**What happens when you push the button? Analyzing the Functional Dynamics of Concept Development in Computer Supported Science Inquiry.**

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Abstract

In this article we analyze how the joint cognitive system of teacher and student actions mediated by cultural tools develops sense making of science concepts, and the use of concepts as tools for explaining phenomena and processes related to energy and energy transformation. We take a sociocultural approach to the analysis of how material and digital learning resources become tools for thinking and reasoning. We combined ethnographic descriptions with analysis of video records of classroom interactions in a high school and examined how a teacher and a group of students engaged in a computer-supported collaborative inquiry. Our results show that students through inquiry are enabled to make sense of concepts and their experiences with resources and also to use science concepts as explanatory tools. However, this is mediated by the teachers' practices for supporting students, such as providing relevant clues for them to continue their inquiry, eliciting their initial understanding of concepts thereby making them available for further development, pressing for explanations, and reformulating their explanations. The teacher is continuously alternating between withdrawing and making students inquire by themselves and supporting their inquiry. In and through such social interactions, materials and digital tools become tools for thinking. We argue that one of the practical implications of our study is that it is crucial that teachers explicitly draw students into their system of activity throughout the entire learning trajectory and that the teachers and students together make sense of science concepts for explaining energy transformation.

*Keywords:* Collaborative learning * Digital learning resources * Science learning * CSCL * Functional systems * Multi-representational learning settings

## Introduction

We report on how students inquire into matters of energy and energy transformation and how their participation in computer-supported collaboration is mediated by tools and changing divisions of labor within a developing functional system. We show how this cognitive unit solves the task of explaining how a heat pump works,[1] and how students' participation in explanations changes during an

[1] A heat pump is an inverted version of an air conditioner.

inquiry trajectory. Students' inquiry is mediated by a variety of material, digital, and social means.

We are interested in how students and teachers learn together as part of an evolving sociocognitive system. This involves extending the unit of analysis beyond the individual learner. In the computer-supported collaborative learning (CSCL) field, Stahl has contributed significantly to demonstrating the fruitfulness of extending the unit of analysis to what he terms group cognition (Stahl, 2006). Group cognition refers to how individuals perform a cognitive act together through interaction. In the learning sciences, Enyedy and Stevens (2015) recently introduced the notion of collaboration-as-learning as a way of seeing learning as "relational changes to a system with multiple parts" (Enyedy & Stevens, 2015, p. 204). Pursuing a sociocultural approach, we emphasize how a task is solved by a *functional system* comprising tools and the actions of students and their teacher (Luria, 1932; Newman, Griffin, & Cole, 1989).

Tools are meaningful ideal/material human creations that mediate human practices (Cole, 1996). In joint problem-solving, there is often a sequence of actions to be accomplished where divisions of labor among participants change over time (Newman et al., 1989). The meaning of a task is negotiated among interlocutors, but the task to be accomplished remains rather stable, and, over time, interpretations gradually align as students become more expert participants. However, students' understanding is never simply a replication of what is already known. The development of conceptual understanding is unpredictable and may take multiple directions.

An interest in mediational means implies that we pay particular attention to how digital and material tools become important resources in inquiry (Wertsch, 1998). Tools are often ambiguous and inference-rich, and in educational settings this ambiguity can constitute a basis for the emergence and development of conceptual discussions in social interaction (Roschelle, 1992). Digital technologies can offer more dynamic, interactive, and context-sensitive resources for learning (Rogers, 2008). Still, research indicates that students often find it difficult to make sense of multimodal artifacts combining pictures, texts, models, and moving images, and particularly to make sense of science concepts across tools (Ainsworth, 1999; Furberg, Ludvigsen, & Kluge, 2013; Jornet, Roth, & Krange, 2016; Jornet & Roth, 2015). The aim of this article is twofold. First, we introduce the notion of functional systems as a useful unit of analysis for making sense of how material and digital artifacts mediate science learning. Second, we aim to use this notion to analyze how the use of science concepts emerges as part of an interconnected dynamic system, and to show how the division of labor between teacher and students changes over time (John-Steiner, Meehan, & Mahn, 1998).

In our analysis, we examine in detail how students learn to use science concepts to account for and explain energy and energy transformations. This involves an interest in designing for and analyzing students' explanations and not just their descriptive accounts of phenomena. Explanations require attention to unobservable processes and the concepts that can account for them (Braaten & Windschitl, 2011). What Vygotsky (1986) describes as scientific concepts constitute important mediational means for explaining such processes. These concepts are, however, difficult to comprehend because they are abstract and detached from reality. Research has documented that the development of scientific concepts represents a fundamental challenge in the learning sciences (Bransford, Brown, & Cocking, 2000). According to Vygotsky: "The greatest difficulty of all is the application of a concept, finally grasped and formulated on the abstract level, to new concrete situations that must be viewed in these abstract terms…"(Vygotsky, 1986, p. 151).

Considering this background, we pursued the following research questions:

- How do science concepts emerge during interactions in multi-representational learning settings?
- How do students learn to use science concepts as explanatory tools?

The data we analyzed were produced as part of a learning design featuring explicit interventions for supporting students' development of concepts across mediational tools. The article consists of four main parts. We start by reviewing the literature on computer supported collaborative inquiry learning and how teachers and digital tools support such learning. Then we describe our analytic approach and introduce our case and methods. In the analysis we introduce a rich and comprehensive account of students' and a teacher's inquiry trajectory, and how their interactions are mediated by cultural tools. We end the paper by discussing the theoretical and methodological implications of our research and identifying research contributions.

**Supporting Students Learning Scientific Explanations in Science**

Research shows that in science education, a focus on activities rather than on sense making remains the most common practice in classrooms (Windschitl, Thompson, Braaten, & Stroupe, 2012). In a CSCL setting, Greiffenhagen demonstrates how the teacher's routine work involves a whole range of actions whose primary objective is not to support learning, but rather to support social regulation (Greiffenhagen, 2012). Traditional pedagogies emphasize a procedural approach in which complex concepts are treated as sets of unrelated tasks (Windschitl et al., 2012). Students' prior knowledge is rarely taken into account and teachers seldom press for explanations through questioning (Windschitl et al., 2012). In contrast, in CSCL and related fields, a growing number of studies demonstrate the positive effects of inquiry pedagogies and how various teaching practices and tools can support learning. Research demonstrates quite clearly that guided inquiry is more effective than traditional instructional methods (Donnelly, Linn, & Ludvigsen, 2014). Having said that, research also shows that students struggle with formulating theories and hypotheses, connecting practical procedures to science knowledge, and developing continuity in applying science across activities and tools (Van Joolingen, De Jong, & Dimitrakopoulou, 2007). The teacher's actions, such as eliciting information and providing cues, are crucial for supporting computer supported collaborative learning (Furberg, 2016; Mercer, 2000).

Across theoretical approaches, there has been substantial interest in CSCL to study how different kinds of digital artifacts scaffold or support learning as part of collaborative activities (Arnseth & Ludvigsen, 2006). The scaffolding metaphor has been central in constructivist approaches to studying how learning is supported and structured by social and material resources. The notion of scaffolding was introduced by Wood, Bruner, and Ross (1976) as a metaphor for explaining and understanding the role of adults in joint problem-solving. In the literature, there is a tendency to define scaffolding as a process through which the more experienced other erects temporary intellectual scaffolds that enable the learner to accomplish tasks she normally would not manage by herself. Lately, the focus on the individual has been extended to how collaborative activities can be scaffolded (Tabak, 2004).

