Analytical tools in engineering education research: The "learning a complex concept" model, threshold concepts and key concepts in understanding and designing for student learning.

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Abstract*: For a long time, most research relating to science and engineering education has examined "misconceptions" about "single concepts", despite the fact that one common objective in many subjects is "to learn relationships". In this paper we introduce the notion of "a complex concept", i.e. the idea of describing knowledge as a complex, a holistic unit, consisting of interdependent and interrelated "single concepts". We describe how this conception could be used to identify both problems associated with learning as well potentials for learning. We will also relate the notion of a complex concept to the notion of threshold and key concepts.*

Introduction

In recent years there has been increasing research into the critical factors associated with learning within engineering education; indeed, the engineering education research (EER) field has started to mature (cf. Baillie & Bernhard, 2009; Borrego & Bernhard, 2011). Within EER there has been little explicit discussion of the issue of methodology (cf. Case & Light, 2011). Any such discussion should be closely intertwined with theoretical perspectives and the selected epistemology. As succinctly stated by Marton and Pang (2008, p. 543), we must start with the questions *why?* and *what?* (e.g. Borrego & Bernhard, 2011; Melezinek, 1977) and "first of all, [ask] what kind of capability do we want [students] to nurture?" In both engineering and physics education, a common objective is that students should *learn* to *use* theories and models in order to understand the *relationship* between theories and models, and objects and events, and to develop holistic, conceptual knowledge. Engineering students are expected to *use*, or *learn to use*, symbolic and physical tools (such as concepts, theories, models, representations, inscriptions, mathematics, instruments and devices) in order both to understand the phenomena being studied, and to develop the skills and abilities to use the tools themselves to solve real-world engineering problems. Rorty's (1991) statement that knowledge is not "a matter of getting reality right, but a matter of acquiring habits of action for coping with reality" and Marton and co-worker's statement that knowledge is a "capability of handling novel situations in powerful ways" (Marton, Runesson, & Tsui, 2004, p. 5) quite accurately describe important aims associated with engineering students' learning.

However, EER has been inspired by longer-established research traditions, such as science education research (cf. Fensham, 2004). But engineering epistemology differs from that of science as noted, for example, by Henryk Skolimowski (1966): "science concerns itself with what *is*, technology with what *is to be*" (p. 375, italics in the original). Hence there are differences in epistemology and consequently in the *object of learning* (Runesson & Marton, 2002) that should be reflected in the methodologies used in EER (cf. González Sampayo, 2006). A necessary condition for learning, as noted by Ference Marton and his co-workers (Marton & Booth, 1997; Marton & Tsui, 2004), is that students must be able to focus on the 'object of learning' and discern its critical features. They note that the 'object of learning' is not a 'thing', but a set of relationships, concepts, theories, capabilities etc., that the students are supposed to learn (the intended object of learning). The critical aspects of the object of learning must enter the focal awareness of students. In their work they also pointed out that

> "people act … in relation to situations as they perceive, experience, and understand them. … If we want learners to develop certain capabilities, we must make it possible for them to develop a certain way of seeing or experiencing. Consequently, arranging for learning implies arranging for developing learners' ways of seeing or experiencing, i.e., developing the eyes through which the world is perceived" (Marton, et al., 2004).

Hence, the development of capabilities (cf. Bowden, 2004) is important in engineering education. To achieve this requires developing "learners' ways of seeing and experiencing" and following, for example, Dewey (1925/1981, 1938/1986) and Wells (2008), whose concepts should be considered to be "…tools for making sense of the world around us, or tools 'to see with'" (Marton & Pang, 2008, p. 543). Students and experienced engineers use artefacts, i.e. symbolic tools (concepts) as well as physical tools, to "see with" (Bernhard, in press).

