

ANNA-KARIN CARSTENSEN AND JONTE BERNHARD

## **THRESHOLD CONCEPTS AND KEYS TO THE PORTAL OF UNDERSTANDING**

*Some Examples from Electrical Engineering*

### INTRODUCTION

For many years research into science education has dealt with misconceptions about single concepts, even though one of the common objectives in physics is to develop an understanding of the relationships. Research into threshold concepts examines related ideas, and is thus opening up a new dimension of our understanding. In our own research we have been examining what we call ‘complex concepts’, i.e. concepts that make up a holistic system of ‘single’ interrelated concepts.

In the field of electrical circuits there has been a great deal of research on the understanding of direct current (DC) circuits among pre-university students, but hardly any research on alternating current (AC) circuits. Confusion between concepts such as current, voltage, power and energy has been reported. One possible reason that these are troublesome is that they are highly interdependent, so perhaps they cannot be learned one by one, but have to form an integrated whole.

How then does this relate to research on threshold concepts? How can we recognize threshold concepts? And how can we possibly find a way to approach teaching that facilitates thresholds being crossed?

We suggest that it is necessary to distinguish between ways to identify threshold concepts and ways to identify what needs to be addressed in order to open up learning spaces. We propose to use the term ‘*key*’ *concepts* for those concepts that open up the ‘portal’, but not in the sense that the term is often used in some educational contexts, as interchangeable with ‘core’ concepts, and meaning simply that the concepts are an important part of the prescribed syllabus. Here we use the term as a more precise metaphor to mean that the concept in question acts like a key to *open up* the ‘portal’ of understanding. We try to explore how a threshold concept may be identified. By studying video recordings of lab-work we have been able to propose a way to identify troublesome aspects of any given concept. We describe how variation theory can be used to open up new dimensions in the learning space, thus finding ‘keys’ to open up the portal. We have then been able, again by video recordings, to evaluate the new learning sequence.

RESEARCH REVIEW

*A Pilot Study On Bode Plots*

A troublesome concept, according to teachers who teach electrical circuits and control theory, is frequency response. This can be explored through interviews with teachers and it will generally be agreed that this is a threshold concept. The subject is explained in most textbooks on electric circuits and control theory. In control theory there are two tools that are used to illustrate frequency response: Bode Plots and Nyquist diagrams. Carstensen and Bernhard (2002) suggest that the Bode plot is a 'key' concept (in the specialist sense in which we have indicated above), but the Nyquist diagram is not. Although both are tools that can be used by an engineer, they are not both good tools for learning. Our pilot study (ibid.) shows that a change in the way that Bode Plots are explained not only facilitates students' learning the plots, but also results in them gaining higher scores on a test following the course. The students even get higher scores on tasks that have not been taught; this suggests that teaching a 'key' concept, according to our definition, does not just open up that particular concept, but also the learning of other concepts related to it. This pilot study suggests that further research needs to be carried out in order to investigate what the characteristics of a concept are when it acts in this way like a key. We also suggest that such 'key' concepts deal with more than one semiotic register, as suggested by Tiberghien (2000): 'A hypothesis on learning is that an individual's understanding of a concept (or, more generally, an idea) develops when relations are established between different semiotic registers associated with that idea.'

The concept of Bode Plots is also one where some students are reluctant to make an effort, partly because they know it will be difficult, and will take a lot of time. This hesitation is referred to in the field of threshold concepts as 'troublesome knowledge' (Perkins, 1999). In the pilot study this was explored by making completion of the first Bode Plot compulsory. The plot had to be brought as a 'ticket' to the lecture on frequency response; this is a very unconventional way to make university students 'do the homework'. It resulted in all students completing the task.

The pilot study suggests that to make learning possible it is necessary to incorporate arrangements that make the students engage in the learning activity, in addition to opening up learning spaces. It is not enough to change only the students' engagement, or to develop teaching sequences informed by research; *one must do both*.

