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Introduction: How Science Works—and How to Teach It

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The contents of this special issue of *Science & Education* are the offspring of a workshop named *How Science Works and How to Teach It*, which was organized in collaboration with European Society for the History of Science and held at Aarhus University, Denmark, in June 2011.

The purpose of the workshop was to bring together historians and philosophers of science *and* science education researchers to discuss how to improve teaching and learning of how science works in science education. (The term *how science works* was considered appropriately inclusive. For brevity we will also use the more familiar NOS).

The workshop had 30 participants from 12 countries (Cyprus, USA, Brazil, France, Australia, Germany, Italy, Finland, Denmark, Colombia, Spain, and Austria) approximately equally distributed between historians and philosophers on one side, at science educators on the other. There were 21 presentations and additional workshop discussions.

The rationale behind bringing the two groups of expertise together can be stated at two levels: At a pragmatic level, teaching of *how science works* must balance validity in the representations of science with (systemic) educational purposes and perceived meaningfulness on the side of the students. To achieve this both kinds of expertise are clearly necessary. Direct contact between groups should enable a dialogical renegotiation of the balance between elements. At a theoretical level, the workshop rationale relates to forms of knowledge and knowledge-transformations.

We know that there is a large gap between academic knowledge about history and philosophy of science, and the NOS-knowledge enacted and learned in classrooms. Even in the ideal classroom situation one should expect some gap, since knowledge necessarily is transformed as it crosses institutional contexts, from the field of knowledge production (History, Philosophy and Sociology of Science) to the field of reproduction (Science Education). Basil Bernstein (1990) has used the term recontextualization to designate this transformation process, while the French mathematician Yves Chevallard talks about ‘didactical transposition’ (DT) (Chevallard 1985).

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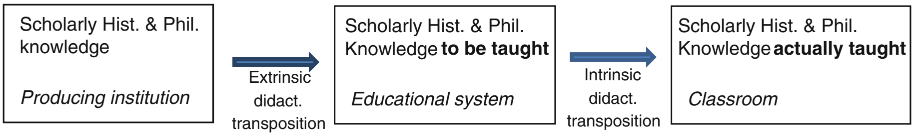
Referring to Chevallard, NOS-knowledge can be described as transformed through a two-stage process:



To Chevallard the essential point is that:

> … scholarly knowledge is nothing other than knowledge used, both to produce new knowledge and to organize the knowledge newly produced into a coherent theoretical assemblage. Teaching is thus faced with a permanent problem. The knowledge to be taught, and every "piece" of knowledge that it comprises, exist only in contexts than cannot be faithfully replicated within school. (Chevallard 1989, p. 9)

Extrinsic DT comprises at least two knowledge transformations that may be interrelated:

- Knowledge must be declared
- Knowledge must be made into a body of knowledge, i.e., into an organized and more or less integrated whole

Bodies of knowledge for teaching have to be recognized and legitimized by the educational system. Educational purposes and priorities may enter the processes upfront, hermeneutically, or as criteria for acceptance/rejection of constructed bodies of knowledge for teaching.

The subsequent intrinsic DT has to be made by teachers (inspired by teacher-educators) implementing the curriculum. At the core of this transformation is teachers' PCK, a notion invented by Shulman precisely to describe distinct transformations of subject matter knowledge into subject matter knowledge for teaching. It includes:

> … the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others. (Shulman 1986, p. 9)

From the perspective of knowledge transformations our joint workshop elaborated on questions like: What happens to knowledge from History and Philosophy of Science when it is it made into a body of knowledge for teaching? How disciplinary/interdisciplinary is such a body? How much can it be declared and decontextualized—and still remain valid? Will other bodies of knowledge be possible or even attractive? What distinguishes a body of knowledge for NOS teaching of science teachers versus a body for students? And, crucial to the teaching/learning process, what kinds of transformations must scientific NOS-knowledge undergo to be learned by and be useful to teachers? What further transformations will enable NOS insights to better be grasped by students?

At the final workshop plenary, where future joint collaboration between the groups of expertise was discussed, the perspectives of knowledge transformation and a recontextualization discourse tended to frame the debate. Looking at the individual contributions to this volume you will find that they address one or more of these issues.

