessing students’ answers at
the third level, the data were used to indicate whether the teachers’ actions (Level 2) were operationalised in the classroom in a way that led to better student learning (about what constitutes a scientific theory). At the operation level, the teachers had to consider their students’ previous knowledge in relation to the affordances offered in the instruction.

Results

The results are presented in terms of the three levels of analysis (activity, actions, and operations) and in relation to the research questions. However, these levels are intertwined, because the activity was composed of the actions and operations during the process. Therefore, the presentation of the results moves from the general to the specific rather than linearly. The levels of analysis were also linked to the research questions. The first question was general and theoretically grounded: ‘How do teachers justify why the content should be taught?’ We now describe the actions conducted in the activity as well as the object of activity.

Level of analysis: activity

The activity consisted of 16 main steps, with several actions in each step, and spanned a period of 3 months. There were eight meetings, three cyclic interventions including pre- and post-tests, four measurements (pre-test, post-test, screening, and delayed post-tests), and a presentation of the results at an international conference. Figure 1 shows the steps in the project. The agenda at the meetings were typically planning and evaluation of screening, tests, and lessons. For example, at 4 October 2012, meeting, the teachers and the researcher evaluated Lesson A using video recordings and student tests, and suggested ways of communicating the identified critical aspects in the next lesson. Between the meetings, the teachers assessed students’ tests and watched videos recorded during the lessons. Two or more teachers were present during the research lessons, either teaching or video recording. Data from six of the seven teachers’ anonymous evaluations were also analysed (one of the teachers did not provide an evaluation).

In this particular team, the two teachers who took initiative to the initial study were included, which have inspired the other teachers to participate. The school development project was mandatory, but the teachers were free to define what object of learning to focus on. The syllabus of natural sciences for secondary school have changed from what Holbrook and Rannikmae (2007) call ‘science through education’ to ‘education as science’ in the latest syllabus, which was a challenge for the teachers. The activity was also motivated of the teachers’ experiences of students’ difficulties to differentiate natural scientific theories from everyday common knowledge, and undeveloped argumentative skills to value what constitutes scientific theories. To find out more about the students’ skills, interviews were conducted by the teachers. This showed that the students seem to differ between scientific theories and everyday common knowledge, but could not explain in what way or what constitutes scientific theories. The teachers argued that knowing what constitutes a scientific theory is crucial for critical review of information needed to make wise socio-scientific decisions in the future, which justified their decision of content.
**Level of analysis: action**

The question addressed at this level of analysis was: ‘What actions constitute teachers’ formation of what content should be taught?’ The analysis focused on the teachers’ learning actions and steps in (a) concept formation, (b) expressions of agency, and (c) discursive manifestations of contradictions.

**Concept formation**

In this study, concept formation during the professional development project was based on the theoretical framework of variation theory as a guiding principle of designing learning situations. The theoretical concepts from variation theory used by teachers were critical aspects, contrast, generalisation, and learning object (i.e. what constitutes a scientific theory). The subsection on analysis of operations, below, describes in detail how the theoretical concepts to enhance student learning were used in the operations. Teachers also showed the development of their use of the theoretically based concepts during their presentations at an international conference. These included ‘Teaching strategies (e.g. how to enact the theoretical tools contrast and generalisation)’ and ‘Increased knowledge about how to use group discussions to find critical aspects’. Some of the teachers’ comments about theoretical insights also indicate theoretical concept formation in a scientific community: ‘Interesting with new and different research, it opens your eyes and encourages looking for literature on your own and finding other research articles on BLS [B: abbreviation of name of school; LS: learning study]’ (Evaluation form 121024). Concept formation also directed the content to be taught in the activity and the explanation of what constitutes a scientific theory. Several actions defined, delimited, and exemplified these concepts during the activity. During a staff meeting on 18 September, the teachers evaluated the student group interviews that were the basis of the initial screening of the students’ knowledge and came to the following conclusion:

We listened to the student interviews and noted that the students are well aware of which theories are scientific theories, but not why. The students seem to believe that a hypothesis becomes a theory when it has been tested sufficiently. One theory is closer to the truth than a hypothesis, but there is no absolute truth. Students also discuss the relationship between different observations and the weight of the connection to create a theory. In the BLS group, we discussed whether a hypothesis leads to formation of a theory. What leads to formation of a theory? Is a hypothesis enough to build a theory? Hypothesis theory model: How does a scientific theory come about? We have found that we could employ a more moderate object of learning. (Minutes, September 18)

