Identification of threshold concepts involved in early electronic engineering: Some methods and results

Jonathan Scott
University of Waikato, Hamilton, NZ
scottj@waikato.ac.nz

Ann Harlow
University of Waikato, Hamilton, NZ
aharlow@waikato.ac.nz

***Abstract**: This manuscript reports the Threshold Concepts (TCs) identified in early circuits & electronics courses through our work to date. We suggest some novel methods used to quantify the identification. We identify some concepts that ought to have been mastered in high-school physics courses but that are often absent from student repetoires. This may be a confusing factor for us and a source of trouble for students.*

Introduction

To students, TCs (Cousin 2006) are abnormally troublesome to learn. To practitioners their importance lies in the transformation in the \ways of thinking and practising" of the learner as Davies (2006) puts it, what we engineers might call acquiring the competencies of our profession. Meyer (2010) has asserted that concepts do not present in a continuum, but fall all-or-nothing into being "threshold" or not. Being both the hardest to learn and the most influential to "identity and ways of thinking" amongst the ideas within a discipline, it would seem important to identify Threshold Concepts. This proves to be diffcult for various reasons. (Davies 2006) In this manuscript we put forward a small catalog of concepts we believe to be central to EE and to be threshold. They were identified in the first place by working with students and observing where they reported difficulty, or had learning troubles exposed through assessment. Later each was evaluated against the five attributes of Meyer and Land (2003). Debate between EE educators and instances from the literature have added weight to our selection. Rountree and Rountree (2009) favour the search for "the ways in which practitioners in related disciplines solve similar problems" offered by Davies (2006) to identify TCs. This manuscript puts our findings up for debate, and presents some novel approaches we are using to bring some objectivity to the evaluation.

Postulated Threshold Concepts

We commence by describing the concepts we would offer as TCs, in no particular order, and without attempting to justify the selection. This is to ensure clarity in identification and terminology.

Thévenin's theorem/Modelling

Thévenin's theorem is the first example of circuit modelling that students encounter in electronics & circuit theory. It causes learners an inordinate amount of trouble. It is not Thévenin—any model would present the difficulty.

Dynamic Resistance/Linear Approximation

The idea that quantities can have an "ac value" as well as a "dc value" appears first and foremost in electronics in the replacement of something like a diode junction with a resistor subject to the limitation of small disturbances—its "dynamic" resistance. The same phenomenon—a tangent as a linear approximation of a curve in a local region—appears as marginal cost in economics and the β of a BJT, and ought to be familiar from differential calculus, but the connection is seldom made.

Reactive Power/Phasors

Perhaps the most widely-acknowledged TC in EE revolves around the complex nature of impedance. This concept is often encountered first in the use of Phasors. Reactive Power is the name that appears commonly in the literature, and continues to cause conceptual difficulty even for experts. (Willems 2011)

Feedback/Operational Amplification

The opamp is the "simplest" example of feedback. Many practitioners realise that opamps cause learners a great deal of trouble. We believe it is the analysis of a circuit with feedback that links the various instances associated with this difficulty.

Transconductance/Dependent Sources

Dependent sources link V or I of one element with V or I of a separate element. In transistors—"trans-resistors"—it is a transconductance, $g_m = \partial i/\partial v$, and students have trouble coming to grips with this. A further three concepts—potentially threshold—give trouble in early EE courses. We consider these to be strictly not part of EE. They should be encountered and understood in high-school physics courses. In threshold-concept jargon we might say that the students never completed the liminal passage to full understanding.

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Holistic Current Flow

The holistic appreciation that current flows "incompressibly" through conductors escapes many students at high school. The student may show "localised thinking" and conclude that a change in one part of the circuit will have no effect upon branch currents in a distant ("earlier") part of the circuit. This should not be confused with Kirchoff's rules that simply apply mathematics to obtain quantitative results. We do not consider the current and voltage laws to be threshold, but the underlying physics appears to be.