*Research on the conceptual understanding of electrical circuits*

Most of the research on students' understanding of electric circuits has focused on the domain of pre-university learners' understanding of DC circuits. According to this body of research (see, for example, Bernhard & Carstensen, 2002; Cohen,

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Eylon, & Ganiel, 1983; Duit & von Rhöneck, 1997; Shipstone et al., 1988; Stockmayer & Treagust, 1996) students tend to confuse concepts such as voltage, current, power and energy. This means that students do not clearly distinguish between these concepts and, typically, confusion follows from not relating them properly to each other, for example:

Current consumption;  
Battery as constant *current* supply;  
No current – no voltage;  
Voltage is a part or a property of current.

Research has also shown that it is very difficult for students to perceive a circuit as a whole system and to understand that local changes in a circuit result in global changes, affecting all voltages and currents. One can observe both:

- *Local reasoning.* Students focus their attention upon a single point in the circuit. A change in the circuit is thought of as only affecting the current and/or voltages in the node or mesh where the change is made.
- *Sequential reasoning.* If something is changed in the circuit the student thinks that this only affects current and/or voltages in elements located after the place where the change was made, not before it.

This has been further investigated by Margarita Holmberg (González Sampayo, 2006), as part of her thesis. She used a questionnaire to investigate engineering students' understanding of some concepts in electrical circuit theory. The work looked at students in three different countries. Her results are similar to those from earlier studies of pre-university students. She found inconsistencies in student reasoning, typically occurring in cases of extreme values (zero or infinite) of voltage, current or resistance.

We argue that the reason behind these results is that students see concepts as isolated 'items' and not as being inter-related.

#### *Linking the Laplace Transform to the real world*

Tiberghien and co-workers (e.g. Tiberghien, 2000; Vince & Tiberghien, 2002) categorize knowledge into two domains: the object/event world and the theory/model world. This dichotomy has proved very effective when analysing and developing lab-instructions. She points out that it is important in education to make explicit the links between the theory/model world and the object/event world (Figure 1).

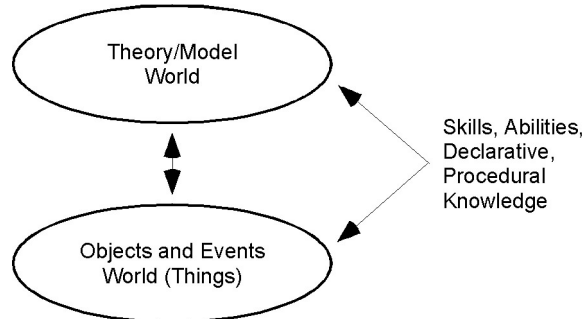


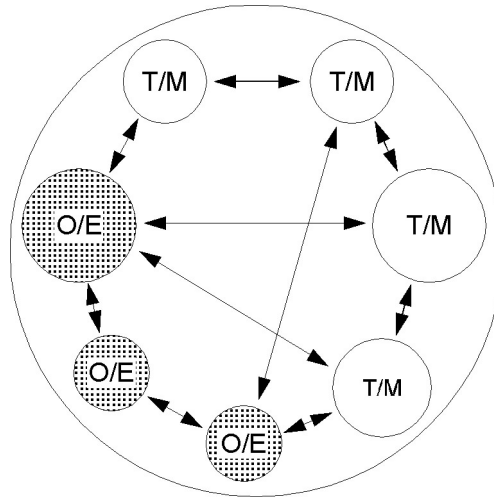
Figure 1. Categorization of knowledge based on a modeling activity (Vince & Tiberghien, 2002, p. 53)

The links that students at university level are supposed to make between the theory/model world and the object/event world are most often links between mathematical models and measurement data, or graphs stemming from mathematical calculations and graphs derived from measurements. Earlier research has shown that these links are not formed spontaneously (Ryegård, 2004; Tiberghien, Veillard, Buty, & Le Maréchal, 1998). In the research by Tiberghien, like our earlier research (see for example Bernhard, Carstensen, & González Sampayo, 2005), it is apparent that students do not even use textbooks or their lecture notes during lab-work. It is, therefore, important to clarify the nature of these links, both in terms of the concepts/relationships in which they are incorporated and the concepts they link. In engineering education the concepts taught are mostly complex, and some links transcend one world while others belong within a single world. In order to map and elucidate these links, and enable them to be highlighted in the lab-instructions, an extended model showing all of the links, and whether they belong to one of the worlds or connect them is required.