The issue of how to define scientific theories was on the agenda for the next meeting with the researcher and teachers on 25 September. The purpose of the meeting was to formulate the object of learning and prepare pre- and post-test questions. The definition of a scientific theory became urgent when discussing pre- and post-test questions and their evaluation. The concept formation was developed in the minutes from the meeting on 25 September:

What criteria are suitable when evaluating the questions for a ‘successful lesson’? The students’ description of a scientific theory should meet the following criteria:

- Arguments from authority won’t do
• Isolated examples that cannot be generalised won’t do either
• Testable: at least its parts
• Possible to repeat and the test has been repeated producing the same conclusion
• No definite truth, more preliminary. (Minutes, September 25)

The criteria for a scientific theory were reduced to four at the next meeting (27 September):

(1) The theory is possible to investigate/test and/or falsify.
(2) The theory is supported by previous findings.
(3) The theory may be used to make predictions.
(4) The theory may be modified and developed and/or the formulation is a human construct.

During this process, the teachers developed their concept formations. Table 2 shows excerpts from one student’s answers in the pre- and post-tests. Based on the teachers’ concept formation, the student has correctly answered all questions about whether the examples are scientific theories or not. However, the aspect that the student used to make these decisions were replaced with another aspect after the lesson (shown at the post-test). The result shows the use of a single criterion in the pre-test and the change to the use of another single criterion in the post-test. During operation, the action of concept formation resulted in students discerning different aspects one by one rather than discerning different aspects simultaneously and comparing them. Therefore, a deeper understanding or a broader perspective of the different criteria was not developed after the lesson. The analysis shows that there is more to learning beyond merely answering direct questions correctly, suggesting that learning cannot be measured just by quantitative analysis. Therefore, the teachers’ concept formation gradually developed in an iterative process during the activity.

The teachers’ concept formation was also expressed in their actions when they assessed the students’ test answers. Each student’s answers were analysed according to the four criteria used for assessment (see above). All items (a–d) were summarised in the analysis.

Table 2. Pre- and post-test responses from Student #330.

<table>
<thead>
<tr>
<th>Test questions</th>
<th>Pre-test (1 criterion, no. 2)</th>
<th>Post-test (1 criterion, no. 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Gravitation</td>
<td>Yes, because^2 scientific arguments support the theory (It is most likely, there is ‘evidence’)</td>
<td>Gravity is^3 consistent with experiments and so on. You can try to contradict the theory without success. That is correct!</td>
</tr>
<tr>
<td>(b) Telepathy</td>
<td>No, because there are no scientific arguments that support the ‘theory’</td>
<td>Experiment is not consistent with this hypothesis. There is no evidence that it is correct/there is evidence that it is wrong because the experiments are not consistent with the hypothesis. It is wrong!</td>
</tr>
<tr>
<td>(c) Astrology</td>
<td>No, because there are no scientific arguments that support the ‘theory’</td>
<td>Experiment is not consistent with this hypothesis. There is no evidence that it is correct/there is evidence that it is wrong because the experiments are not consistent with the hypothesis. It is wrong!</td>
</tr>
<tr>
<td>(d) Astronomy</td>
<td>Yes, to scientific arguments supporting the theory (It is most likely, there is ‘evidence’)</td>
<td>Astronomy is consistent with experiments, etc. For example, the Earth’s rotation in a day/month. The theory is not contradicted. It is correct!</td>
</tr>
</tbody>
</table>