Graph Understanding

Some students seem unable to draw even obvious conclusions from graphs, and unable to grasp that a graph and a written sentence are saying the same thing. They may have difficulty reading data off a graph. For example, students cannot see why the switching of an ideal diode should yield a plot of a vertical or near-vertical line in one quadrant and horizontal in another quadrant.

3D to 2D Mapping

This skill manifests itself in the EE world in an ability to associate nodes on a circuit diagram with conductors in a constructed circuit. There is a kind of mapping between the physical wires of the 3-dimensional construction and the lines on the 2-dimensional circuit diagram. This ability resembles that examined in aptitude tests offered to students in the form of questions asking students to say which of several images represents the correct shadow that an object drawn in perspective might cast.

Comparison Against the Five Criteria

The five EE-centric TCs above were initially identified by observing students and listening to their questions and fears—troublesome learning in progress—and comparing notes with other lecturers. We now examine the extent to which each satisfies the other 4 criteria of Meyer and Land (2003).

Boundedness

Boundedness seems to be quite easily satisfied for our candidate concepts. **Thévenin's model** has a clear boundary: It fails for nonlinear circuits. **Reactive Power**, and in particular the representation of it by phasors, has clear boundaries: Calculations only hold for sinewave excitation, and values hold at one frequency only. **Dynamic Resistance** fails abruptly to be useful as signals cease to be "small".

The very question of what is small can only be answered once you understand the concept. **Feedback** theory becomes irrelevant the moment the circuit goes unstable, and when stable the open-loop properties are indiscernible. The opamp only became a common component once the burden of guaranteeing stability was assumed by the opamp designer in the form of "unity-gain compensation", a description that can only be understood once feedback theory is mastered, while the open-loop opamp transfer function is very hard to characterise from closed-loop measurements. **Transconductance** has an effective limit in its application: It gives circuit equations that are a jump up in complexity from the case without them. These are really only practically solved by computer. The example most practitioners recognise is that of analysing the operation of a cascade of transistor amplifiers, where we apply Miller's Theorem and other techniques to separate the input-side and output-side parts of the circuit surrounding each transistor and so render the analysis tractable and conceptually insightful (compared to being an emergent property of involved mathematics).

Irreversibility

Irreversibility is hard to assess objectively. Everyone seems to accept that riding a bicycle is a skill that is not unlearnable. One senses no degradation in the memory, but there is no guarantee that this is not an illusion. We interviewed people who have qualified and since long-ceased to use their skills explicitly. We asked subjects about 17 ideas, including our TCs, some concepts taught in EE courses that we felt were not threshold, and some ideas from other disciplines. For each concept we established that the subject recognised the idea, typically that they "had once understood it", but that they had not had formal cause to consider or apply it for at least 5 years. When this was the case we asked them to explain the idea, and assessed whether it "came back" easily or at all. We have so far located only 7 subjects, but seek more. The results have been fascinating. Subjects often claimed to fully understand a concept, but then surprised us and themselves by not being able to describe it to us, or eventually exposed themselves as having never really understood the idea. To date we have seen *no evidence that our TCs are any more irreversible than other concepts*. We suspect that irreversibility is a derivative property arising from the transformation of thinking: TCs are no more readily remembered than other ideas, except that they are frequently used in a subject's routine thinking.

Integrativeness

Where an idea recurs in diverse threads, it will necessarily open portals of understanding between the threads, exposing "the previously hidden interrelatedness" in the words of Meyer and Land (2003). We will substantiate the integrative nature of our postulated TCs by looking at examples of their application in disparate areas.

Thévenin's theorem is used as a model for innumerable things from a power station to an electric guitar, from a flashlight battery to an MP3 player. Amongst EE ideas it is one of the most widely employed of all. Rossouw, Hacker, and de Vries (2010) find that modelling is one of the most uniformly accepted "unifying concept/themes" in engineering and technology. Thévenin's theorem is easy to establish as an integrating idea.

