Engineering undergraduates' conceptions of critical thinking

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For proper engagement with their studies, future work environments, and life in general, students need the ability to think critically. The evident importance of critical thinking in higher education, as well as lecturers' struggle to make sense of their students' ways of engaging with critical thinking, motivated us to explore students' conceptions of the phenomenon 'critical thinking'. Semi-structured, open-ended interviews were conducted with thirteen engineering undergraduate students who described their experience with a critical thinking activity designed for the purpose. From these descriptions, four qualitatively different conceptions were identified through a phenomenographic lens – critical thinking is experienced as *sifting*, *relating*, *exploring*, and *creating*. These results provide lecturers with a better appreciation of what students understand they are learning to do and the means to provide students with feedback about what more is expected of them when engaging with critical thinking.

Introduction

Problem-solving is considered the heart of engineering practice, and critical thinking (CT) is regarded as a key component of problem-solving (Donald, 2002; Passow & Passow, 2017; Sheppard et al., 2008). It is therefore vital that engineering students learn to think critically. Brent and Felder (2014) point out that there is a widespread complaint amongst engineering educators that their students cannot think critically or creatively, without seeming to realize that the skill should be developed in *their* classrooms. Together with the findings of Ahern et al. (2012) (on the grounds of interviewing thirteen academics from a variety of disciplines at an Irish university), this suggests that engineering academics, unlike their colleagues in the humanities, are only able to recognize the presence (or absence) of the skill of CT. This is concerning, especially if teacher competence is determined by the extent to which teachers *understand the ways in which their students think* – a phenomenographic perspective on teacher competence (Gibbs et al., 1982).

This study was motivated by the struggle to understand engineering undergraduates' ways of engaging with CT. The objective of the investigation is to understand engineering undergraduates' conceptions of the phenomenon of "CT". This research pursues the following question: What are the different ways that engineering undergraduates experience CT? The paper employs a phenomenographic approach to explore the collective experiences of thirteen undergraduate engineering students learning to think critically at the Cape Peninsula University of Technology in South Africa. The results provide lecturers with a better understanding of how students experience CT, the means to explain to students what else they expect of them when engaging with CT, and insight to design activities that are appropriate for the development of CT.

Literature review on the meaning of critical thinking

CT is a complex phenomenon made up of many skills, subskills, and dispositions. The literature describes a multitude of predominantly discipline-independent definitions for CT. Among these is the landmark Delphi definition where the American Philosophical Association convened a panel of 46 noted experts (including leading CT scholars such as Ennis, Facione, and Paul) to produce a definitive account of the concept (Abrami et al., 2008). The outcome was a definition which is as long and comprehensive as it is dense and hard to follow (Davies, 2015). Kuhn (2019) nonetheless maintains that researchers are moving away from conceptual definitions of CT at an abstract level toward definitions that are more closely linked to identifiable and observable cognitive behaviours. We found both types of definition useful – Table 1 represents the result of an intensive attempt to find definitions which collectively describe the essence of CT in engineering education and their significance for this study. This table (and the rest of the literature to follow thereafter) serves as guide to design an activity which elicits CT only. The rationale being that because, in phenomenography, the focus is on others' ways of experiencing a phenomenon, the need for an open understanding of the topic of investigation is thus more important than being a leading expert on this topic (Collier-Reed, 2006).

Table 1. Definitions for CT and their significance for this study.

Definitions and Structure	Significance
There are certain subprocesses involved in every reflective operation. These are: (a) a state of *perplexity, hesitation, doubt*; and (b) an act of *search or investigation* directed toward bringing to light further facts which serve to corroborate or to nullify the suggested belief. – Dewey (1909)	Dewey is considered by many to be the "father" of CT
CT is *reasonable, reflective* thinking that is focused on *deciding* what to believe or do. – Ennis (1989)	Frequently cited.
CT is the art of *analysing* and *evaluating* thinking to improve it. – Elder and Paul (2013)	Renowned scholars.
CT is essentially *self-disciplined*, *self-monitored*, and *self-corrective* thinking. – Singh (2022)	Focus on agency.
We understand CT to be purposeful, self-regulatory judgment which results in *interpretation, analysis, evaluation*, and *inference*, as well as *explanation* of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based. CT is essential as a tool of inquiry. As such, CT is a liberating force in education and a powerful resource in one's personal and civic life. While not synonymous with good thinking, CT is a pervasive and self-rectifying human phenomenon. The ideal critical thinker is habitually inquisitive, well-informed, trustful of reason, open-minded, flexible, fair-minded in evaluation, honest in facing personal biases, prudent in making judgments, willing to reconsider, clear about issues, orderly in complex matters, diligent in seeking relevant information, reasonable in the selection of criteria, focused in inquiry, and persistent in seeking results which are as precise as the subject and the circumstances of inquiry permit. – Facione (1990)	A definitive account of the concept by 46 noted experts on CT.