Still, the aim is often to see how characteristics of the collaboration produce what Enyedy and Stevens (2015, p. 199) call distal learning outcomes on an individual level.

In their extended review of descriptive and experimental studies of scaffolding in science education, van der Pol, Volman, and Beishuizen (2010) identified a set of common characteristics. They find a narrow focus on how to carry out a task, and much attention is given to the idea of *fading*, which is when the teacher gradually withdraws support. As a consequence, the teacher can slowly *transfer the responsibility* for carrying out the task to the individual learner.

Van der Pol et al. (2010) introduced an additional term, *contingency*, which describes how support is tailored and responsive to the collaboration and the students' level of cognitive performance. According to them, the need for contingent assistance does not necessarily decrease throughout a learning trajectory.

Quintana et al. (2004) developed a framework for designing software tools that scaffold science inquiry. They highlighted support for sense making, process management, articulation, and reflection. They drew on the *knowledge integration framework* by stressing the integration of scientific ideas with common-sense ideas (Linn, Davis, & Eylon, 2004).

Coordination of multi-representational resources involves joint sense making. However, the literature on learning with multiple representations has traditionally been concerned with the psychological processes involved in interpreting, understanding, and coordinating different visuals (Mayer & Moreno, 2003; van der Meij & de Jong, 2006). During the last few decades, these constructivist interpretations have been challenged by learning scientists who have been paying increasing attention to the role of multiple representations in the context of collaborative learning (Tabak, 2004). Consequently, the focus has shifted towards investigating the ways in which representations enable joint activities. For instance, Schwartz (1995) reported that dyads working with graphical representations outperformed individuals in conceptual performance, and theorized that this advantage is based on the need to build a common ground for mutual understanding. Roschelle (1992) described collaborative learning with representations as a process of convergence, where students would mutually construct meaning in and through their interactions with each other and a digital resource. Both Schwartz (1995) and Roschelle (1992) make analytic distinctions between collaboration and cognition, and emphasize how certain forms of collaboration, such as establishing shared understandings, have positive effects on cognitive performance. The notion of convergence was later taken up by Furberg et al. (2013) who, through a detailed analysis of students' interactions in a project about energy and heat transfer, demonstrated how representations become productive social and cognitive resources in students' conceptual sense making. These studies initiated a research agenda that seeks to investigate the ways in which multiple representations are involved in processes of joint activity. Our contribution to this literature is a more explicit focus on a joint unit of analysis. Hopefully this will enable us to produce new insights into how tools support computer supported collaborative learning of science concepts.

## Theorizing Conceptual Development as Changes in Functional Systems

Vygotsky makes a distinction between spontaneous and scientific concepts; spontaneous concepts are formed in relation to concrete experience, and they emerge from concrete experience with the world (Bakhurst, 2007). Spontaneous concepts "…sort entities into kinds according to criteria formed by abstraction from the entities' surface characteristics" (Bakhurst, 2007, p. 70). According to Vygotsky, "The development of spontaneous concepts knows no systematicity and goes from the phenomena upward towards generalizations" (Vygotsky, 1986, p. 157). Scientific concepts, on the other hand, unite experiences through a principle of *unity*. This principle explains why members of a category are what they are; they become resources for explaining experiences with phenomena and processes in the world. Scientific concepts seem abstract, general, and remote from the concrete experience of the world. "In the case of scientific thinking, the primary role is played by *initial verbal definition* (italics in original), which being applied systematically, gradually comes down to concrete phenomena" (Vygotsky, 1986, p. 157). According to Bakhurst (2007), Vygotsky does not value an abstract and decontextualized form of knowing. On the contrary, for Vygotsky it does not make sense to make a sharp distinction between the abstract and the particular because the two mutually inform one another. Scientific concepts very much enable us to make sense of particular instances.

According to Vygotsky, concept formation alternates between association and abstraction. "The transition from the abstract to the concrete proves just as arduous for the youth as the earlier transition from the concrete to the abstract" (Vygotsky, 1986, p. 151). These are two different forms of reasoning that can inform one another and merge into one another over time. In addition, Vygotsky argues that scientific concepts often develop earlier than spontaneous concepts, and that scientific concepts influence the development of spontaneous thinking and vice versa (Vygotsky, 1986). "Deliberate introduction of new concepts does not preclude spontaneous development, but rather charts the new paths for it" (Vygotsky, 1986, p. 161). Students' development of scientific reasoning is also mediated by already-acquired concepts.

We see the mind as "a leaky organ" that spills over into the social environment and is distributed among people, tools, and surroundings (Clark, 1997). In regard to understanding students' changing participation in scientific reasoning, we want to make use of the notion of *functional system* as a conceptual tool. In contrast to the notion of activity systems in which human activity is seen as mediated by communities, rules, and divisions of labor, a *functional system* is more focused on a particular task or cognitive function (Newman et al., 1989). Changing functional systems represents transformation on interconnected levels, but in contrast to the notion of activity systems, it does not denote how the whole person acts in the world as part of changing social practices. It is part of the person interacting as part of a system who performs a task or a function. Following Luria (1932) and Newman et al. (1989), the notion of *functional systems* is a useful unit of analysis for studying scientific reasoning. Describing changes in functional systems becomes a way of analyzing cognitive change. According to Luria (1932), there are two distinguishing features of functional systems: the presence of a task that is performed by variable mechanisms, and the complex composition of the system. Working in the field of neuropsychology, Luria (1932) used the notion of functional systems as a construct for describing how other parts of the brain can take over functions following brain damage. We use the notion to describe the interpersonal system of mediational tools and students and teachers actions situated within the zone of proximal development (ZPD), which is a system of interactions in which the actions of the students are drawn into and become incorporated into the teacher's system of activity (Newman et al., 1989). A ZPD is a particular kind of functional system in which one participant acting within the system could not accomplish or work on the task alone. The teacher provides the directionality for the development of the system, but there is a mutually constitutive relationship between the changing participation of the students and the changing system as a whole. Thus, the ZPD is a developing system of social interaction in which the student gradually takes over and appropriates the teacher's functioning within the system. The ZPD is a mechanism for appropriating cultural tools. Learning is changing participation within the ZPD, and the ZPD explains how cognitive functions are sociocultural phenomena (Newman et al., 1989).

Resources are crucial parts of functional systems. To learn is to be able to appropriate and use ideal/material resources. However, when interacting in the ZPD, participants do not necessarily need a shared understanding of resources and their functions. Students are not required to understand the full meaning of a tool to be able to use it in interactions, and the teacher can use students' actions and incorporate them into the larger functional system without having a very sophisticated analysis of their thinking (Newman et al., 1989). Students' and their teacher's interactions with resources can serve as a stepping stone for the development of scientific concepts.