Dynamic Resistance is a term generally limited to the context of active devices in electronics. However, the concept is in wide use by other names. The dynamic resistance of a device is simply the circuit-theory manifestation of using the tangent of a curve as a local, linear approximation of a nonlinear function. It appears to a nonlinear control engineer as the response to small disturbances, and to a mechanical engineer a linear approximation of a nonlinear stress-strain relationship. To an economist it appears in marginal cost. In all cases it links into the linear world of analysis.

Reactive Power appears in many unexpected places, indeed it was taken fully-formed from mathematics. Recall that it arises as a way of dealing with differential relationships in the context of periodic excitation: To deal with capacitors and inductors whose voltage and current are related by differential equations the practitioner restricts herself to sinewave excitation and uses complex numbers. In other words, differential equations become linearly soluble in one frequency at a time. Communications engineers describe the complex modulation that has enabled modern cellphones and advanced radar with a similar complex mathematics. Invocation of phase in addition to magnitude completes knowledge of reflection coefficients dealing with transmission lines in acoustics and microwave engineering.

Feedback occurs everywhere. Before cruise control in cars the driver regulated vehicle speed, a form of feedback. An archer improving subsequent shots applies feedback in a sampled system. From horseriders to pilots, people master the art of steering a system through strange motions, feeding back their perception. The question is then logically asked, why is this so hard to learn if it is not a new idea? The answer lies in the rigour and difficulty of computing answers and minimising error without instability, and the concealment of the open-loop gain that is at work. However, the applicability of the technique is enormously widespread, so once mastered it is strongly integrative.

Transconductance is the hardest case in the search for integration. It is present in the models of all active devices from vacuum tubes to HBTs, but not commonly elsewhere. Of our postulated threshold concepts it is the one of which we are least certain. There is an argument that it is simply another instance of modelling, but applied to a three-terminal (or more) network instead of a two-terminal one. We include it separately because there seems to be something freshly confusing to students at its introduction.

Transformativity

Various methods have been applied to gauge the transformativity of concepts. Davies and Mangan (2005) looked at concepts historically featured in exams. They also looked for näivete in qualitative student responses compared with expert's responses around candidate concepts, associating gradual liminal passage away from näivete with the transformation. Atherton, Hadfield, and Meyers (2008) suggest that practitioners of "hard disciplines" such as engineering identify TCs through introspection with greater ease and consistency than softer disciplines. Davies (2006) concentrates on the transformative aspect of TCs. He seems sceptical of taking a consensus approach, even with expert teachers, but in the end he offers mostly introspective solutions. How can we say that an understanding of reactive power (or some other candidate concept) has changed *another person's* way of thinking? Introspection is the main option simply because few of us has close enough a view of another individual throughout the transformation. Kiley (2009) offers perhaps the best opportunity to identify TCs through the relationship between doctoral candidates and their supervisors that lasts 3–5 years and involves a close working situation. Most researchers settle for the view over a single course, typically a semester.

The literature portrays transformative discipline ideas as those that give rise to characteristic ways of thinking. We suggest that if this is the case, they will be used by practitioners in disparate situations, because to be transformative they must be powerful. Out-of-context applications can pinpoint deeply-influential concepts. For example, experts tend to betray their professions in "dinner party conversations" through their use of their "ways of thinking" and listeners can identify speakers as psychiatrists, economists, engineers, or whatever, simply from the way they respond to provocative problems by applying their characteristic "ways of thinking", or concepts and associated jargon stereotypical of their community of expertise. Sadly, it would take a long time to identify TCs using these methods, but we can provide examples where the essence of our TCs appears in other disciplines or in stereotypical behaviours. (Space does not permit our full set of examples.) In the case of **Thévenin/modelling**, we cite "foreign" examples such as Freud's models of the mind or Bohr's atom. Regarding **Dynamic Resistance**, there is a pervasive desire to use linear approximation in many fields: Virtually all scientific disciplines have their "linear approximations".**Feedback** is encountered in daily manual functions: A shake in a person's outheld hand is seen as loop instability, and caffeine as increasing gain that the engineer expects to worsen the shake.