CT is the process of making *judgments* or *choices* and backing them up with *evidence* and *logic*. – Brent and Felder (2014)	Engineering specific.

Kuhn (2019) maintains that there is a trend that scholars are increasingly recognizing that CT is best examined in its *developmental* context. She reasons that knowing what the developmental progression is enables a better understanding of an achievement in its final form, as well as guidance toward the goal. William Perry – a student counsellor at Harvard in the 1970's – pioneered such a scheme. Perry's cognitive development scheme describes the qualitative development in *students' thinking* during their college years. Perry (1999) maintains that students' thinking develops from *absolute* (there being only one right answer to each question*),* to *relative* (there being many right answers to each question*),* to *committed* (students experience responsibility of having to make choices). Perry also makes provision for variation in an individual's development through his scheme through processes which he labels 'retreat' and 'escape'. Similar schemes have been developed, and Magolda's (2004) more recent schemes are, for instance, concerned with the development of reflective judgment and epistemological reflection respectively – skills closely related to CT.

Phenomena such as CT have also been studied via people's *conceptions* thereof. The seminal work from this line of research (focused on *peoples' conceptions*) was done by Säljö (1979), who interviewed people from a range of educational backgrounds and age groups to explore their conceptions of *learning*. Many scholars have subsequently employed the same approach. Morse (2009), for instance, explored a group of first-year *law* students' conceptions of CT, and found that they experienced CT as: negative, instrumental, a sense of argument, a general sense of analysis, and as a way of being. Phillips and Bond (2004) found that a group of undergraduate students who enrolled in a *management* course experienced critical reflection (a phenomenon very closely related to CT) as: weighing up, looking at it from all the angles, looking back on, and looking beyond what is there. The study which probably has most in common with ours (in terms of the context and content being thought about, albeit from a different perspective) is where Trigwell et al. (2002) investigate university science educators' different ways of understanding what it takes for their students to solve problems. From these educators' perspective, science students experience problem-solving as: *applying what you know* to the problem in terms of pre-existing bits of information and skills, *applying what you know* to the problem in terms of pre-existing related *principles* and *procedures, mapping the problem* into formalism in terms of pre-existing disciplinary *concept structure, relating the problem* to a knowledge structure in terms of a pre-existing *conceptual structure,* and *relating the problem to* a phenomenon in terms of the phenomenon represented in the problem. They maintain that for the first two conceptions, problem solving is seen as *applying*, whereas in the final three, it is seen as *making sense* of the problem.

Research Design

In contrast to Kuhn (who is supportive of the examination of CT in its developmental context, as described previously), Marton (1981) argues for the abandonment of the notion of *stage* as applied to individuals on grounds that the stability or generalizability of people's behavior cannot necessarily be assumed across situations. He argues in favour of *categories* that describe *ways in which people perceive the world* because such categories are *stable* and *generalizable* between situations, even if the individuals "move" from one category to another on different occasions.

A phenomenographic approach to research

Marton and Booth (2013, p. 111) claim that:

> In order to make sense of how people handle problems, situations, the world, we have to understand the way in which they experience the problems, the situations, the world, that they are handling or in relation to which they are acting.

Phenomenography is a research approach concerned with determining the different ways in which people experience, interpret, understand, apprehend, perceive or conceptualize various aspects of reality; its most distinctive feature is its focus on conceptions of specific aspects of reality (Marton, 1981).