In the CSCL field there is a tendency to treat scaffolds as separate from collaborative learning. In constructivist approaches scaffolds support or fail to support students' learning. Tabak extends this approach by emphasizing that systems of scaffolds are necessary for learning the complexity of a discipline (Tabak, 2004). She argues that learning designs need to take into account sequencing and integration of different forms of support. In sociocultural approaches the teacher is portrayed as important, but often in rather generic terms. Thus, in CSCL there is a tendency to appeal to research that addresses the role of the teacher (see Furberg, 2016, p. 111). In our view, this needs specification in terms of how teachers' actions mediate learning. We do not want to take for granted that mediational means support students' changing agency in the functional system. On the contrary, their supporting functions are emerging features in social interactions. In order to make sense of their functions in practice, we want to contribute to CSCL research on support by carefully scrutinizing how they are introduced, oriented toward, and taken up by the participants and, as a result, how they emerge as important integrated support structures for changing participation in functional systems over time.

## Case and Methods

In order to provide a comprehensive account of how resources mediate teacher-student interactions, we conducted a video ethnographic case study of students working in groups (Schaeffer, 1995). Video ethnography enabled us to describe and summarize activities and combine them with more detailed analyses of interactions. In and through our analysis, we are (re)constructing a learning trajectory through narrative, that is, how a particular way of using and orienting to science concepts changes over a certain time span. A case study approach is useful for studying sense making practices as these unfold and relate to situational particulars (Flyvbjerg, 2006; Jornet & Roth, 2015). Video ethnography enabled us to analyze and describe activities and the ways in which participants made sense of and displayed their interpretations to one another of what they were doing (Schaeffer, 1995). The method provided ways of foregrounding the participants' expertise, knowledge, and understanding of their own local circumstances. It is also well-suited to our analytic interest in understanding changing participation in science reasoning and how this reasoning is mediated by cultural tools. It provides us with tools for analyzing how participants themselves make meaning in social interactions, how that meaning-making is tied to local circumstances, and also how it changes over time.

The data were collected as part of a larger project in which 24 first-year upper secondary students worked on concepts of energy and energy transformation using both material and digital tools. The students were tasked with explaining how a heat pump works. A heat pump is an example of an energy transformation system, and the goal described in the Norwegian national curriculum is that students apply scientific knowledge to explain how it works.

The students participated in a designed trajectory in which they went from describing what happened to explaining how and why. The trajectory was also designed to enable them to make connections across resources and tasks. The activities were meant to provide students with a broad range of experiences pointing towards relevant physics knowledge. Our aim was to create a situation in which learners could use abstract concepts introduced by the teacher or inscribed into educational materials to explain energy, to bodily and perceptually experience energy transformation, and to form spontaneous explanations through experimenting with materials and representations. Our analysis provides analytic generalizations of changing participation in developing functional systems.

The total corpus of the data consists of about 37 hours of video recordings involving two groups of students. The data set for this particular study involved video records of the activities of only one of these groups. Two methodological principles guided our construction of the data set. First, we chose data in which students were working with material and digital learning resources. Second, we selected data for which participants, including the teacher, were using and oriented to specific concepts relating to energy and energy transformation. From these data, we aimed to reconstruct a temporal unfolding of how participants used certain concepts. Our data set was thus identified by our analytic interest in conceptual development and how that development is mediated by cultural tools (Braun & Clarke, 2006). Our selection of excerpts from the data set was purposeful. We have deliberately included episodes in which we observed crucial changes happening in the functional system of teacher, artifacts, and students in terms of how they use concepts as part of explanations and accounts. In our analysis we examined how a particular theme is constituted over time: how students and their teacher develop their scientific thinking and conceptual accounts of an energy transformation system together. We used excerpts to flesh out our arguments and to provide backing and detail to our claims, not to perform the analysis per se. We also provided broader ethnographic descriptions of the trajectory by describing the development and emerging characteristics of the functional system. While transcribing the data, we primarily focused on word and sentence meaning, putting less emphasis on the details of delivery or turn-taking. We have used the following transcription conventions: [square brackets indicate overlapping talk]; (single brackets indicate talk that is difficult to hear); ((double brackets are our comments on what is going on in the talk)); and … refers to longer pauses in the interactions.

In terms of analytical procedures, we have oriented to two principles. The first was to examine the use of categories and concepts – how they are used and how they are connected in and across utterances. The second was to look at how conceptual meaning is developed sequentially and how particular topics in the data develop across episodes of interaction.

The learning trajectory was structured in the following manner. First, the teacher gave a talk about energy and sustainable development, which constituted the societal and more authentic context for the task. Second, the students were urged to activate their prior understanding of energy. Third, the students worked in groups with material artifacts, in this case a spray can, a syringe filled with lukewarm water, and a bike pump. These materials illustrated important principles that students can use to understand the inner workings of a heat pump. The students produced videos in which they provided explanations and accounts of their experiences with the artifacts. A heat pump is an energy transformation system that works in the following manner: It contains a fluid that boils at low temperatures, and through manipulations of pressure, it can transform energy from outside the house into heat. Three science concepts help explain this process.

1) The relationship between pressure and temperature: Increasing the pressure increases the temperature, and vice versa.
2) Phase transition from liquid to gas and vice versa: Evaporation requires energy, and condensation produces heat energy.
3) How the boiling point in a fluid varies with pressure: When the pressure decreases, the boiling point also decreases. This makes it possible for the fluid to boil in low temperatures.

Fourth, they went to a science museum to engage with exhibits on the topic of energy. Fifth, they worked with digital models of heat pumps to produce accounts of how they work. Finally, they made presentations to the class.

In our analysis we will focus on how they worked with the spray can and the digital models. Information and communications technology (ICT) supported students' activities in the following ways: They could access task formulations, animations, and models, and could also upload videos through one integrated system. They were also able to make notes on the animations and models and save these into the system. The system also comprised a visual model of their learning trajectory, making visible the sequencing of activities. The students could access these resources through their mobile phones or their laptops.

Inspired by an inquiry approach, we also encouraged the teacher to provide hints or suggestions instead of direct answers to problems students encountered. Furthermore, designing for inquiry, we aimed to make both spontaneous and scientific concepts into relevant tools for solving their tasks, something which might lead the students to reflect on these concepts and their meanings and functions. We will address these issues in detail in the analysis. We start with focusing on how the students approached everyday artifacts, in this case a spray can.

**The Science of Everyday Things – Everyday and Scientific Accounts of Energy Transformation**

When students started working with material artifacts, they were touching them, pressing buttons, experiencing the effects of what they were doing, and discussing and inquiring into the meanings of tasks and their experiences. This inquiry was mediated by the task description made available to them through their mobile devices. Such experiences enabled them to construct spontaneous accounts that were not necessarily mediated by any scientific concepts.

The spray can contained pressurized air. The task was to press the button on the can and describe what they felt and then, without consulting any external information sources, speculate about the explanation behind what they felt. As part of the task, the group was also asked to record a short video summarizing their interpretations. In the excerpts below, we see how concepts emerged and how students made sense of them. The participants were Ray (R), Ahmed (A), Ingrid (I), Allan (AL), and their teacher (T).