Note. Bold italics and superscript numerals refer to the criteria numbers.
Each criterion (1–4) mentioned was marked in all answers from each student. **Table 2** shows that student #330 mentioned one criterion at the pre-test: criterion 2, which states that a theory is supported by previous findings. In this case, scientific argumentation was defined in terms of the previous findings, because these are the foundations of a scientific theory. At the post-test, student #330 mentioned criterion 1, which states that a theory is possible to investigate/test and/or falsify. In this case, the student mentioned several times in the post-test that a theory has to be consistent with experimental findings. However, student #330 did not mention criterion 2 in the post-test (although this was mentioned in the pre-test). Even though student #330 correctly identified which examples are scientific theories, s/he failed to score more than 1 point on both the pre- and post-test because the explanation was based on only one criterion. As the students were also asked to argue; that is, to provide reasons why the examples were or were not scientific theories, in the test, they needed to provide more than one criterion and use their argumentative skills. Although student #330 mentioned one criterion several times, they only scored 1 point. Taking all items together (a–d), each student was able to score a maximum of 4 points because four different criteria could have been mentioned in their argumentative answer. This is exemplified in **Table 3**, which shows the results from student #317. This student mentioned only one criterion at the pre-test, but mentioned all four criteria at the post-test.

**Expressions of agency**

In this activity, the teachers’ expressions of agency were both constituted and restricted in the tension between the formal policy documents (e.g. syllabus and curriculum), the teachers’ teaching experiments, the students’ needs, and the assumptions of the guiding theoretical framework (variation theory). As the teachers were familiar with the content taught and had extended teaching experience, their agency was more profound in this
Agency was expressed in relation to the above-mentioned concept formation and also discernable as a growing collective responsibility for how the object of learning should be communicated to meet the goals. This was manifested, for example, through joint efforts to develop the pictorial representation used to communicate the content, which increasingly served as a tool for learning during the learning study.

**Manifestations of contradictions**

Several of the contradictions described in detail at the operation level below relate to actions at the group level. The analysis of the intervention videos revealed frequent dilemmas, such as hesitations (‘on the one hand … on the other hand’). For example, after Lesson A, which consisted of a long group activity, the discussion focused on the dilemma of whether to let students excavate the problem further given the time constraints. The resolution (or planned resolution) was to articulate the prerequisites of the assignment more clearly in the next lesson. Another recurrent dilemma was the assessment of students’ answers to pre- and post-tests. However, this was an area that the teachers thought they had developed: ‘… also good to have collaborated when deciding criteria and done the assessment together’ (Evaluation form, 121024), and ‘we took joint responsibility to assess the tests’ (Minutes, 11 December). Their work with concept formation, when the definitions were clarified, made the assessment easier to conduct.

Contradictions also occurred about procedural issues, such as who was responsible for what, but they were resolved in an atmosphere of collective responsibility: ‘I appreciate that everyone has done their best because it contributes to my own efforts to contribute’ (Evaluation form, 121024). Some of the procedural conflicts were because of logistics within the school, such as where to find stamps and DVDs, dealing with the Internet platform used, and a lack of general information from school principals.

Serious, critical conflicts were rare, but in one early instance there was a change in planning because of a serious mistrust of school management. The plan made on 11 September was changed during 18 September staff meeting because the assigned teacher did not want to be video recorded. She was afraid that the school principal would see the video. This was resolved by changing the teacher, and the researcher took responsibility for the videos.

**Level of analysis: operation**

Patterns of interaction during the interventions were analysed to answer the third research question: ‘How do teachers enact the content during the interventions?’ The results at the third level are presented with reference to two themes: (1) how the teachers handled the content in their lessons; and (2) the conjectures used to increase the students’ learning outcomes. Using the multiple-case model, we compared the results both within and between the three cyclic interventions (cases). Within each case, the conjectures used to enhance students’ learning outcomes were assessed by comparing the scores at pre-, post-, and delayed post-tests. The results of the students’ learning outcomes were used to indicate teachers’ developed skills to operate conjectures that improve student learning. We compared the groups to determine which operation most powerfully affected the students’ learning gains. The three lesson designs were analysed within each case, describing
which aspects of the content were focused, and how they did or did not vary. We compared the designs in each group using the conjectures of variation theory as a guiding principle to analyse differences in how the aspects varied or were invariant. Finally, we analysed the teachers’ developed skills in terms of how their designs further developed during the cases.