This interpretative, qualitative research approach is premised on the belief that there are a limited number of logically related, qualitatively different ways of experiencing any particular phenomenon (Marton & Booth, 1997). In phenomenographic studies, researchers need to investigate how participants experience the same phenomenon in different ways. To this end, participants generally engage with the same activity – referred to as the 'shared experience'.

The 'Shared Experience'

We needed to design an activity that afforded participants the opportunity to think critically. Ahern et al. (2012) describe a structure that outlines their conception of CT, and which they (and we) argue facilitates the design of activities that afford the development of students' CT:

> CT is a movement from the concrete, from the factual to the abstract and back again – an ability not only to use knowledge and facts to create ideas, concepts and solve problems, but also to use these developed concepts, theories, and ideas in the real world.

Because of the correspondence between mathematical modelling (the process of translating a real-world problem into a mathematically formulated representation, solving this mathematical formulation, and then interpreting the mathematical solution in a real-world context) and Ahern et al.'s description of CT, we argue that engagement with mathematical modelling affords engagement with CT. In the context of engineering education, model eliciting activities (MEAs) are open-ended, real-world, client-driven problems which focus on the process rather than the product, thereby developing students' higher-order thinking skills (Diefes-Dux, 2004), and for the purpose of this study an MEA was thus created.

Data collection and analysis

Johansson et al. (1985) point out that conceptions (ways of seeing) are not visible – they remain tacit, implicit, or assumed – unless thematized by reflection, so semi-structured interviews were conducted where participants were encouraged to reflect on and describe *their* experience with CT, as experienced through undertaking the MEA. In this regard, participants were made aware that their *experience* was the focus of the interview, and that as such, their answers could not be wrong. Interviews were semi-structured. Questions were open-ended and probing to allow both the interviewer and students the flexibility to express themselves properly and thereby promote understanding; key questions were, however, prepared beforehand. Interviews were recorded, and transcribed verbatim. Analysis was aimed at identifying the minimum number of logically related and qualitatively different ways in which the phenomenon is experienced. We first familiarized ourselves with the data, then separated extracts that relate to participants' experience with the phenomenon from their transcripts; compared these extracts with one-another and grouped extracts that conveyed similar meaning together through an iterative, non-linear process. The original context within which utterances in the extracts were made, were continuously checked to ensure that utterances were not misinterpreted. The categories of description finally emerged.

Results

We sought to describe the ways that thirteen undergraduate engineering students at the Cape Peninsula University of Technology collectively understand what it means to think critically. We first present the results in the form of four categories of description. An explanation of each of the categories of description is provided, with specific emphasis placed on what makes each category unique and how the categories relate to and differ from one another on a qualitative level.

Category 1: Sifting through data

In this category, students are accustomed to having an apprentice-master type of relationship where their lecturers (the masters) provide training before directing them to tackle similar challenges. When they encounter problems unlike those they have encountered before – such as problems that contain irrelevant data, are realistic (rather than decontextualized), have no apparent reference to their course, or have an unfamiliar format (expressed exclusively in words, rather than via formulae, for instance), they feel ill-prepared and are unable to decide which approach to follow. They experience a lack of self-efficacy, which they attribute to a lack of experience and guidance – as the following extract illustrates:

> P7: In class, you are given something, and you are told how to do that something, and then you do [it] according to how you were told to do it. On this activity that you gave me yesterday… I couldn't even come up with a solution like, at all. I couldn't come up with a solution because I **didn't know where to start**. First of all, I have **never done** something like that – so I didn't know where to start. I **didn't have, like, guidance**…

The objective is to find the actual solutions to problems. In other words, the focus is on finding the 'thing' that solves the problem, not understanding the problem, or 'arriving at the solution appropriately (i.e. to reason soundly). The *process* of finding solutions entails managing data – by sifting through it to retain only what is relevant for solving the problem. Isolated pieces of data ('isolated' in the sense that it relates to nothing whatsoever) are retained from the sifting, and these isolated pieces of data then serve as knowledge to solve problems. The data that students sift through comprise the *actual data presented in problems,* and the data is employed directly to find solutions. The following extract (where a participant describes their process) illustrates:

> P4: Extract key information from the data which has been given. You need to take out the unnecessary information that is given.