The "learning of a complex concept"

The model

In education research, for example in science education research, it is common to investigate "misconceptions" about "single concepts". However, when we analysed engineering students' learning during a course on electric circuit theory, we found that examining student learning in terms of "single concepts" was not sufficient. As a result, the notion that learning should be seen as the *learning of a complex concept*, i.e. a "concept" that makes up a holistic system of "single" interrelated "concepts" (a *whole* made up of interrelated *parts*) emerged (e.g. Bernhard, Carstensen, & Holmberg, 2010; Carstensen & Bernhard, 2004, 2008; Carstensen, Degerman, & Bernhard, 2005). Below we introduce the ideas behind our model of learning as the "learning of a complex concept" and demonstrate some of the power of this analytical tool.

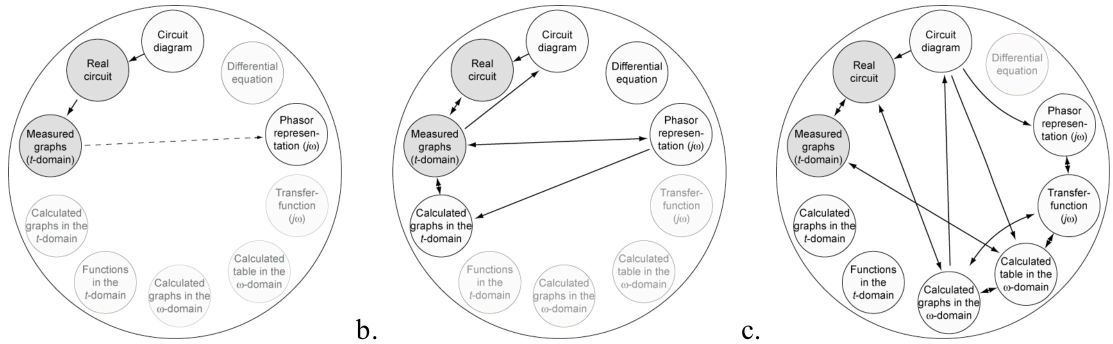
In our model "single concepts" are illustrated as nodes or "islands" that may be connected by links, while the links students actually make (identified by analysing the experienced object of learning, i.e. what students actually learn, using empirical data such as video-recordings), or are supposed to make (identified by analysing the intended object of learning), are represented by arrows. The nodes in our model can be found empirically, by looking for "gaps" (Wickman, 2004) in the actions and dialogue of students. A gap corresponds to a link that has not been established, and when a gap is filled and the students establish a relationship between two nodes, this is represented by a link (a generalised version of the model is presented in figure 1b). This methodology is a further development of Wickman's (2004) practical epistemologies, which were based on Wittgenstein's (1953/2003) philosophy of language.

The idea behind our model is that *knowledge is holistic*. Knowledge is built by learning the component pieces, the islands, as well as by learning the whole object of learning through making explicit links. Hence, the more links that are made, the more complete the knowledge becomes. It is important to note that we have analysed the *use* of concepts, models, representations and experimental equipment (cf. Airey & Linder, 2009; Wells, 2008). Hence, we did not study, or attempt to draw any conclusions about students' eventual mental models. We studied what students *do*.

This study is part of a larger piece of research (Bernhard, 2010). We have, over several academic years, studied laboratory work carried out during a first year university level course in electric circuit theory for engineering students (Carstensen & Bernhard, 2004, 2007, 2008, 2009). Using digital camcorders, students' courses of action have been recorded. In this study we present an analysis of the course of actions of one laboratory group (two male engineering students) in two 4 h lab sessions on electric circuit theory. For this, we use the analysis model briefly presented above. The lab sessions analysed both concerned AC-electricity. The topic of the first was learning to use phasors (the *jω*-method) in analysing and representing currents and voltages in AC-circuits. The topic of the second lab was analysing the frequency dependency of currents and voltages in AC-circuits and representing these using transfer functions and Bode plots. The results from these two AC-electricity labs are compared with the results from a 2×4 h lab sequence, from the same course and year, the topic of which was transient response (Carstensen & Bernhard, 2004, 2007, 2008, 2009; Carstensen, Degerman, González Sampayo, & Bernhard, 2005).