*Excerpt 1: Emerging concepts*

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1.   R:   Okay, what do we feel? [We feel air.]
2.   A:                          [We feel power.]
3.   I:   And what is power, and what is air? Energy or something,
4.   A:   Yeah, but what is it we are supposed to do?
5.   R:   ((Reading from a mobile phone)) It says: «describe what
6.        you experience and feel, what might be the cause of
7.        what’s happening?» Yeah?
8.   A:   It’s the pressure.
9.   I:   It’s the pressure.
10.  R:   Yeah.
11.  A:   It’s air.
12.  I:   ((lifts the can and blows on her hand))
13.  A:   The reason why it is happening.
14.  I:   It is pressure so you ((Sends the bottle to AL)), you
15.       gotta push the button.
16.  A:   Oh, they ask what is it that makes it feel cold. What
17.       makes it cold?
18.  AL:  Is that it? ((Reads the task on the mobile phone again))
19.  R:   Isn’t it because of that thing inside?
20.  I:   It is cold ((Sends the bottle around))
21.  A:   Very cold, right?
22.  R:   Yeah, it is cold.
23.  AL:  Yeah, but what is causing it?
24.  I:   What is the cause?
25.  A:   What is in this thing? ((Reading on the label))
26.  I:   It only says pressure.
27.  AL:  It is written here.
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Ray and Allan suggested *air* and *power* in lines 1 and 2 as relevant concepts describing their sensations, but Ingrid problematized their suggestions in line 3 and introduced *energy* as a third overarching concept. In lines 7 and 8, Ahmed and Ingrid introduced *pressure* as a relevant concept for explaining their experiences. In lines 14–22, they established *coldness* as a sensation that they needed to explain. To summarize, at this stage the group agreed that they felt air coming out of the can and that it got cold. *Pressure* was introduced into the functional system as a relevant concept for explaining these observations. Thus, in line 26, Ingrid said pressure was mentioned on the label. The meaning of the concept pressure is mediated by the textual description on the can. The group’s ability to make the distinction is mediated by the task formulation and the properties of the artifact.

Students experienced the task as ambiguous. At first, it was not clear to them exactly where on the can they should feel something or what they were supposed to feel. They were also searching for relevant concepts they could use to account for their sensations; to put it differently; they looked for concepts that could mediate their understanding of their sensations. However, they made a useful distinction between *description* and *explanation* (Braaten & Windschitl, 2011). They described their sensations in a relevant manner, and invoked a concept that might explain these sensations. Thus, the functional system of students and materials temporarily established pressure as a relevant explanatory concept.

Addressing the gradual development of a more sophisticated use of concepts requires examination of how the teacher mediates conceptual development: that is, how the teacher is incorporating students’ actions into a developing functional system of activity (Newman et al., 1989). This is achieved through requesting accounts of experiences, providing hints and suggestions, and corroborating student accounts. In more general terms, the teacher challenged their concepts.

*Excerpt 2: The teacher (T) provides support and direction for the developing functional system*

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T:   What happens when you press the button?
A:   Air comes out of it.
R:   Yeah.
T:   Air is coming out, that’s right. Anything else happening? ((Spraying on Ingrid’s hand)) What happened?
I:   Gas.
T:   Was it cold?
I:   Yeah, I was a bit cold
T:   Were you scared?
I:   No. It was only a tickly feeling, so just.
A:   I know what,
T:   Yeah, you were cold right?
I:   Yeah, I was cold.
T:   But why? This thing isn’t cold.((Gripping the can))
A:   We were thinking that it is cold vapor.
T:   Yeah, but vapor, is that cold?
AL:  No.
R:   No.
A:   Chilled vapor is not.
T:   If you push it, hold it for a while and feel.
R:   ((Receives the can)). Should I push it and hold?
T:   Feel the temperature on the can.
R:   Should I just push here?
T:   Yeah.
R:   ((Pushes and holds the button for a while)) It gets cold, freezing cold.
T:   It is getting cold all right. Why is that?
R:   Yeah, why is that?
A:   ((Grabs the can))
T:   Why is it cold?
A:   Interesting.
R:   Why is it cold, folks?
T:   Think about the flow of energy.
R:   Okay.
```

In the first few lines, the teacher asked the students to describe what happens. Through a series of questions, they agreed upon *coldness* as the relevant phenomenon to be explained, and the teacher challenged them to explain why (Vygotsky, 1986). Within the functional system, the teacher was eliciting students’ spontaneous concepts and challenging them to explain their reasoning (Windschitl et al., 2012). Through a series of questions the teacher elicited the relevant descriptions, and corroborated what the students agreed on in the previous excerpt. Within the functional system he contributed to establishing something as shared knowledge, and he also made clear that this knowledge is relevant for carrying out the task. Thus, the students could continue their inquiry trajectory.

Instead of employing widely-used pedagogical moves that construe their explanations as mistaken, he provided guidance that supported further inquiry (Braaten & Windschitl, 2011). In line 33, he urged them to consider the *flow of energy* as a relevant process to inquire: that is, the transformation from liquid into gas. In and through this account, a process underlying and explaining surface features is introduced into the developing system (Bakhurst, 2007). An explanation was necessary to describe what happens when something changes from a liquid state to a gas state. To make sense of what is termed a *phase transition* in science, the students needed to use more sophisticated concepts.

After the teacher moved on, they produced a short video. Later, after they had uploaded videos of their explanations, the teacher reviewed some of them with the entire class. The purpose was to summarize, identify and clarify misunderstandings, and also to illustrate appropriate solutions.

The teacher said that the purpose of the experiments was to illustrate three important science concepts, and that the goal was to make sense of these concepts and later to apply them to a concrete case. The first was what he termed the law of *pressure-temperature*, which states that increased pressure leads to increased temperature, and vice versa. The second was the law of *liquid-gas*: Energy in the form of heat is needed when liquid evaporates, and when it condenses, heat is produced. The third was the law of the *pressure-boiling point*: When pressure decreases, the boiling point also decreases, and vice versa. In the following section, we refer to these as *science concepts* that can mediate students' meaning-making.

The teacher introduced science concepts into the developing functional system. The science concepts were not just presented to students as abstract principles, but were also connected to students' emerging concepts. He also used this activity as an opportunity to check for understanding. Furthermore, the videos became a shared resource and represented a way for the teacher to introduce science concepts. The next step in the learning trajectory of the functional system was to use science concepts to explain concrete particulars. This became contextually relevant when the students started working with animations and models.

## Working with Digital Animations and Models

Here students were trying to make sense of two digital resources. The first is an animation illustrating the process of phase transition in a heat pump, and the second is a model of the heat pump demonstrating its different parts (evaporator, compressor, condenser, and valve). The representation also contains relevant information that can be made visible using a mouse-over. Here the students had the opportunity to use concepts as tools for explaining phenomena. The focus was on making connections between phenomenon and concept.

*Excerpt 3: Making sense of animation part 1 (see also Figure 1)*

I: It is, if you look down there ((Pointing towards the lower part of the screen)). Down there the temperature is pretty low.
R: Yeah.
I: Then it increases here. ((Moving the cursor up on the left chamber of the model))
AL: It is just like the syringe.
I: Same as the syringe?
AL: Yeah, the pressure is increasing, right.
I: The pressure increases, yeah. It has to be something like that.
AL: Look here at the pressure.
I: You see the pressure, that is because, here. ((Pointing on the right chamber))
AL: It is much higher, find that one, Ahmed.
I: But what kind of pressure is it?

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17.  A:   Hmm?
18.  AL:  It is about those laws.
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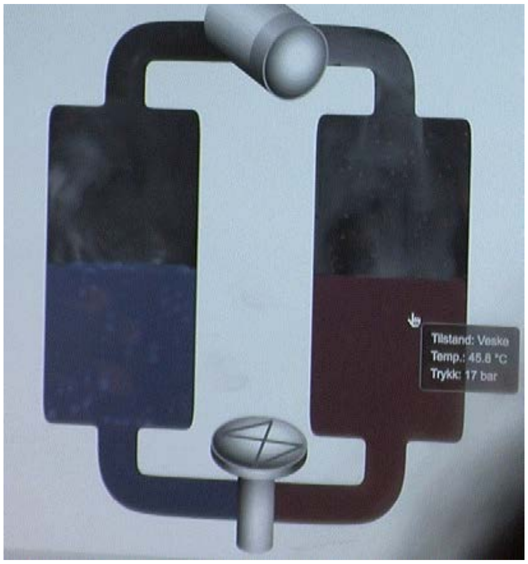


*Figure 1. Model 1, which is an animation of the process of phase transition.*

In the first few lines of the excerpt above, the students agreed that the temperature was quite low in the bottom part of the animation. In lines 5–6, Ingrid said the temperature increased, an inference based on the representation of *steam* on the upper left side of the model. Allan drew an analogy between the syringe and the left part of the figure. This is partly correct. Similarly to the syringe and because of the valve, the pressure decreases in the left chamber, and the liquid starts to boil. Allan and Ingrid agreed in lines 12–15 that pressure was a relevant concept. In line 12, Allan oriented them to the right side of the representation, pointing out that the pressure was higher. They grounded their interpretation in the textual description of the pressure, which states 17 bar (Figure 1). Thus the concept of pressure was made relevant by the model. The abstract concept became something else – something they could make sense of because of the sign. The model mediated a new understanding emerging in the system, namely that pressure is not static but a dynamic phenomenon, and that this is relevant to the explanation. Through this, Allan was also able to introduce the three laws as relevant concepts in the functional system.

Students exhibited difficulties in distinguishing and understanding the relationship between the two separate but connected systems of the heat pump. They used spontaneous concepts inferred from “reading” the representation, but they were not able to use science concepts as mediational means.

They knew that the concepts were relevant for explaining what was going on, but they did not know exactly how they could be used. To unpack this issue, they brought forward a different representation, which situated a heat pump in a physical environment mediating between the inside and outside of a house.

*Excerpt 4: Making sense of animation part 2*