Alternatively, the data that students sift through comprise the recounted formulae or procedures, which are then employed indirectly – as "ready-made tools from theory" to calculate solutions – as the following two extracts illustrate respectively:

> P2: It's not easy to think out of the box. I have to think of all the equations I've used in Maths to solve this problem.

and

> P13: I was not sure what tools that I have already in Maths that I was supposed to use. I wasn't sure if I was supposed to use Newton

Raphson, I wasn't sure if I'm supposed to be differentiating or using integration, applying what I know.

Regarding students' *role* in CT in this category, students understand their role in two different ways. For some, they play no role – the ability to think critically is a gift (or talent), as the following extract illustrates:

P8: It's kind of unique to each individual, that higher-order thinking is a natural gift given. Over time… yes, it can be developed – but at some point…it's planted in you.

Alternatively, it takes willingness think critically – effort is required and not everybody is willing to put in the effort – as the following extract (a participant's reply to whether they thought all students could be taught to think critically) illustrates:

P10: We can, depending on how the person is – if that person is lazy to think.

Category 2: Relating to prior experience or similar systems

Apprenticeship is no longer a focus of this category. The lack of self-efficacy experienced in Category 1 is replaced by task-specific confidence. Students may, for instance, not be confident with applying certain abstract concepts (such as logarithms, for instance) to real-life situations and be aware of personal shortcomings (such as a lack of experience or a lack of disciplinary knowledge, for instance) – as illustrated:

P6: In the real life that I'm used to, I don't think that I will ever meet with things like ln or ever meet with log. If you were to ask me to deal with the real life, to use logs in real life, I don't even know where I can start. Otherwise, I know how to solve equations for ln, and I know how to solve equations for log, but with real life... I don't know how they are associated.

However, they may have confidence in their ability to solve realistic problems – as illustrated:

P6: I'm finding that when I'm having [to solve] real-life problems, I will find that some will need Mathematics. Although not deep Mathematics, things like using ln, like using logs, like using e to the power of something. The kind of Mathematics that they use is just the basic Maths… And then it's easy, much easier.

Category 2 represents a recognition that the type of problems which require CT cannot be solved by drawing on isolated pieces of data and that there are restrictions on the time for solving problems. Students do, however, also realize that realistic contexts open the way to draw on previously acquired knowledge (comprising *prior experience and knowledge.*)

The *objective* in this category is thus to *understand authentic real-life problems and find their solutions in limited time (efficiency);* for the sake of efficiency, students draw on what they understand already or existing solutions to solve problems (rather than, for instance, filling the gaps in their knowledge that they are aware of, acquiring further knowledge before solving problems or solving problems from first principles.) This entails relating *information to previously acquired knowledge. Information is first transformed* either by estimation, visualization, imagination, or sketching – a more sophisticated *process* than the management of data – whereafter problems are solved by *drawing on isolated configurations of previously acquired knowledge*. To illustrate:

P3: It was all about solving the problem using what you already know. ... take it to something that you know. You put it into diagrams, you put it into graphs, you put it into whatever is familiar to you.

Alternatively, they reach the objective (efficiency) by relating current problems (regularly referred to as systems) to similar problems (or systems) – through a process of systemization (turning something into a system) information is first transformed, and ‘systems’ are then solved by drawing on isolated configurations of ‘processed’ knowledge (readily available knowledge about systems that are similar to the current one, and their solutions.) The following extract illustrates a participant’s motivation for relating current problems to similar others via an analogy of building a house:

> P9: If someone asks me, build a new building, [I have] expectations [that it] is something that someone has done [before] – therefore I just need to find their approach on how to solve it. … I’m still researching on how to solve it, but I haven’t created anything new. I’m still using the systems – from one system to another, to another… if the problem is governed by time, then the best way to solve [it] is by [a] systematic approach – it’s not to reinvent the wheel.

There is, furthermore, an awareness that *knowledge is required for CT* (whether it be previously acquired knowledge, or readily available solutions of similar systems) – as the following two quotes illustrate:

> P6: When I met up with the questions that came yesterday, it was just easier for me to do. I already just knew what I was going to know. I just read and understood what they wanted and obviously, the solution for it came easily.

and

> P9: Once I found them [similar systems], then I just look what he was doing, and try to apply what he was doing into the new problem.