We assume that *knowledge is holistic*, but that pieces of knowledge are taught in different sessions, and that if interactions between different parts of the learning objectives are encouraged during lab-sessions (or what we would rather call integrated problem-solving and lab-sessions), relationships between the theory/model world and the object/event world will evolve. The resultant knowledge that the students acquire will be more than the sum of the parts.

We therefore suggest a new model: that of a complex concept (see figure 2). This builds on Tiberghien's model. The different concepts taught are illustrated by 'islands' of different sizes according to the content of knowledge they represent. The arrows show the links between different concepts. To analyse the links is to find the arrows, to determine which 'islands' the arrows should be drawn between and in what directions the arrows should point. The model may be used for analysis of the intended links, or the links actually made by students, depending on whether

the research concerns analysis of ‘the intended object of learning’ or ‘the lived object of learning’ (Runesson & Marton, 2002).



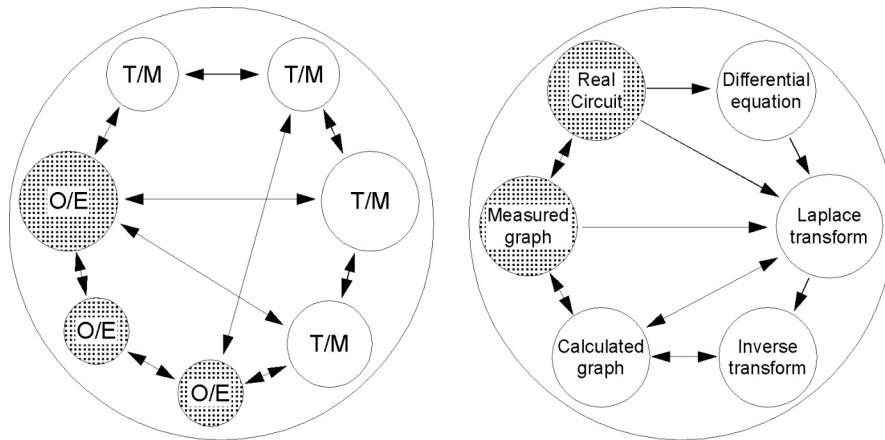
*Figure 2. Our suggested new model – Model of learning a complex concept.<sup>i</sup>*

The idea behind our model is that knowledge is built both by learning the pieces, i.e. the islands, and by learning the whole, i.e. making explicit links through simultaneous work upon the issues associated with several objects. Some links follow the whole cycle, while others jump across it, thus skipping sequential links. We believe that the links may become established through interaction between different pieces of knowledge as a result of interaction between the theory/model world and the object/event world. The more links that are made, the more complete the knowledge becomes.

In our studies we have found that it is important to determine which links result in the assimilation of more knowledge, and which links appear to be more accessible to students. Some of the links take the form of constructing graphs. To the experts, graphical representations are a single tool, but to novices they are experienced differently depending on whether they are derived from mathematical expressions or from data collection and measurement.

Our method for identifying the troublesome elements was to consider the questions raised during lab-work. This method provides a different insight into what really is troublesome from the commonly used recall interviews. The latter can only highlight what is remembered afterwards; this might not be the same as the real problems encountered. We suggest that this is particularly likely, since those aspects assumed by teachers to be problematic tend to be highlighted during such interviews.