Results

In figure 1 we present an analysis of the courses of action of two male engineering students' (Adam and David) in the AC-electricity laboratory sessions. The situation 29 minutes into the session is presented in figure 1 a. Adam and David have established links (although only uni-directional) between the *circuit diagram*, *real circuit* and *measured graphs (time-domain)*. The students are about to establish the link between *measured graphs (time-domain)* and the complex-valued *phasor representation*.



a. b. c.

Figure 1: For analytical purposes, the shaded circles are attributed to the object/event world and the unshaded circles represent the theory/model world (Tiberghien, 1998; Vince & Tiberghien, 2002). Established links are represented by a solid black arrow and those in the process of being established by a dashed arrow. The "single concepts" that the students have become aware of are represented by black circles and those that they have not by grey circles. a) An analysis of student learning in the first AC-electricity lab. The figure shows Adam and David's *lived object of learning* 29 minutes into the session. b) Adam and David's *lived object of learning* at the end of the AC-electricity lab. c) Adam and David's *lived object of learning* at the end of the frequency dependency lab.

During the next 10 minutes the students struggle with this link and it is not fully established until 42 minutes into the session. The links that Adam and David have identified and the "single concepts" that have appeared after 4 h are presented in figure 1 b. It should be noted that *differential equation* has appeared as a "single concept" but no links to this concept have been made. Also it is noteworthy that, although the students were asked to establish links to *functions in the time-domain*, at this stage it does not even appear as an isolated "single concept" in our data.

In the frequency dependency lab, the picture is more complex. In this lab students are supposed to use concepts and representations related to the time-domain as well as the frequency-domain. Several links have been established by the end of the lab, as displayed in figure 1 c. Although *calculated graphs in the time domain* and *functions in the time-domain* do appear as "single concepts" no links have been made, nor have there been any attempts to make such links. The reason for this, and the similar result with respect to *functions in the time-domain* in figures 1 a–b, is that Adam and David did not follow the instructions provided and decided that they could do this later at home.

An analysis of the *lived object of learning* at the end of the later lab about transient response showed that the "single concepts" *circuit diagram* and *real circuit* presented in figures 1 a–c had fused into a single *real circuit* "concept" (Bernhard, et al., 2010; Carstensen & Bernhard, 2008, 2009). The initiation of this fusion process was already apparent during the previous sessions. In our analysis of the videotapes we noted that, during the first AC-electricity lab, the "gap" between the *circuit diagram* and the *real circuit* became less and less apparent as the session went on. In the frequency dependency lab, the fusion process had gone so far that, on many occasions, it was difficult, in our analysis of students' courses of actions, to determine if links were being made to the *circuit diagram* or the *real circuit*. Our interpretation of this process of fusion is discussed further below.

Discussion

Our studies show the feasibility of using the model of *learning a complex concept* as an analytical tool in studying student learning in labs. The model facilitates analysis of longer sequences of video-recordings that would otherwise be difficult to summarise and overview. It should be noted that the model is circular, not hierarchical (as most models are), allowing linking across the circle. The model *learning a complex concept* reveals and illustrates the complexity of knowledge.

In contrast, it is common in education research to investigate "misconceptions" about "single concepts". In our view this is problematic since these "single concepts" do not, in fact, exist in isolation. In electric circuit theory, for example, the "concepts" of current, voltage and impedance are interdependent. Rather, the central physical phenomenon is "electricity" represented by a generalised Ohms law, which models the current/voltage/ impedance/frequency-relationship of a circuit or circuit element. In the thesis of M. Holmberg (González Sampayo, 2006) it was argued that some problems associated with learning electric circuit theory may be due to the common failure to appreciate that concepts should be seen as relationships.