The students’ learning outcomes increased between pre- and post-tests for all lessons, with a mean score increase of +0.17 (Lesson A), +0.87 (Lesson B), and +1.54 (Lesson C). Regarding the long-term outcomes (the difference between the scores from the pre- and delayed post-test), the students’ learning outcomes decreased in the first lesson (−0.8) but increased in Lesson B (+0.26) and Lesson C (+0.75). The qualitative analysis of students’ responses showed that no students in Lessons A and B mentioned more than one criterion in the pre- and post-tests; however, as the number of criteria mentioned increased from zero to one, the outcome scores increased. The results for Lesson C showed a different pattern. The students in this group mentioned more criteria. In the post-test, 1 student did not mention any criteria, 6 students mentioned one, 10 students mentioned two, 4 students mentioned three, and 3 students captured all four criteria. The students’ learning outcomes were used as indicators of those teachers’ operations that were able to meet the students’ needs regarding the taught content. The operation of the teaching during the learning study project can be summarised as follows.

Mostly, the design was the same for all lessons. In the dialogue, a scientific theory was exemplified using the story about Ignaz Semmelweis’ work in a hospital in Vienna, Austria, around 1847. Semmelweis ‘observed that women delivered by physicians and medical students had a much higher rate (13–18%) of post-delivery mortality (called puerperal fever or childbed fever) than women delivered by midwife trainees or midwives (2%)’ (Best & Neuhauser, 2004, p. 233). Semmelweis tested several hypotheses to determine the reasons; each hypothesis was falsified in turn. When one of his colleagues caught puerperal fever after cutting himself during a necropsy, Semmelweis suggested that physicians and medical students should wash their hands before touching patients. Although Semmelweis was unaware of the existence of microorganisms, his hypotheses led to a decrease in death rates. The anecdote about Semmelweis is claimed to be an example of the hypothetico-deductive method.

The main aspect that differed between lessons was the model the teachers drew on the whiteboard, which was used and developed differently. In the first lesson, the model consisted of a simplified schedule that an observation leads to a conclusion, which constitutes a hypothesis that can be tested and verified or falsified. This lesson was only about hypothesis testing; the most interesting lessons were Lessons B and C, in which this model was developed. Figure 2 shows the differences between these two lessons. In the figure, teachers’ actions during instruction are transcribed, and the analysis focuses on teachers’ use of a chart. In Lesson B, the presentation is sequential; the teacher focuses on one area at a time. What constitutes a scientific theory is exemplified by a schedule, and then an example is given (Semmelweis). These two parts are not merged. In Lesson C, the teacher uses the chart to explain what constitutes a scientific theory. Then she reuses the chart when she introduces Semmelweis’ theory and explains the theory in relation to the criteria for what constitutes a scientific theory. One of the conjectures of variation theory is that simultaneity is effective for learning; the teacher uses simultaneity to explain which aspects are critical for understanding what a scientific theory is.
In Lesson B, the teacher combined hypothesis testing with what constitutes a theory, which made it difficult for students to understand the difference between the criteria for a scientific theory and the nature of hypothesis testing. The relationship was not understood.

<table>
<thead>
<tr>
<th>Lesson 2</th>
<th>Lesson 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>At time (h/min/s)</td>
<td>Operation</td>
</tr>
<tr>
<td>0.03.30</td>
<td>T: informs students of the syllabus. The students are given matchboxes in groups, and are asked to construct a hypothesis about what the boxes contain. They are not allowed to open or destroy the boxes.</td>
</tr>
<tr>
<td>0.08.20</td>
<td>T: writes 10.30 on the WB.</td>
</tr>
<tr>
<td>0.09.10</td>
<td>T: collects the boxes.</td>
</tr>
<tr>
<td>0.10.08</td>
<td>T/Ss: every group reports what they think the boxes contain. Talks about theory and not hypothesis. Why do they think the box contains this?</td>
</tr>
<tr>
<td>0.13.30</td>
<td>T: writes on the WB Problem Observation (what you think about something) Experiments which leads to Conclusions</td>
</tr>
<tr>
<td>0.15.55</td>
<td>T/Ss: conclusions about what the box contains. Referred to the atom model (atoms cannot be seen visually or ‘opened’).</td>
</tr>
<tr>
<td>0.18.45</td>
<td>T: shows PowerPoint slides about Semmelweis (maternal mortality).</td>
</tr>
<tr>
<td>0.21.53</td>
<td>T/Ss: Why can’t earthquakes cause maternal mortality?</td>
</tr>
<tr>
<td>0.24.05</td>
<td>T: asks the students Why is this unlikely? Two sections in the same building would have been affected similarly.</td>
</tr>
<tr>
<td>0.25.37</td>
<td>T: asks the students to define their hypotheses.</td>
</tr>
<tr>
<td>0.26.54</td>
<td>Ss: group discussions.</td>
</tr>
<tr>
<td>0.32.05</td>
<td>T/Ss: hand hygiene.</td>
</tr>
<tr>
<td>0.36.25</td>
<td>T: Ss different hypotheses.</td>
</tr>
<tr>
<td>0.38.05</td>
<td>T: Semmelweis’ colleague died of the same symptoms – PowerPoint slides.</td>
</tr>
<tr>
<td>0.39.43</td>
<td>T: asks how this could be tested. Ss: wash their hands.</td>
</tr>
</tbody>
</table>