Interestingly, all contributors add to the discussion of what body of NOS-knowledge should be taught? Considering the prominence that general consensus-descriptions of NOS (McComas et al. 1998; Lederman et al. 2002; Osborne et al. 2003) have gained within science education during the last decade, it is surprising that the contributors in various ways all seem to challenge existing consensus lists: Some challenge the very idea and validity of (any) such declarative list (Duschl and Grandy), others more or less explicitly challenge the universal nature and completeness of such lists by introducing discipline-specific elements (van Dijk, Vesterinnen et al., Schumacher et al., Kjeldsen et al., Abd-El-Khalick), while finally one author adds science as communicative practice to the existing lists (Nielsen).

Concerns about validity in the representation of NOS may be seen as the driving force behind several contributions, but also concerns about meaningful student learning are used as justification. The related discussion of the purpose of NOS teaching is briefly touched upon in most of the papers. Reference to scientific literacy as an aim does, however, not clarify things fully here, as scientific literacy comes in flavors: A Vision-I flavor consistent with a cultural argument for NOS, and a Vision-II flavor consistent with a democratic argument for NOS (Roberts 2007). Vision-I oriented NOS calls for more valid representations of scientific culture, than does Vision-II oriented NOS teaching with its emphasis on decision-making and citizenship. So educational aims partly determine to what extent, and in which way, NOS-validity and concerns about scientific authenticity need to be recognized.

Most contributions in this issue hold a position on how NOS can be learned—by teachers and/or by students. Course designs to facilitate NOS learning among teachers tend to take text reading of a more general nature as their point of departure, and only one description uses historical case studies *plus* inquiry to shape the body of NOS knowledge selected. The NOS content is made explicit, and effort is taken to transform this into knowledge for practice through teacher reflection, dialogue, and planning of NOS-oriented teaching sequences. Implicitly, this state of affairs provides a composite answer to the question: *What kinds of transformations must scientific NOS-knowledge undergo to be learned and be useful to teachers?*

Apparently, teachers are considered capable of learning highly decontextualized forms of NOS-knowledge. And while transformations for practical use may be scaffolded within courses they largely remain a job for participating teachers. Since this is known to be a difficult task, a critical question is whether practical NOS-implementation would benefit from teachers being taught in contextualized ways that model and ease practical use in classroom settings. In contrast, but consistent with research recommendations (Bell 2013), the approaches to student NOS learning in this issue are contextual, with NOS knowledge recontextualized to inquiry, model-based practices, historical cases, or socio-scientific issues. Again, the explicit-reflective characteristics seem to apply, however, in one article the term 'explicit' is ascribed a new and potentially disturbing meaning (Duschl and Grandy).

Remarkably little is known about the *relative* effectiveness of various interventions and recontextualizations at the levels of teachers and of students, respectively (Lederman 2007, p.870). However important such issues are, they are complicated by the fact that effectiveness is closely related to the intended outcome such as learning objectives. At the level of teachers it makes a lot of difference whether declarative teacher knowledge of NOS or teacher capacity to enact NOS-teaching competently is used as a criteria for success. Correspondingly, at the student level, curricular aims like declarative knowing of NOS, NOS-informed decision-making, or ability to participate in science-related practices (model-based, discursive, inquiry-based) are distinctly different outcomes, and must be assessed differently. And probably each will give preference to learning through particular recontextualizations.

And now brief introductions to the individual contributions to this issue.

In the opening paper, *Nielsen* reminds us how important communication is in all areas of scientific work. In fact he insists that knowledge and language (or rather the use of language) are intertwined in the sense that language is more than just the stuff that we use to wrap our knowledge in. Without communicative endeavors, communicative tools, and communicative strategies there would simply be no science. Language is not a neutral tool of observation, but an enabling technology for knowledge-making.

As particular relevant to science teaching, he stresses how scientific practice often is aimed at persuasion. All knowledge is somehow shared, and knowledge-making requires participation and collaboration. So knowledge demands communication, and we (or the teachers) need to recognize the role of rhetoric in knowledge production and knowledge communication. To sum up:

> The meaning of scientific knowledge is not only established by its internal qualities or the method by which it has been produced, it also depends on what other scientists make of it, that is, how scientific knowledge is being communicated.

Nielsen does not insist, however, that communication can take over the role within NOS traditionally ascribed to epistemology, but wants to supplement an epistemological view with an approach that incorporates communicative aspects of scientific practice. Communicative dimensions of science should be made explicit parts of NOS-curricula, instruction, and assessment. He discusses two different strategies for incorporating such dimensions into an existing list of seven NOS-tenets (Lederman 2007): As a first strategy he simply suggests to add an eighth communication component, '*Science is a mode of communication that enables and sustains knowledge in certain ways*'. As an alternative strategy to this he suggests to integrate communicative aspects with each of the seven items on the Lederman list.