```
1.   I:   But what kind of pressure is it? It has to be high or
2.        low pressure. ((Retrieving the figure depicting the
3.        heat pump))
4.   AL:  What is going on? Here it is energy from the
```

5.        surroundings.
6.   I:   Yeah.
7.   AL:  It is coming into this thing here.
8.   I:   That thing?
9.   AL:  And then.
10.  I:   Not thing, the chamber: into that chamber over there
11.  AL:  Chamber?
12.  I:   Yeah, it says chamber.

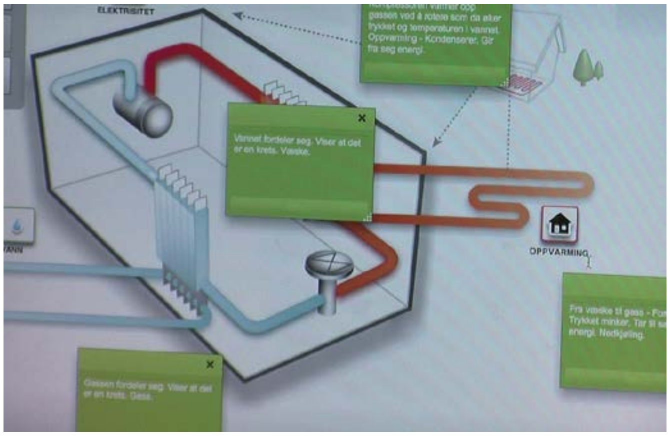


*Figure 2. Illustration of a heat pump in a physical environment mediating between the outside and the inside of a house.*

In lines 4 and 5, Allan pointed out how the pump takes energy from the surroundings, and Ingrid and Allan in lines 6–12 agreed that energy is transferred into the chamber. The figure enabled the group to see how the heat pump takes energy from the surroundings, but it did not help them explain the changes in pressure and temperature. They retrieved the science concepts they had written down, and Ahmed read the pressure-temperature concept aloud in lines 3–7 in Excerpt 5. The written notes of the concepts became an important mediational tool in the functional system.

*Excerpt 5. Connecting knowledge and representation part 1*

1.   A:   Three physical laws or principles.
2.   I:   Wait, heat, can we…
3.   A:   Yeah, yeah, there is something here, I think. ((Reading
4.        on his screen)) When the pressure in a gas increases,
5.        the temperature increases as well. When pressure
6.        decreases, temperature decreases. This is called the
7.        pressure/temperature law of gases.
8.   I:   Mm, as you can see here.
9.   AL:  Just push that one.
10.  1I:  ((Brings forward the model with two chambers and puts
11.       the cursor on the left chamber))
12.  AL:  So when the pressure increases, the heat increases.
13.  I:   Yeah, but here. ((Puts the cursor on the right chamber))
14.  R:   The pressure decreases.
15.  I:   Here, it decreases.

The students returned to Figure 1, and in lines 10 and 11 Ingrid made the left chamber salient. In line 12, Allan claimed the pressure was increasing as the heat was increasing, and in line 14, Ray stated that the pressure decreased in the right chamber. The students were able to mobilize relevant concepts, but they struggled with connecting them to the model. They knew that all three concepts were relevant for explaining the workings of the heat pump, so without coming to a conclusion, they moved on to the second concept: the boiling point of a fluid decreases when the pressure decreases. This helped explain how the fluid can start to boil.

*Excerpt 6. Connecting knowledge and representation part 2*

```
1.   A:   Let’s read further. ((Reading from his machine)) The
2.        boiling point of a fluid decreases when the pressure
3.        above decreases.
4.   AL:  Right, here the pressure is low: 5 bar. The boiling
5.        point decreases, and it boils at 5 degrees C.
6.   I:   (But this here) the pressure is high…
7.   A:   Yeah, that is true, it-
8.   I:   But does the pressure increase as well?
9.   A:   It boils at a low temperature, right?
10.  AL:  Mm.
11.  A:   At 5, 6 degrees C.
```

When they mobilized the second concepts, they were able to change their interpretations. In lines 4 and 5, Allan correctly states that the pressure is low in the left chamber and is able to connect that to the fact that it boils. Introducing the second concept thus enabled them to compare and distinguish between concepts and their relevance. We saw earlier how the teacher drew the students into his system of activity by introducing the concepts into the functional system. These concepts were taken up by the students to carry out parts of the task. We observed that the students were able to make use of the mediational means and take over the function previously carried out by the teacher. Students were not simply parroting the concept; they were using it to explain the fact that the fluid boils at low temperatures.

They did struggle with taking the functions of the compressor and valve into account. The heat pump also constrained their meaning-making of the concepts, since they also needed to know the heat pump functions to be able to make use of the concepts to explain concrete cases. The group then invoked the third concept, which is about phase transitions. It states that turning a fluid into a gas requires energy, and that when a gas turns into a fluid, energy is transformed into heat.

*Excerpt 7. Connecting knowledge and representation part 3*