Figure 2. Comparison of the operations in Lessons B and C.
<table>
<thead>
<tr>
<th>Time</th>
<th>Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.41.43</td>
<td>T: Semmelweis was not believed because medical doctors had greater authority than midwives who worked in the section where mortality was low; Semmelweis was fired.</td>
</tr>
<tr>
<td>0.35.29</td>
<td>T: Ss could predict — if they continue to wash their hands, that mortality will continue to be low.</td>
</tr>
<tr>
<td>0.42.37</td>
<td>T: Has our view changed about this example?</td>
</tr>
<tr>
<td>0.37.28</td>
<td>T: the trustworthiness was low because of the social context. Semmelweis was fired as the medical doctors (working in the section where the mortality was high) had greater authority than the midwives in the section with low mortality.</td>
</tr>
<tr>
<td>0.44.00</td>
<td>T: return to the schedule; if the hypothesis can be falsified, a new hypothesis is formulated and tested.</td>
</tr>
<tr>
<td>0.38.10</td>
<td>T/Ss: discussion about trustworthiness.</td>
</tr>
<tr>
<td>0.45.21</td>
<td>T: earlier models can be used instead of experiments. Hypothesis used to predict, verify the conclusion. Many studies shape the constitution of a theory and the theory can be generalised to new situations.</td>
</tr>
<tr>
<td>0.39.15</td>
<td>T/Ss: How do we understand this problem (‘corps particles’) today? Has our view changed or developed?</td>
</tr>
<tr>
<td>0.47.30</td>
<td>T: have to do many experiments to formulate a theory and use many different methods.</td>
</tr>
<tr>
<td>0.39.48</td>
<td>Ss: Bacteria instead of ‘corps particles’.</td>
</tr>
<tr>
<td>0.49.08</td>
<td>T: a theory can be disproved if someone finds contradictory results.</td>
</tr>
<tr>
<td>0.40.37</td>
<td>T: returns to the model on the WB about what constitutes a theory, puts Semmelweis’ study into the model.</td>
</tr>
<tr>
<td>0.49.31</td>
<td>T: new example and the students are asked to see if this example follows the criteria set in the schedule.</td>
</tr>
<tr>
<td>0.41.32</td>
<td>T/Ss: How can we test the hypothesis in other ways than the experiment? (Draws in the model: Previous models and findings). Use theories for predictions. If continuing to wash hands — it is predicted that the mortality rate will be low.</td>
</tr>
<tr>
<td>0.50.03</td>
<td>T: presentation of numerology.</td>
</tr>
<tr>
<td>0.43.27</td>
<td>T: falsification of hypothesis referring to the model and discuss using the example of Semmelweis.</td>
</tr>
<tr>
<td>0.52.40</td>
<td>T/Ss: numerology is not testable and the text is trying to convince the reader by referring to authorities.</td>
</tr>
<tr>
<td>0.43.56</td>
<td>T: to develop a scientific theory, many experiments and verifications of the theory’s assumptions are needed. Reinforcing the theory. A scientific theory can be: — developed, — tested, — used to predict, — rejected by new findings, — in accordance with other findings, — not a function of authority arguments.</td>
</tr>
<tr>
<td>0.53.44</td>
<td>T: numerology is a pseudo-theory.</td>
</tr>
<tr>
<td>0.47.48</td>
<td>T: test unconditionally.</td>
</tr>
<tr>
<td>0.48.56</td>
<td>T: theories are shaped by humans, and the social context (such as norms and religion) affects their trustworthiness (the Semmelweis example).</td>
</tr>
<tr>
<td>0.49.19</td>
<td>Ss: take notes.</td>
</tr>
</tbody>
</table>
clearly expressed, and this aspect was not understood as a part of a bigger whole. In Lesson C, the teacher referred to the model (Figure 3) of what constitutes a theory during the lesson, and the model was gradually constructed and expanded during the dialogue she had with the students. This enabled the students in group C to see the parts and whole continuously during the lesson.