During the analysis of the lab-work, the model of learning a complex concept emerged. The transitions from the real circuit to the differential equation, and on to the Laplace transform, through the inverse transform to the calculated graph, can be considered ‘obvious’ or ‘self-evident’, but we have never seen anyone describing ‘the object of learning’ in such a way before. Therefore we conclude that the circular paradigm is not self-evident, but is perceived in that way because the links between the ‘islands’ are taken for granted, and are therefore not made explicit during teaching. Teaching often follows the circle as a ‘logical order’. Presenting the sub-concepts, but progressing only around the circle will make it difficult to make links between the theory/model world and the object/event world since the routes between the worlds then have to go through two steps (one between the real circuit and the differential equation and the other between the graphs). To make more links across the circle, especially crossing from the theory/model world to the object/event world would open up a more thorough understanding. As an example, the link from the Laplace transform to the calculated graph can be simulated using computers.



*Figure 3. Our model – Model of learning a complex concept – and the model translated into the example of the Transient Lab*

The links can be examined by asking two questions: 1) what links do teachers want the students to make, i.e. how can we find a way to teach a specific link (i.e. foster an understanding of the connections between certain concepts)? and 2) what links do students actually make during the lab, i.e. what are they doing or talking about?

An example of how the links can be explored through the students’ conversations focuses on Tess and Benny. Tess has been doing all the calculations, and Benny has worked on the simulations. After about 40 minutes they are supposed to wire up the circuit, and they read:

Tess: (Reads from instruction) "Wire up the circuit".  
 (Turns her head towards B)  
 It seems taken for granted what circuit he's talking about.  
 Benny: Yeah, we'd better read this again.

The gap in understanding may be illustrated by the circle which shows the relationships that the students were intended to learn.

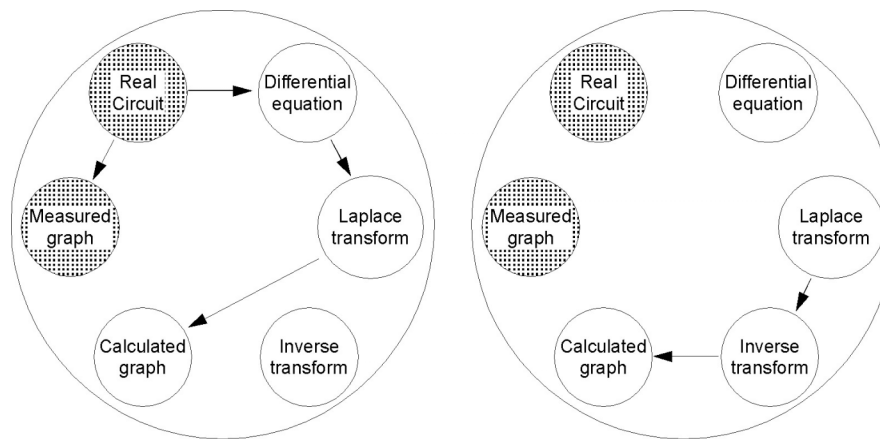


Figure 4. a) Benny's 'lived object of learning' in this first part of the lab session  
 b) Tess' 'lived object of learning' in this first part of the lab session.

In this part of the session, Tess and Benny encountered different 'objects of learning'. At this point, neither of them is thinking about the real circuit, because in order to do so they have to make links back: Benny from the graph and Tess from the mathematics.

The circular model was used to identify the difficulties that the students had when the course was presented in 2002; it was then used to identify which links required extra emphasis. In 2002, learners did not make links between the Laplace transform and the calculated graph. This link would symbolize the direct relationship between the frequency domain and the time domain, an aspect of knowledge that is intended. This link could be made explicit via simulations of the step response using Simulink, where the transfer functions in the Laplace domain can be entered and the result in the time domain can be graphed. Thus it is possible to make the link between the two concepts explicit. In addition, the simulated examples were not just randomly chosen from a textbook, but systematically varied according to the theory of variation (See for example: Marton & Tsui, 2004; Runesson & Marton, 2002).