```
1.   A:   ((Reads)) To make a fluid turn into a gas, it takes
2.        energy. When a gas is transformed into a fluid, energy
3.        is released. This is transfer of energy through a phase
4.        transition.
5.   AL:  Is that it? ((Pointing at the right chamber))
6.   I:   I think that’s the one. It turns into fluid.
7.   AL:  Or it’s dripping down.
8.   I:   And that means that the pressure is low.
9.   AL:  Oh, I thought the pressure was high.
10.  I:   How do we explain this?
11.  AL:  It looks like the pressure is 17. ((Pointing at the
12.       right chamber))
13.  I:   It is 17.
14.  A:   The pressure is constant all the time, right?
15.  I:   Yeah.
16.  R:   The pressure is the same.
```

AL: The higher the pressure, the higher the temperature, right?
A: The higher the pressure-
AL: The pressure is much higher.

The students were able to connect this concept to Model 1. In line 6, Ingrid pointed to how energy is released in the right chamber, because of the droplets that were made visible in the model. This indicated that it turned into fluid. However, in lines 8 and 9, Ingrid and Ahmed disagreed on whether the pressure decreased or increased. Here, with regard to this particular aspect of the model, the third concept is primarily relevant. What the students found difficult was to infer *when* each concept was relevant for explaining *what.* In line 14, Ahmed noticed that the pressure seemed to be constant, and they all agreed that the pressure was high. This account is mediated by the representation, which says “17 bar” on the right chamber of the figure. Thus, students struggled with the level of description; that is, they were not able to *describe* what the heat pump is, what the various parts are, and what their functions are. They needed to establish this as shared knowledge before they could use concepts to explain the processes involved.

The students also found it difficult to make use of three different concepts to understand one system. In the excerpt below, the valve finally becomes salient for the group. Understanding the functioning of the compressor and the valve is crucial to understanding how the pump works as an energy transformation system.

*Excerpt 8. Connecting concepts to interpret the system*

AL: ((Pointing at an object (a tap) at the bottom end of the figure)) It is probably that one that does it.
I: Yeah, it is gotta be something-
R: [The pressure is probably the same the whole time.]
AL: [That’s probably where the power is coming in.]
I: Because it is that valve that-
AL: It is the one that takes care of the pressure.
I: It is probably that which boils the water. ((Pointing at the tap/valve at the bottom of the figure))
A: First, we gotta figure out if the post it should be used for that one—it should right? Or which of the two should it be used for? ((Pointing at the two chambers of the figure))
AL: It is for both of them.
A: For both of them?
AL: Mm.
A: All right ((Reading his notes)). The boiling point of a fluid decreases when the pressure above the fluid decreases.
R: But none of the pressures are getting higher or lower. They are remaining the same the whole time.
AL: But they are different from one another.
A: We say that this one decreased.
AL: It is like this thing that needs to be pushed.
A: We say that this one is, we say that the pressure has decreased because it is low. It hasn’t really decreased since 5 is constant, but since it is that low, we say it decreased and the boiling point. The law of pressure and boiling point states that the boiling point of a fluid decreases, and we see that here. ((Pointing at the figure))
AL: Mm.
A: It boils at only about 6 degrees Celsius or something.

The students noticed that the valve must do some important work. In lines 1 and 2, Allan made the “tap at the bottom” into a salient feature, but they were not sure what kind of work it did. In line 7, Allan correctly said it “takes care of the pressure,” but then in lines 8 and 9, Ingrid said that it boils the water, which is not aligned with the correct solution to their task. There was some disagreement in the group. Ray claimed in lines 20–21 that the pressure remained constant, but Allan said in line 22 that they are different. Ahmed did not clarify this issue but argued instead that they should say that pressure decreased, even though they did not know the precise reason (lines 25–30). This is a correct account, even though they were not able to explain the exact functioning of the valve. They were unable to make sense of the fact that the valve regulates pressure. This made it difficult for them to articulate how the two chambers are connected to one another to form one energy transformation system. In this sense, the representation did not mediate their meaning-making towards a correct understanding of the pump. It is not necessarily only the science with which the students were struggling; it may also have been the digital and physical objects and their mediating functions in the overall functional system.

*Excerpt 9. Struggling with coordinating concepts*

```
1.   I:   I am sure you can put that stuff in there. It is the
2.        boiling point law as well. ((Pointing at a sheet where
3.        the laws are written down))
4.   AL:  (?)
5.   I:   You can use the boiling point law, too.
6.   AL:  (?) ((Writes))
7.   I:   It is energy. ((Filling in the words while AL is
8.        writing))
9.   AL:  Energy, so then you have to get energy, right?
10.  I:   Yes.
11.  AL:  ((Writes))
12.  I:   ((Reading from the sheet where the laws are written))
13.       When a gas is transformed into a fluid, energy is
14.       released. Energy is released.
15.  AL:  Energy.
16.  AL:  Right, that is what we find here. It is transformed
17.       into a fluid, and energy is
18.       released. ((Moving the cursor onto the right chamber))
```

Here the students moved between the model and their written notes, and these cultural means become available through talk. They were also engaging in writing down their accounts. Allan took a leading role in the developing functional system, and he was writing down and articulating the correct account of how phase transition happens in the heat pump. He did not take up or incorporate into their written account Ingrid’s suggestion (line 5) about using the boiling point concepts. Instead, Allan treated Ingrid’s suggestion about energy (line 7) as salient and incorporated her account into making a more coherent explanation about how phase transition results in transformation into heat energy.

*Excerpt 10. Connecting knowledge and representation part 4*