In Lesson B, the model was constructed in 2 min and 30 s and subsequently referred to once; it was completed in 5 min. In Lesson C, 16 min of the work in the classroom related to the schedule drawn by the teacher on the whiteboard (marked by arrows in Figure 2). The teacher frequently used the schedule to explain and reinforce her instruction. The operations were integrated with each other, rather than presented one by one without an explanation of how they related to each other. Throughout Lesson C, the instruction focused more on trying to construct an argument based on the different components.

Figure 2. Continued

Figure 3. Schedule drawn by the teacher in Lesson C.
Lesson B focused more on explaining the different parts, leaving the students to create the meaning and connect the parts to each other.

In relation to the content, patterns were implemented in the lesson designs. The idea of fusing the criteria was present from the first lesson insofar as the lesson started with a lesson task (the ‘black box’) that was supposed to give relevant structure by pointing towards the legitimate question: What is this about? The black box technique was also used to elicit a number of aspects concerning the object of learning (perhaps not all of them were critical). Teachers’ operationalisation of the pattern contrast developed throughout the study. Particularly in the final lesson, the contrast was explicit and led to a generalisation of aspects that were critical, such as understanding that a theory can be tested in different ways rather than only in a single way. The teacher in that final lesson also used simultaneity when presenting the contrast by referring to the cases during the drawing of the structure on the whiteboard. The last fusion was evident only in the final lesson, where all critical aspects were seen simultaneously and in relation to each other and the separate moments in the lesson were intertwined by the rich references between them.

Both the short-term and long-term results of the students’ learning outcomes show the impact of a design in which aspects of an object are identified to make them discernible both separately and as a part of a whole. Shifting these connections within the content seems to make students’ learning outcomes sustainable and gives them learning techniques to develop or use in future situations. The delayed post-test results for the three groups were as follows: group A, −0.08; group B, +0.26; group C, +0.75.

Discussion

The analysis of the activity, based on Leontiev’s model of analysis, showed how different experiences became ‘directors of change’. The activity followed the iterative model for teachers’ professional development (namely the learning study) and the teachers had a substantial effect on the content chosen and on the learning process. Concept formation fuses the teachers’ beliefs with both formal content knowledge and their students’ knowledge. Teachers’ concepts are expressed by their agency to design interventions based on their interpretation of the formal policy documents and how the students’ learning outcomes contradict the teachers’ initial beliefs. This is a complex activity and the teachers’ learning gradually results in greater agency in classroom actions with a higher level of confidence, as expressed in their anonymous evaluations. The shift to ‘education as science’ (Holbrook & Rannikmae, 2007) focusing on students’ socioscientific arguments was initially a challenge for the teachers as they had to reconsider their way of teaching. The non-dualistic standpoint results in a focus that is split between the content offered during instruction and the students’ differing experiences of the content.

The teachers’ aim in this activity was to develop their students’ ability to discern what differs a scientific theory from everyday common assumptions, and develop the students’ argumentation skills by using several aspects in their reasoning. We analysed how the teachers developed their skill in designing lessons to stimulate student learning. At the level of activity, this study was part of a larger school development project in which teachers were supposed to develop their teaching skills. As the entire school was involved in a learning study project using variation theory as a guiding principle for designing their lessons;
therefore, professional development communities were developed at a school level and not only in relation to science teaching (Jones, Gardner, Robertson, & Robert, 2013).