In a highly condensed last paragraph Nielsen outlines learning objectives and reflections related to teaching and assessing science as communicative practice. Communication amongst students is seen as constitutive for the targeted NOS-outcomes, indicating a combination of explicit and practice-embedding approaches to the teaching.

Abd-El-Khalick starts by observing that for many years the two goals of improving students' NOS understanding and letting students engage in 'authentic' scientific work have lived side by side in a long declared, but never consummated, marriage. For example, research clearly indicates that the two objectives of informing students about NOS and letting them experience inquiry learning do not automatically support each other, and learning about NOS cannot be anticipated as a side effect of science content or science method classes.

Drawing on his previous work, he underlines that dealing with inquiry or HPS in the classroom is in itself not sufficient to achieve NOS-learning. In order to accomplish learning objectives like informed epistemological understandings about generation and validation of scientific knowledge—in order to teach about NOS—the teacher must work with an explicit and reflective framework and can, among other approaches, draw on historical case studies, authentic scientific practice, or inquiry-based contexts. An important aspect of scientific knowledge is its group based or social character. Abd-El-Khalick stresses this social side of NOS and corroborates the previous paper when he notes that often the communicative dimension of science—pertaining to the production and validation of knowledge—is ignored in classrooms.

There is a need to make NOS instruction an integrated and meaningful component of science teaching. The answer to this challenge, says Abd-El-Khalick, is to let teachers develop ‘deep, robust and integrated’ understandings of NOS and let them teach science in such ways that NOS becomes more than an ‘add on’, but is integrated and supports the learning of concepts and theories.

He further argues that teachers who have such knowledge of NOS are better positioned to develop their teaching and teach *with* NOS in an epistemologically and methodologically informed way. They are more likely to avoid some of the pitfalls that traditionally restrict teachers and thus enforce students’ naive views of NOS. They are, for example, better positioned to enact authentic inquiry learning environments in their classrooms, or to teach induction or theory choice in an epistemologically sophisticated manner. Abd-El-Khalick refers directly to philosophy of science (Popper’s deliberately absurd instruction to, ‘go observe’ and the Duhem-Quine problem of the under-determination of scientific theories) to illustrate how NOS-knowledge can help the teacher address students’ underlying epistemological commitments in an explicit manner.

Abd-El-Khalick goes on to discuss the necessary and sufficient teacher knowledge domains for teaching about and with NOS. Drawing on an intervention study by Wahbeh (2009) with highly NOS-motivated veteran teachers, he establishes a model where NOS-understandings overlap with science content understandings and pedagogical knowledge of student-centered inquiry. As part of the model, NOS-knowledge is divided into heuristic/general and domain-specific understandings. The empirical study indicated that knowledge of domain-specific/content specific NOS understandings as well as narratives or recontextualizations that integrate historical, philosophical, sociological etc. aspects of science were crucial when teachers were to transfer domain general understandings into classroom practice.

Again this raises the question of what kinds of NOS recontextualizations will be most useful for teachers to engage with at teacher training courses, heuristic and/or narrative and contextual? Abd-El-Khalick finally introduces NOS-PCK and discusses how best to go about developing it. His recommendation is carefully planned on-site interventions, coupled with long-term communication and support by researchers and teacher educators to help teachers translate:

> In other words, cycles of classroom implementations, followed by structured reflection and refinement of the sort that Shulman (1986, 1987) suggested for the growth of teachers’ PCK would be needed for the development of science teachers’ NOS PCK.

Dushl and Grandy open by giving a survey of the post WW2 development of thinking about the nature of science and science education in the light of developments in philosophy of science and in learning psychology. Recent developments in philosophy and cognitive science must be taken into account. NOS characterizations must be shifted away from general heuristic principles towards cognitive and social elements, and the authors are concerned about the effects that dated ideas about NOS may have on curriculum, instruction, and assessment. They note with approval how emphasis in policy papers has shifted away from teaching ‘what we know’ (facts and skills) to focus on ‘how we know’. The authors also recognize this shift in the most recent US recommendations for science teaching with its emphasis on science practice (NRC 2012).