```
1.   I:   Should we include the main points in (?)
2.   AL:  I’ve got it.
3.   I:   Where is it ((inaudible))?
```

AL: And then I'll set it like this, the lower the pressure,
the lower the boiling point. We can say that it boils
at about 5 degrees C. When the fluid transforms into
gas, energy is generated. Yes, I'm finished with that.

The students were accounting for what was happening in the left chamber; here, the boiling point concept was relevant. Allan articulated this in lines 4–7. When the pressure decreases, the boiling point decreases and the fluid takes energy from the environment and transforms into a gas. Phase transition is also made salient, and they are able to connect the two different concepts to account for energy transformation in the heat pump. This is a correct account of why the fluid starts to boil and transforms. A more scientific use of concepts is emerging in the functional system.

*Excerpt 11. Connecting knowledge and representation part 5*

AL: Look, here it goes down (decreases) right, and then
energy is released, as it is written here. ((Switching
from Figure 1 to 2)) When a gas is transformed into
liquid, energy is released. It is transformed into a
fluid. Energy is released and is turned into heat
inside the house.
I: Heating the water.
AL: And then it moves around and (?) in a cycle like this.
I: It… here it is heated or something. Air is heated.
AL: Then the pressure is lower.
I: Yeah, lower pressure and then heating, yeah, no, it is
(?)
AL: Here, the pressure is high.
I: Yeah, it is warm at least.
AL: Then it is warm, right?
I: Hot air that rises.
AL: And then it should transform into a fluid. Then energy
is released, and then it warms ((the house))

Allan correctly articulated how energy was transformed from gas to liquid in the right chamber and how the pump generated heat using this process (lines 1–6). Allan also introduced the concept of a *cycle* in lines 8–9, which is a sophisticated account of energy transformation. The students did not take up or account for the functioning of the compressor and the valve. Nevertheless, the developing functional system was able to make use of science concepts to explain the workings of the heat pump. They were able to use the three concepts and to see their relevance for explaining various aspects of the energy transformation cycle. Interleaving between different representations mediated this work in that it enabled them to zoom in and out, and thereby to connect the relevant science concepts to the particular feature of the figure.

**The Teacher Is Modeling the Interconnecting Use of Concepts in the Functional System**

The teacher walked around to all the groups as they worked and assessed their accounts. In Excerpt 12, we see that he asked about the differences between the models. He asked an explicit question about the compressor and was given a correct response. He then moved on to the right chamber, where energy is transformed into heat. One of the members in the group came up with the correct explanation. He also came up with a correct account of the functioning of the valve.

Towards the end of the trajectory, the teacher is doing what Braaten & Windschitl (2011, p. 666) term “pressing for explanation.” That is, he asks *how* and *why* questions, and asks students about how concepts relate to the energy transformation system.

*Excerpt 12. Teacher is facilitating the development of a systematic use of concepts*

```
1.   T:   Mm. What is indicated by that level compared to the
2.        previous one?
3.   AL:  It shows these two. ((Pointing at Figure 2))
4.   T:   Mm.
5.   AL:  And that and that one.
6.   T:   Mm, what happens if we try this voice over, no mouse
7.        over.
…
8.   T:   What is it that the compressor does?
9.   AL:  It increases the pressure.
10.  T:   Mm. What happens in that chamber? ((Dragging pointer to
11.       the red part of the figure))
12.  AL:  It is the pressure, that the gas should transform
13.       into fluid and release energy, which in turn heats up
14.       the house.
15.  T:   And why is it transformed into liquid?
16.  AL:  The pressure is high.
17.  T:   Mm, and what about the valve down there at the bottom?
18.  AL:  It releases pressure, so that the pressure decreases,
19.       So that it might boil over here.
20.  T:   Mm, yeah, good. Brilliant. What circulates here, then?
21.  AL:  Hm.
22.  T:   The arrows, what do they illustrate? ((Signify))
23.  AL:  Liquid and gas.
24.  T:   Mm. Okay, it is the same material that circulates. It
25.       is a closed system. It is one substance that travels in
26.       a circle. It is what we call a medium, which is a
27.       substance that can easily change from liquid to gas,
28.       and vice versa. It is what circulates in this system,
29.       and that circuit, that circuit is something else.
30.       ((Pointing at Figure 2))
```

Overall, the students managed to come up with an explanation of the workings of the heat pump. In the conversation with the teacher, Allan demonstrated a sophisticated account of the heat pump as an energy transformation system (lines 12–14 and 18–20), which is acknowledged by the teacher in line 20. What happened here in relation to the developing functional system was that the teacher oriented them to the functioning of the valve and the compressor, thereby making it salient for them. Finally, in lines 24–30, the teacher modeled a more coherent account of phase transition in the heat pump.

*Excerpt 13. Teacher models the use of concepts*