Reactive power and **transconductance** are more difficult with respect to transformativity. It is hard to see how these might alter one's way of thinking. They are important in the EE's toolkit but applications appear to be restricted to only a few fields, including engineering, physics, and mathematics. Surely any transformation must be *local*, having little intellectual impact beyond circuits. It is worth noting that of our concepts, these two are the ones of which we are most, and least, certain, respectively.

Quantitative Identification

We have started investigating two potential quantitative indicators. The first is the double-peaked characteristic that one often sees in the grade distribution. Scott, Harlow, Peter, and Cowie (2010) shows results that suggest that a bimodal grade distribution will appear in assessment involving a single TC. A larger-scale study is planned for 2012.

The second indicator involves topological metrics applied to concept maps constructed around the discipline. Concept maps are a structured way of representing a series of statements about ideas in a discipline in the form of a network graph. (Novak and Gowin 1984) Two concepts (nodes) are linked through an action or dependency. For example, "Dynamic resistance depends upon operating point" would create a link between the concepts of dynamic resistance and operating point. The analysis of networks has become an area of intense interest in the last decade or so, with many characterisation metrics available that can be readily applied to a connected network graph. (Cui, Kumara, and Albert 2010) We suggest that the degree (of connectedness) of nodes associated with threshold concepts will differ from that of non-threshold ones. The reasoning is that the map will evidence the integrative property of the threshold concepts as an increased number of edges or links to those particular nodes. The analysis could resemble the assessments of connectedness after the fashion of the well-known Erdös and Bacon numbers familiar to mathematicians and film buffs. The problem is that topological metrics are meaningful only when applied to large networks. Constructing a concept map that is large enough for the metrics to reflect the integrative nature of some concepts is proving to be a challenge.

Correlation with Existing Concept Catalogues

The idea of a "Concept Inventory" was introduced 20 years ago by Hestenes, Wells, and Swackhamer (1991), in the area of physics, with the Force Concept Inventory (FCI). A number of such inventories have appeared in disciplines ranging from thermodynamics to chemistry. (Evans et al. 2003) These inventories typically lead to an assessment tool designed to assess *understanding*—in TC jargon one might say to assess that the user has passed through the portal with respect to each of a series of concepts considered important to the discipline. The Foundation Coalition project has been associated with a number of the tools.(Corleto, Kimball, Tipton, and MacLauchlan 1996) Some are developed and maintained more effectively than others. For example, the Signals and Systems Concept Inventory (SSCI), associated with a 25-question tool, is well researched and identifies the concepts it tests very explicitly. (Wage, Buck, Wright, and Welch 2005)

Simoni, Herniter, and Ferguson (2004) have reported on an Electronics Concept Inventory (ECI). In an attempt to see if our ideas of TCs correlate with the concepts considered important by the contributors to the index, we obtained the exam of (Simoni et al 2004) and looked for the appearance of our concepts. The ECI does not address Reactive Power (it is usually considered to be "circuit theory" rather than electronics), but it does use Thévenin's theorem and the equivalence of Thévenin's equivalent circuit as a model, the trans-action of dependent sources, the action of opamp circuits. It implicitly assumes a knowledge of dynamic resistance, and of its change with operating point of a nonlinear element. It also implicitly requires an ability to discern the action of a circuit from graphs. We consider the ECI to endorse the importance of four of our five concepts.

We looked into the Electric Circuits Inventory (also labelled ECI) of Ogunfunmi and Rahman (2010). This ECI was limited to dc circuits, and so did not extend to reactive power and could shed no light. We plan the development of our own inventory in 2012.

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