To improve the learning outcomes, we manipulated the environment and the learning space: problem-solving and lab sessions were integrated rather than delivered separately, and the learning space was opened through variation.

#### IMPLICATIONS FOR RESEARCH ON THRESHOLD CONCEPTS AND CONCEPTS ACTING AS ‘KEYS’

During the conference on ‘Threshold Concepts within the Disciplines’ (Glasgow, August 2006), different methods for recognizing threshold concepts were discussed. These included phenomenographic research, teacher and student interviews, analysis of textbooks, and analysis of a concept directly based on the categories that define a threshold concept. Meyer, Land and Davies (2006) focused on appropriate analytical frameworks, and suggested four ‘modes of variation’: ‘sub-liminal’, ‘pre-liminal’, ‘liminal’ and ‘post-liminal variation’. They suggested that these analytical procedures required as inputs either qualitative or quantitative data that are ‘procedure compliant.’ (See also Chapter 5, this volume).

One question then is whether results from different data collection methods can be compliant, i.e. if different data sets can be examined using a single suite of analytical tools, categories and theoretical frameworks. Thus, the question arises, should different data sets be analysed by using different tools? If so, are the results directly comparable or complementary?

Below we discuss some of the problems associated with different data collection methods. This is not intended to be a thorough description, but it should serve as an introduction to a discussion on what different methods can contribute.

##### *Some reported problems with interviews as the data collection method*

In many papers on threshold concepts (Meyer & Land, 2006) it is suggested that teachers should be interviewed in order to identify troublesome knowledge, and that research into students’ understanding should be undertaken in order to find out how they have learned about or experienced the threshold concept. One benefit is that it makes teachers engage in learning in a new way. But, as stated by Davies (2003), this also becomes problematic since teachers may either mention the ‘fundamental building blocks’ or the things that are already included in their course, and thus confuse what is fundamental to the discipline and what is fundamental to learning. We have identified two additional problems: 1) Teachers often seem to take threshold concepts for granted, and thus they may never be mentioned during such interviews, and 2) they perceive a whole conglomerate of disparate concepts to be troublesome, instead of seeing a single integrated concept as the threshold concept.

When interviewing students there are problems associated with asking the students directly what they consider ‘troublesome’. Several reports show that the students’ own descriptions of what is difficult do not always agree with those provided by an expert. This is especially so when interviews are conducted with

students who are still novices It has been shown that students may not consider something they have yet to understand as being difficult.

*What happens when a research method is used beyond its scope?*

Research results can be regarded as models of the real world. No research can describe the whole picture. If one could represent the world as it is, in all its aspects, the result could only be the world itself. Therefore all research aims to find a model that describes a particular aspect of the world. Seen as such, different methods and different theoretical or analytical frameworks open up different dimensions of the world. When one tries to use a model outside its limitations, or a research method beyond its scope, it is likely to fail. One mistake, for example, is to say that phenomenography cannot be used to identify threshold concepts, because concepts are social constructions and phenomenography examines the differences between students' experiences of the real world. To accept that disciplinary knowledge is a social construct implies that it is not constant and has not been defined absolutely. Davies (2003) claims that in phenomenographic studies on 'price and cost', disputes and ambiguities were not identified, nor was the extent of what is currently considered valid knowledge. However, if specialists are interviewed in phenomenographic studies, they may reveal both ambiguities, and the extent of what experts in the field today consider relevant knowledge. Such a study would be an interesting one to carry out in the context of the domain of research. In one such study on the understanding of the 'mole' concept in chemistry, Strömdahl (1996) found a number of differences in conceptions among experts and researchers in chemistry.