Two alternative approaches to thinking about NOS and going about NOS-teaching at pre-college level are presented and discussed. A *version 1* based on ‘Consensus-based Heuristic Principles’ which is tied to the view of science developed by philosophers like Kuhn, Lakatos, and Laudan (the historical turn in philosophy of science) and presenting a rational reconstruction of scientific development and growth of knowledge. Opposed to this, and advocated strongly by the authors, is a *version 2* based on involving students in

'Building and Refining Model-Based Scientific Practices' including class based peer-to-peer critique and communication enacted in longer immersion units and learning progressions. This second version takes heed of recent developments in philosophy of science (the naturalistic turn) and in learning theory. Both tend to emphasize notions of epistemic and discursive practice. Consequently, the authors' advice is to design and enact school science (K-16) in accordance with authentic science practices. Importantly, in this view NOS is seen as seamless with scientific inquiry and the two cannot really be separated. Core science practices are explicated: Building of models, data collection and data analysis, construction of arguments, and communication of claims and arguments (talking, writing, representing). Once again the importance of communication, accentuated by Nielsen, is touched upon. Teaching should strive at making it clear how we develop scientific knowledge and why we favor such knowledge above other claims.

The implementation of the second version is contingent on the teachers' possibility of planning long sequenced units mixing the teaching of scientific concepts, of NOS, and the immersion in scientific epistemic and social practice. In such a combination, NOS becomes domain specific, and the domain general consensus list principles can no longer guide the teaching. To the authors, explicit teaching of NOS takes on a new meaning as engaging students with science-like practices in extended curriculum units. The practice based NOS view is elaborated in relation to research studies by Metz (2004), (Smith et al. 2000) and Lehrer and Schauble (2012).

Van Dijk also refers explicitly to modern philosophy of science when considering what NOS is and the conditions for teaching it. She finds that there is at present no general characterization of the nature of science, and questions whether such a characterization will ever be achieved. She suggests replacing flawed unitary conceptions of science with descriptions in terms of the family resemblance concept. She calls for:

> …a more representative portrayal of the nature of science within science education, that takes more fully into account the view that science is disunified in the sense that there is probably no such thing as a singular nature shared by all fields of science at all times.

However, the call for valid representations is balanced with concerns about meaningful student learning, explicated through her aim of students' functional Vision-II scientific literacy.

In the light of this she recommends that NOS be taught as cased based treatments of socio-scientific issues. Because science has no singular nature, the cases and what they illustrate about science must come out of specific situations or issues related to specific disciplines. I her paper van Dijk presents an exemplary case study about biodiversity conservation related to the field of Conservation Biology. The case launches textbook analysis as the primary source for identification of (NOS) features of Conservation Biology that are also relevant for people's critical engagement with socio-scientific issues. These features are elaborated and demonstrated through a context rich description of debates within related scientific communities (conservationists vs ecologists) about a remarkable Biodiversity report from 1999.

Conservation biology is explicitly value-laden, and the analysis identifies particular features of this value-ladenness as essential disciplinary characteristics. One important driving motive characterizing the entire discipline is the need to preserve biodiversity, in particular endangered species. In conservation biology it appears to be outside of discussion that nature has an intrinsic moral and esthetical value, and preservation is the ultimate goal for the scientific work.

Ecologists, approaching nature and nature's preservation from a different tradition, have attacked this view, claiming that such predetermined scientific goals endanger the struggle in science for objectivity in conclusions. Ecologists hold rather different views on biodiversity and why and how it should be sustained and on a number of other issues, so the disparity is not only in realm of values but also concerns interpretation of data and scientific claims. Conservationists have retaliated by claiming that *all* scientists have values (e.g. the strive for objectivity) and include them in their work, but oftentimes the scientist does this unaware of what is going on. In the light of the general view that science ought to be value-free, questions arise about the role of values in science and their potential effects on its trustworthiness. Ecologists claim that the values so cherished by conservationists lead to bad science and, worse, may put the entire reputation of science as a provider of reliable knowledge at stake in society.

To achieve functional scientific literacy, it is necessary to help students dismantle the naïve view that science is objective and value free, and give the more realistic impression that objectivity is not an all or nothing thing. There are degrees of objectivity. Contemporary cases, e.g. recontextualizing narratives of recent debates within scientific communities may be one fruitful way of making discipline-specific NOS-insights available to students. However promising this approach seems, Van Dijk acknowledges the need for creating a framework that can be used to organize case-based NOS-learning.

Different values, affiliated to members of distinctive scientific disciplines, also have a role in the paper by *Kjeldsen and Blomhøj* about mathematical modeling in different scientific practices. A historical case is built around Nicholas Rachevsky's model of cell division. In 1934 Rachevsky, a physicist, gave a talk in front of a group of biologists and presented a 'physico-mathematical' model of cell division. Later this event has been hailed as the start of mathematical biology, but in 1943 the biologist were highly critical, questioning the validity of the model itself and criticizing Rachevsky's thinking and the nature of his arguments and his (mis)understanding of an explanation.