At the level of action, during meetings between lessons, teachers analysed the previous lesson in relation to the pre- and post-test results. In particular, they analysed the video recordings to determine how the ideas of contrast and generalisation were enacted in the classroom. For example, after the second lesson, it was obvious that students successfully discerned only one of the offered criteria, that a scientific theory can generate hypotheses that can be tested and investigated through experiments. More emphasis was needed on the other three criteria. When discussing the two contrasting cases, the emphasis was to compare them and formulate the criteria simultaneously on the whiteboard. The results of the delayed post-tests, 7 weeks after the lessons, showed that students in the lesson with the simultaneous presentation of the criteria retained the knowledge to a higher degree after the 7-week interlude. Carraher and Schliemann (2002) point out the importance of prior knowledge in seeing the initial learning situation as a way to integrate the students’ prior knowledge into the lesson. They also suggest the need to have a theoretical point of departure when designing learning situations stimulating sustainable learning. The teachers have used interviews and screenings to understand the students’ prior knowledge, and used theoretical conjectures to refine the design of the lessons. There is a clear connection between the teachers’ operationalisations during the three interventions or cases and the students’ learning outcomes. The data analysis clearly indicated how the teachers’ understanding about the content from the perspective of the students’ knowledge formed a basis for the increasingly developed designs that they implemented.

In this study, teachers expressed their knowledge during meetings and their operationalisation in the classroom. Over time, they became increasingly focused and exploratory (Mercer, 1995) in the sense that they started to give and take criticism and expressed a collective ownership of the next lesson. When enacting the third lesson and making the contrast between Semmelweis and numerology, teachers opened up a dialogic space (Wegerif, 2008) where the two contrasting theories were held in tension simultaneously. The results of the study suggest that to develop knowledge, we have to rely on (and often develop) both student knowledge and theoretical knowledge about learning. Their mastery (Wertsch, 1991) of the theoretical framework gradually developed and in the collaborative design of the third lesson in group C, the teachers’ appropriation of the theoretical assumptions led to an instructional design in which simultaneity was used.

At the level of operations, the impact of using contrast (as identified in earlier projects, e.g. Holmqvist, 2011) was familiar to the teachers. During the study, teachers in this multiple-case project became more aware of how to introduce patterns of variation in aspects critical for understanding what constitutes a scientific theory. The way teachers in this study were able to gradually shape the design of the lessons using fusion, contrast, and generalisation as teaching strategies (Marton, 2015) – as well as communicating and representing identified critical aspects in pictorial form on the whiteboard – shows how they became more skilled in meeting the needs of their students and in offering content as a whole, moving repeatedly between the parts and the whole to create a coherent presentation of the content to enhance students’ knowledge.
Conclusion

Teaching is complex and multifaceted and is not always based on theoretical conjectures about learning. In this study, a methodology based on a non-dualistic theoretical framework was introduced to analyse teachers’ operationalisations to enhance student learning in science education. A theory of learning, variation theory, was introduced to teachers, who then used the theoretical conjectures as guiding principles during formative interventions. We found that teachers gradually changed their teaching methods during the iterative process by taking into consideration the structure of the content, what the students had already learnt, and what they needed to learn to increase their knowledge of the subject. Initially, the teachers did not give the students enough information and oversimplified the content. They offered what could be understood as new information about the content; however, this new information was separate from other parts of the content and teachers failed to show how the parts related to each other. This left the students with information gaps between what they already knew and what they needed to know. During the iterative formative interventions, the teachers gradually became more skilled in ensuring that their teaching met their students’ needs. The students’ learning outcomes then began to improve and were highest during the last intervention. The teachers’ actions also changed because of their increased knowledge of the topic in combination with their increased knowledge of how to meet their students’ needs. The teachers’ actions then changed because of their increased knowledge of the topic in combination with their increased knowledge of how to meet their students’ needs. The results of the intervention showed teachers that their assumptions about which aspects would benefit students did not reflect the aspects from which students actually benefited. This motivated the teachers to modify their plans during the design-based interventions of the activity. By addressing teaching content to the gap between what the students did not yet know and what they needed to know, and guided by theoretical conjectures during the interventions, teachers were able to teach the students sustainably. This study exemplifies how activity theory can be used to analyse teaching activities, following Leontiev’s (1978) three-level structure of activity, and how this is related to both short- and long-term student learning outcomes. Although this study did have some limitations (the small-scale case studies and the lack of discourse analysis of the teachers’ discussions), the results indicate how the framework can be used not only to describe teaching activity but also to define how teachers’ different operationalisations are related to students’ different learning outcomes.

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