*Is it possible to extend the scope of a research method?*

What phenomenography has been successful in doing is to compare teachers' perceptions of 'the learning object', and the students' understanding and experience. 'Learning studies' (Lo, Marton, Pang, & Pong, 2004) is an emerging field of research. Using this approach, teachers and researchers together use the results of phenomenographic studies or teacher experience to design new learning sessions, and evaluate the intended and the enacted 'objects of learning'. One outstanding example has been reported by Wernberg and Holmqvist (2004). It is well known by teachers that learning to tell the time on an analogue clock presents a number of difficulties. There has been no consensus about the best approach. In a 'learning study', however, one teacher suggested that the critical aspect was that the hour hand was all that was needed to tell the time. It was suggested that the minute hand should not be introduced until all learners understood how to read the time using only the former. Once this has been achieved, the minute hand could be introduced as a refinement, giving a more precise measurement of time.

Our research in the field of electric circuit theory and control theory aims to improve education in the same way, by conducting a learning study. We, however, have chosen not to undertake a phenomenographic study. We tried to identify

troublesome concepts by means of video recordings, rather than interviews with students. The reason for not undertaking phenomenography is that the data from video recordings of classroom sessions is very rich, (a great deal of data to analyse, as well as long sequences where ‘nothing’ happens) and thus it is difficult to discern phenomenographic categories (cf. Marton & Säljö, 1997). However, after using our tool to analyse the relationships that students were identifying during the lab-work, it became clear that it was possible to identify phenomenographic categories, but that this was not necessary. The videoed data did not lend itself to phenomenographic studies unless another tool was applied to reduce the amount of data. In contrast, the learning study could be carried out in three steps:

1. Analysis of learning in labs before changes, by means of the model described above;
2. Changing what is possible to learn by using the theory of variation;
3. Analysis of the learning in the new labs.

## CONCLUSIONS

The purpose of developing new analytical tools, new models and new concepts in research is to try to describe something better than was previously possible. In our research we have found ‘the model of a complex concept’, (see figures 2–4) an essential tool for analysing the relationships that are intended and enacted in lab- and problem-solving sessions. Other ways to perform learning studies have also been discussed. Meyer, Land and Davies (Chapter 5, this volume) offer a way to analyse the process of learning or the process of coming to terms with thresholds.

Interviewing teachers is a good way to identify troublesome concepts, such as object orientation in computer science, or learning to tell the time, but video recordings of teaching sessions can help to clarify which constituents of the concept make it difficult to learn. As suggested above, the pilot study on Bode Plots and the study on transient response not only revealed the concepts involved, but also identified the essential relationships between concepts. In addition, it was possible to explore and modify the ways students engaged in their studies. Two important aspects are highlighted by Davies (2006, p. 74): a threshold concept is likely to be troublesome because ‘it not only operates at a deep integrating way in the subject, but is also taken for granted by practitioners in a subject and therefore rarely made explicit’. Both of these are revealed through video recordings: the interrelatedness, through the analytical tool used, and the ‘taken-for-granted-ness’ through the analysis of questions asked in the classroom and the ways that the teacher answers.

Since many concepts being taught are ambiguously defined, and are negotiated as social constructions, Davies (2003) suggests that threshold concepts could be explored ‘through a comparison of the reasoning employed by economists and sociologists and through a review of student’s thinking about’ the threshold concepts. This could, of course, complement what can be discovered by phenomenographic research, where teachers and other experts are interviewed.

Research into ‘threshold concepts’ thus seems to include three fundamentally different modes of investigation: How do we recognize a threshold concept? In what ways is it difficult and troublesome? And how do we find the critical aspects, i.e. the ‘key’ characteristic of the concept that will open up the portal?

A key is not the foundation that a building is constructed upon; it is what you use to open the door. ‘Core concepts’ are the building blocks, fundamental for building a discourse or syllabus, and the ‘key’ concepts, in our sense, make it possible to enter the building.

#### NOTES

<sup>1</sup> The shaded circles are analytically attributed to the object/event world and the unshaded circles represent the theory/model world.

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