This historical episode has been translated into teaching and used by the authors to develop undergraduate university students' reflections about the function and status of mathematical modeling in different scientific settings: That the explanatory power of a model is linked not only to the context of its use, but also to the underlying philosophical and theoretical position held by the modeler(s) and the scientists discussing the model's use and validity.

The authors briefly take up discussions of case relevant problems like how to use historical cases in a math teaching context, including criteria for selecting historical cases. Discussing how methodologically "correct" teachers should work, they conclude that it is too restrictive to require that only a strict scholarly approach to history is legitimate when history is used in the math classroom.

The Rachevsky case was tested in a teaching sequence involving four third semester university students. The sequence was a success and the NOS learning goals set up on beforehand were fulfilled. The students came to see how theoretical and philosophical differences between scientific cultures translate into more technical differences like how to construct, evaluate and interpret models, and the students reportedly had to rethink ideas acquired in high school about the existence of a standard scientific method. The technical level of the mathematics involved was moderate and the authors estimate that the case can also be used in upper secondary school. They find that historical cases often are better suited for explicit teaching of particular NOS-ideas than contemporary cases. Partly because contemporary disagreements between opposing scientists often are played out at a conceptually and technically inaccessible level, partly because historical cases are 'closed' and therefore more easily focused by the teacher and in general are more manageable in the classroom.

Teaching of NOS may not really gain foothold at the various levels of the educational system before teachers are more adequately educated in teaching NOS. Thus the introduction of NOS into teacher education is essential. Two of the papers included deal with pre-service training of chemistry teachers in Germany and Finland respectively.

In Germany the federal standards for science education spell out that students must acquire competences in areas like 'the application of epistemological and methodological knowledge', 'communication', and 'judgment', the latter comprising the ability to develop arguments and make decisions. The challenge of educating teachers who can adequately teach towards such goals is discussed by *Schumacher and Reiners*, and they report on a first step towards developing a teaching module for pre-service chemistry teachers, which has been tested and evaluated in the context of teacher education at a university chemistry department in Cologne. A fully developed course is to be incorporated into a new bachelor/master program. As a basis for course design, chemistry specific NOS-features had been established through readings from history and philosophy of chemistry. The idea was to introduce these 'criteria' to teacher students, and engage them with using the principles in design of authentic inquiry for high-school students. Chemistry NOS was introduced by text-reading of a more general kind, but this was supplemented with a series of talks by research chemists. Here impressions of the lives of real chemists were recontextualized. Overall an explicit-reflective approach was used. The course component with design and enactment of authentic inquiry activities with high-school students was intended to help teacher students transform the more general NOS criteria.

Focus in the evaluation was on how the students' preconceptions of NOS changed during the activities, and what kind of ideas and problems the students had in connection with transforming their NOS-knowledge into classroom practice. The research tools used to map the students' development were partly developed in connection with the course and are presented and discussed prior to a presentation of the findings, which are summarized, '*all participants changed their preconceptions in the sense of correcting, broadening or concreting their own views*, …'. For the more practical part of the course, the student teachers planned and conducted an out-of-school lab-day for a high-school class, having 'A chemical winter day' as a framing theme. Interviews and portfolios were used to inquire into the student teachers' perceived difficulties during practical transformation. More than half of the novice teachers found it difficult to transform the general NOS criteria, and difficulties related to lack of knowledge of adequate experiments and lack of experience/knowledge of pedagogic strategies for student centered inquiry were prevalent. This resonates highly with the model of necessary and sufficient teacher knowledge presented by Abd-El-Khalick in this issue.

The work on developing a full course continues and the results from the present study will be incorporated:

> further courses should focus on more reflections on inquiry-based laboratories. The courses should allow teacher students to reflect about the involved processes and structures as well as about possibilities to use scientific inquiry as a context to embed characteristics of authentic chemistry into school lessons.

Also *Vesterinen and Aksela* work on developing a pre-service course that will enable future chemistry teachers to teach NOS. The course, intended for master level, has been optimized through an educational design research methodology approach with two four-stage development cycles—problem analysis, design, implementation, and evaluation.