```
1.   A:   What makes them move?
2.   T:   It is the power that we put in. It is the electrical
3.        energy we put into the heat pump. It is not used for
4.        heating because that happens through regulation of the
5.        pressure up and down.
6.   A:   Mm
7.   T:   It is used for regulating the pressure. The compressor
8.        requires power to increase the pressure, right. You
```

remember the bike pump; it took a lot of energy to
compress the air.
A: Yeah.
T: And this is what we use the electrical energy for: to
drive the compressor, to circulate the liquid in the
system.
A: Mm.
T: To adjust the pressure in the valve and stuff like that.
A: Is the pressure what creates the heat?
T: Yes, it is what creates the heat.
A: It is what creates the heat.
T: The pressure increases in the liquid that circulates.
It is on the inside, and the increase in pressure makes
it condensate, which releases heat. And when it gets
out, the pressure decreases, and when the pressure
decreases, you remember from the syringe experiment.
What happened with that?
A: That when we pushed, energy came out.
T: Mm, it started to boil, right?
A: Mm.
T: And when something boils, it requires?
A: Energy.
T: Energy, and it receives that from the air outside.
A: Now I get it.
T: And these two other circuits ((Pointing at figure)), it
is like, they are either, this blue one receives heat
from the outside and into this, let’s call it an
evaporation chamber.
…
T: Because there has to, heat needs to be brought here,
heat needs to be picked up so that it evaporates, and
this transports heat from the evaporation into the
house through pipes in the floor or a device mounted
on the wall.
AL: Mm
T: Mm
I: Yes
T: In a way, this is the main component of the heat pump
device, which is on level three in the animation.
I: ((Bringing forth Figure 3))
T: Right, the two chambers with the valve and the
compressor.

In this final excerpt, the teacher modeled how the concepts could be used to make sense of and explain the workings of the heat pump. He drew together what the students had been saying and articulated it in a more coherent fashion. In and through his account, he modeled a coherent use of science concepts. The teacher also made connections between the experiments they had done previously and the features of the heat pump. This comparison made it easier for the students, and they were able to display an understanding of the relevant connections. This is made evident through their use of agreement tokens. For instance, in lines 6, 11, 15, 28, and 32, Ahmed agreed with the teacher’s accounts. Allan and Ingrid did the same in lines 42 and 44. The teacher engages students in social interaction using concepts as part of causal explanations to describe what happens and how the heat pump works. Through this he also made available to the students an account of what counts as an explanation in this context (Windschitl et al., 2012).

The changing agency in the ZPD is structured in the following manner: The teacher introduces knowledge and provides connections to the world outside of the classroom. The students work on their own to solve problems and to engage in other activities with materials. They try to figure out what is going on. The teacher focuses their attention on what they should treat as salient without providing the answers too easily. Then they work on their own to try to solve their tasks. Gradually, the teacher introduces the relevant knowledge and connects that to what the students have been doing. Finally, the teacher provides the directionality of the development of the system, in that he introduces interpretive frames for the students that make it possible for them to orient to the salient issues, and over time to appropriate the teacher's accounts and to connect the knowledge he introduces to their experiences throughout the trajectory. The distribution of agency within the ZPD as a system changes as the students gradually take a more central role in using concepts as explanatory tools. Still, the teacher performs important functions within the ZPD throughout the trajectory.

**Discussion and Concluding Remarks**

Our analysis shows how students' abilities to participate in evolving functional systems change, and that they are enabled to contribute with more comprehensive and elaborate uses of concepts to explain energy transformation. In and through computer supported inquiry activities, the students have gained concrete experiences, used spontaneous and scientific concepts on their own, and used a set of concepts along with the teacher to explain the workings of a complex energy transformation system. Because of this trajectory of conceptual development, they are able to make sense of what the teacher is saying; it is not abstract and de-contextualized. They are gradually becoming more adept at making use of abstract concepts to make sense of concrete cases (Vygotsky, 1986). Gradually and over time, the teacher has been able to engage students in meaning-making, interpret their responses in terms of his understanding, and model the use of multiple concepts to explain the task. In other words, he is modeling a legitimate way of using concepts as mediational means for explaining (Braaten & Windschitl, 2011).

On a theoretical level, our study contributes to CSCL by utilizing the notion of a functional system as a unit of analysis, and how concepts are made sense of and used within systems. This contributes to our understanding of how the mind emerges as a composite entity made visible in and developed through social interaction. Even though this notion is not novel, applying it to CSCL activities enables us to address the interrelationships between computer support, social support, and science learning – that is, how conceptual development develops as part of complex socio-material configurations. In addition, the notion of the ZPD enables us to explicitly address issues of learning; that is to say, of changing agency within a functional system. Research on support in CSCL settings has mostly pursued a constructivist approach in analyzing how social and material support facilitates collaboration; however, ultimately learning is seen as the individual constructing and refining ideas (Linn & Eylon, 2011). This is perfectly legitimate, but through extending the unit of analysis while retaining a focus on the task to be accomplished, we are able to analyze how particular relationships between elements in a system solve the task. Several sociocultural studies in CSCL have examined teacher-student interactions (Furberg et al., 2013). Mercer, for instance, has identified the functions of teacher actions such as elicitation, reframing, and rephrasing (Mercer, 2000). We are sympathetic to this approach, but we believe it is crucial to treat such functions as part of developing systems. Furthermore, our focus on a trajectory enables us to account for how functions are related sequentially. Consequently, such functions do not make sense in the abstract; they instead get their meaning from how they function within systems and where they occur in a sequence.

Methodologically, our study demonstrates the fruitfulness of combining an ethnographic approach with the use of video. The inclusion of transcripts also serves to corroborate our claims, and it also enables readers to engage more critically with our analysis and findings. In CSCL, studies of support tend to employ either a factoring approach (see Donnelly et al., 2014) or a micro-oriented approach to interaction (Greiffenhagen, 2012; Mercer, 2000). We have demonstrated how a combination of ethnographic description and analysis of interaction enables us to analyze a trajectory of activity on an intermediate level of description. This allows us to address issues of change while retaining an emphasis on detail. A video ethnographic approach thus enables us to focus on the stability and contingency of this composite collective unit of activity (Enyedy & Stevens, 2015).

By combining the notion of functional systems with an interest in changing participation, we make empirical contributions in regard to three issues. First, we address how support works within a functional system. The literature on support tends to take an individualist stance, where the student gradually becomes able to perform a task on his or her own (Wood et al., 1976). By focusing on developing functional systems, we show how the teacher, through the use of particular tools, is able to draw students into a system where successful performance is dependent upon joint activity. Furthermore, we show how support is not something that is erected temporarily and then taken away. Developing students' participation in joint problem-solving is a continuous process of fading and support where the students can gradually exercise more agency. This is in line with the work of van der Pol et al. (van der Pol et al., 2010). Our contribution is to insist that this support is part of a functional system that performs tasks.

Second, we mentioned how research shows that students encounter some difficulties in making sense of multirepresentational learning settings (Van Joolingen et al., 2007). Similarly to Furberg (2016), we also found that students considered it challenging to use a set of concepts to make sense of not one isolated phenomenon, but of a system of processes and outcomes. Rather than simply criticizing students, we showed how the teacher used reformulations to model more coherent uses of concepts in the developing system (Braaten & Windschitl, 2011). Students also experience difficulties with making sense of concepts across materials and representations. Spray cans, syringes, and bicycle pumps are everyday artifacts with specific meanings and functions that are more or less taken for granted by the students. However, in this particular context, they become something else (Jornet & Roth, 2015). They are re-contextualized and offer experiences that the students need to explain in a scientific way. Gradually, the interpretations of the objects are made available to students, and they also make inscriptions of the teachers' accounts for later use. Progressively, they are enabled to connect their abstract knowledge to concrete cases. Similarly to Roschelle, we find that through working with inference-rich and ambiguous materials and representations, students gradually exert more agency in using science concepts (Roschelle, 1992). When relevant knowledge is not simply there in written form, the material and digital artifacts mediate a sustained inquiry into their meanings. Students need to traverse among resources to try to make sense of problems and tasks. The fact that students experience challenges does not have to be a problem. On the contrary, and as we demonstrated, the teacher can use students' problems with using concepts as starting points for instruction (Linn & Eylon, 2011). Still, students need help from the teacher to be able to connect the relevant concept to the particular case. This finding is corroborated by other research in CSCL (Furberg, 2016; Krange & Ludvigsen, 2008).

Third, according to Braaten & Windschitl (2011, p. 665), much of the literature on scientific explanations tends to focus on how teachers can communicate ideas more effectively so that students can more easily absorb them. Our study demonstrates how teachers' communication about science explanations can be more effective as part of shared knowledge construction in social interaction. In and through our analysis we have attempted to study learning as a collective process, and we have demonstrated how the evidence of conceptual learning is an outcome that is demonstrably present in the interaction itself (Enyedy & Stevens, 2015). Still, the students found it particularly challenging to use the concepts as resources for explaining the heat pump. This is a form of relational and systemic thinking that is very demanding. However, this form of reasoning is made available to the students as part of a developing functional system; over time, they are enabled to appropriate a certain way of solving complex science problems. Gillen et al. demonstrated how an interactive whiteboard can provide mediational means for the teacher to create continuity in the students' learning trajectory (Gillen, Littleton, Twiner, Staarman, & Mercer, 2008). In addition, we also found how the teacher can use such means as tools for checking for understanding when going through student products, introduce relevant concepts, and model the use of concepts to explain phenomena. We also found that students' initial interpretations of their experiences using everyday concepts facilitated their use of science concepts as resources for explaining.

In inquiry learning, students find it challenging to make sense of something they do not yet know, using knowledge to which they have not yet been introduced. This is what Bereiter (1985) characterizes as *the learning paradox*, which implies that if "one tries to account for learning by means of mental actions carried out by the learner, then it is necessary to attribute to the learner a prior cognitive structure that is as advanced or complex as the one to be acquired" (p. 202). Our study demonstrates quite clearly that we do not need to attribute any prior advanced cognitive structure as an explanation for student learning. Learning concepts takes place in the ZPD, and the teacher draws the students into the functional system being realized in the classroom. Our study makes visible how complex it is for students to operate within inquiry oriented environments with access to a whole range of digital and material tools. It is very difficult for young people to find their way in this environment and connect the meanings and functions of tools to their task at hand. Having said that, we have also demonstrated how students engage in more sustained inquiry, use concepts as explanatory tools and merge experience based and more abstract knowledge through engaging in these kinds of learning ecologies. Using functional systems as a unit of analysis, that is, as the minimal unit that preserve the characteristics of the whole phenomenon, enabled us to analytically grasp how techno-culture is practiced in science classrooms. In more generic terms, it made us able to show how learning in the computational age is the result of complex interconnections between the human and non-human.

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