Our results suggest that it is not sufficient to discuss knowledge as a dichotomy between theoretical knowledge and knowledge of the "real world". The result that the *measured graph*, *calculated graph* and the *time-function* (see figures 1 a–c) were seen, by students, as separate "entities" was found empirically in our data. For an expert in the field these "entities" would in most cases be fused into one "entity". However, for the students the links between these "entities" were among the most difficult to establish. In our observations we found that the *circuit diagram* and the *real circuit* became fused into a single common entity. This suggests that learning a complex concept starts by establishing more and more links. As links become well established, "entities" that have been separate fuse into a whole. Our model provides a method for identifying "learning difficulties", since these correspond to "gaps" and non-established links. As teachers and experts in a field, we often fail to notice these since, for us, the 'complex concept' has become a conceptual whole and we may no longer be able to distinguish the constituent parts. Another conclusion is that it is not sufficient to discuss knowledge in terms of a dichotomy between knowing and not knowing.

N. Bohr (1958) suggested that we should use the word "*phenomenon* exclusively to refer to the observations obtained under specified circumstances, including an account of the whole experimental arrangement" and he also argued that "it is … impossible to distinguish sharply between the phenomena themselves and their conscious perception". The model of *learning a complex concept* describes how students *use* different *tools*, physical as well as conceptual, "to see with" and with which to make sense of the world. Thus our model represents what is called a *material-discursive practice* by Barad (2007) and *material hermeneutics* by Ihde (2009).

Threshold concepts and key concepts

Previously, we proposed the idea of *key concepts* – concepts that constitute a "bridge to the learning of other concepts" (Carstensen & Bernhard, 2002, 2008). Closely related to our ideas of key and complex concepts is the newly emergent theory of *threshold concepts*. A threshold concept represents a transformed way of understanding something without which the learner cannot progress. It entails a shift in learner subjectivity and makes possible extended use of the relevant discourse. Threshold concepts are, according to Meyer and Land (Land, Meyer, & Smith, 2008; Meyer, & Land, 2006), *transformative*, *irreversible* and *integrative*. According to Meyer and Land (2006) the "*integrative* [aspect of threshold concepts] … exposes … interrelatedness of something". The idea behind the notion of a complex concept is to re-present the interrelatedness of "single concepts", i.e. to re-present a conceptual whole. Thus "threshold concepts" and "complex concepts" have some similar features.

Threshold concepts are of special importance, since a deep understanding of them is necessary to facilitate learning other concepts. Examples previously investigated include *recursive functions* in computer engineering (Booth, 2004), and *opportunity cost* in economics (Davies, 2006). Both of these are difficult to learn, and if they are not understood thoroughly, they will hinder students understanding of subsequent topics. In our research we found 'transient response' to be a threshold concept (Carstensen & Bernhard, 2008), but we also identified the importance of 'critical aspects', aspects that must vary systematically, through variation theory (Marton & Tsui, 2004). Previously, therefore, we suggested a distinction between 'threshold concepts and 'key concepts' (Carstensen & Bernhard, 2002, 2008), not in the sense that the term is often used in educational contexts, as being interchangeable with 'core' concepts, and meaning simply that the concepts are an important part of the prescribed syllabus. We use the term as a more precise metaphor to mean that the concept in question acts like a key to *unlock* the 'portal' of understanding, the 'portal' which opens up to allow learning other concepts.

Conclusion

Our model, 'the model of learning a complex concept', can be used in three different ways: first, to identify what is troublesome for the students when they are learning; second, to find out what needs to be changed in order facilitate learning; and third, to identify changes in students' actions.

New analytical tools for use in research allow us to see things in a new way. We consider that the notions of learning *complex concepts*, *threshold concepts* and *key concepts* are important theoretical and methodological tools in engineering education research, reflecting the skills that engineering students are supposed to learn. We consider that the EER-community should not only import research tools and methodologies from other branches of educational research but also start to develop methodologies of its own that are related specifically to engineering learning. A further development and integration of these (and other) tools would be valuable as part of a critical discussion and further evolution of EER methodologies. This paper is just *one* contribution to this.

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