Two challenges were addressed: First central dimensions of domain specific NOS for chemistry education were identified as core content for the course. The aim here was to challenge the naïve views of the student teachers concerning how science operates in a way that enabled the participants to appropriate the new knowledge. Here the authors looked for explicit and reflective approaches. Secondly the course design should help student teachers translating NOS-knowledge into classroom practice. This challenge implies helping novice (NOS-) teachers to develop NOS-PCK. Reflective writings, peer discussions, and lesson planning assignments were used for the purpose and each played an important role in the learning cycle applied.

According to the evaluation, the course gave the participants new perspectives on chemistry, and a new conceptual framework for thinking and talking about scientific research. Different models and theories of chemistry emerged more coherent. Not everything learned through the course could be transformed into secondary school instruction, but even non-transformable knowledge was seen by the participants as useful as part of general knowledge or as a general resource for teaching. Also the ethics of teaching and understanding why it is important to teach NOS plays a part:

> results thus support the notions that there has to be resonance between the teachers' understanding of NOS and their beliefs of teaching science … and discussing the reasons and justifications for science education can support such resonance.

Four participant case stories are presented. They demonstrate how learning outcomes are mediated by not only teacher beliefs, but also teaching experience, NOS self-efficacy, practice embedding and related mentor feedback, as well as 'traditionalist' school cultures. Some participants with minimal teaching experience abstained from trying out the classroom assignments which they planned during the course, and altogether the challenge of actually teaching NOS in the face of low self-efficacy was obvious. For novice (NOS-)teachers, internalizing the importance of NOS as a valued instructional outcome is a beginning, but it is not enough, and does not necessarily translate into teaching NOS effectively. The teachers also need robust pedagogical content knowledge to translate their NOS ideas into practice and to 'talk comfortably about NOS issues, lead discussions, respond quickly and appropriately to questions, clarify misconceptions, provide good examples, and so on'.

In the next cycle of the course the plan is to add even more reflection on NOS concepts and, in particular, on the way school science cultures interact with the possibilities for change in teacher behavior. And to focus more on the transition to enactments in the classroom. It will be necessary to 'consider alternatives by contextualizing practice within theory and theory within practice'.

The paper by *Koponen and Huttunen* deals indirectly with NOS by examining how scientific concepts—in this case electric current and voltage—develop during learning, and how the learning interacts with the teaching. In the understanding of electricity the two concepts are often poorly differentiated and the variety of students' (mis)conceptions 'seem endless'. The study concentrates on concept development at an advanced level (upper secondary school level or first year university) and builds on interviews with initially 18 upper secondary students of which 9 were selected for closer scrutiny.

The authors provide a new theoretical framework to discuss situations where closely related concepts are learned and conceptual development takes place at a level where the learners' conceptions take on a scientific character and begin to form at basis for explanations and predictions. They look at changes in the students' hypothesis used to explain simple DC-circuits, the causal schemes employed, and the characterizing attributes associated with the concepts of current and voltage.

The new idea of concept development in learning is based on a view of 'knowledge-as-system'. It incorporates aspects from the notion of 'knowledge-as-elements' as well as from the 'knowledge as-theory' ideas, and provides a dynamic picture of how knowledge in smaller and incoherent pieces develops toward more coherent conceptual structures. When a concept changes during learning, it is the connections between the elements involved in the concept construction that change, not the elements themselves.

The findings in the nine student-cases are explained on the basis of this new description and interpretation of concept development. The most important factors determining conceptual development at this level are found to be coherence (if observed phenomena reveal an incoherence in the knowledge-system, adjustments are made by the learner to increase coherence), causality (important for learning physics since incorrectly conceived causal relations seem to underlie many learning difficulties), and utility. There seems to be a balance between utility and coherence since simple—and not so coherent—concept constructs are preferred in simple situations where they have high utility.

Letting the students face problems of increasing complexity is a driver for conceptual development. When students are assigned to simple learning tasks, many pieces of their initial knowledge fit together poorly or loosely, meaning that the pieces are fragmented and incoherent:

> When situations become more complex and opportunities arise to compare the plausibility and mutual support/non-support of a hypothesis, students re-structure and re-organise their knowledge and more coherent clusters of knowledge begin to emerge. Such a re-structuring or re-organisation is strongly guided by causal knowledge.

Conceptual change is also coupled to understandings of the ontology of the phenomena studied. Initially most students embraced a view of current and voltage as 'substances', but during the learning process, they changed to more process-like understandings. However, it also appeared that students can hold 'parallel' and conflicting ontological view simultaneously and shift between them on the basis of their utility.

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