Category 3: Exploring knowledge, perspectives, methods, biases, and assumptions

In this category, the *objective* is to *reason appropriately* towards solutions. The following extract (a participant’s reflection on their experience with the shared experience) exemplifies their goal for learning:

> P3: It’s basically the approach that matters – that’s what I thought. I thought… OK, it won’t really matter what I get but at the end of the day, it’s how I’m going to get to the answer.

The entire CT process is thus in focus (not only the product of CT, as was the case in Category 1, or the efficiency of the process, as in Category 2). Students realize that there are many ways to reason toward solutions and relish opportunities to express themselves via their work. They are intrinsically motivated to learn, find learning exciting, and are so fascinated by issues and the larger ramifications of what they are learning that they can exhibit addictive behaviours at times. CT is now a process of exploring. The *process* entails *managing knowledge* – primarily through research (as the following extract, where a participant describes the tight relationship between CT and doing research, illustrates):

> P10: It’s very important to use this type of thinking because in Engineering we are dealing with real-life problems. And then in the field, you’re going to meet up with a situation that you have never learnt from school. So, we need to teach ourselves how to do research.

Students are furthermore aware of managing knowledge about their own and their peers’ metacognition processes. The following extract illustrates how a participant is aware of compensating for a weakness in their approach by drawing on knowledge of their peer’s approach:

> P5: I make sure that I do not spend too much time researching but also do something where I can see the progress. Because one problem that I

have is that the progress can be here (pointing at his head) … I can see the progress and everything, I can see it… but now I just have to do it. So, his [my peer's] way of thinking is that I [you] just have to do it – do it, edit it, and then have the idea… be wise with research. But now my limitation and his strengths… I'm adding his experience of thinking to my limitations to better my thinking…

Students thus draw on integrated configurations of knowledge beyond the scope of the course and metacognitive knowledge related to their own and others' perspectives, biases, and assumptions to solve problems. With regards to what it takes to think critically, students are aware that they learn the skill by practicing it (as the first of the following two extracts illustrates) and more specifically that they learn to solve problems by solving problems (as the second illustrates):

P10: I learn by practice, so I think that's a way of learning. If you don't practice something, you will never learn it.

and

P6: If I was trying to figure out how to do something… like getting a calculator to display numbers… As I'm trying to find a solution for displaying numbers … I'm learning.

Category 4: Creating arguments

In Category 3, students draw on what they could find out (integrated configurations of existing knowledge). In Category 4 they create the knowledge themselves. In this category, the objective is to construct arguments – either arguments which support the application of theory to a specific situation in practice, or arguments that have no other purpose than to provide the opportunity to think critically.

Whereas knowledge was at most 'managed' in the previous categories, students are now creating knowledge. They are finding arguments by themselves – not only putting existing arguments together or comparing them (synthesizing knowledge). Students realize (as illustrated by the following extract (where the conversation in the interview was about whether it was possible to teach someone to think critically, and what it took to think critically) that an ability to notice or 'see' (awareness) is required to think critically. The extract shows a participant's analogy of Newton 'seeing' something when the apple fell from the tree, something which – were they put in similar circumstances – they would not 'see'.

Interviewer: What does it take to do that type of thinking?

P8: That moment, that time when the apple fell… if I had to be placed in a similar position … would I be able to propel, would I be able to build on my observations? Will I be able to come up with an equation? That's now the question. Can that be taught? … You can teach ways of thinking – I think it's logic. Maybe you can teach logic in schools whereby now you can be able to think and to be able to solve questions. But to think… genuinely. I think it's impossible to be taught. … Yes, we teach someone how to build a car. Then you teach someone logic. That person could be able to build an aeroplane. Yes, we can do that – building on. But for someone to… completely from scratch… I don't think that can be taught.

The knowledge required – for developing original arguments – is constructed by students themselves in Category 4.

Conclusions

These categories of description provide a readily accessible way of understanding the qualitatively different ways that engineering undergraduates experience CT. They are hierarchically related and describe what it means to think critically in ever-more sophisticated ways. The results enable improved communication between lecturers and students when discussing lecturers' expectations for CT while also providing lecturers with insight to design activities that afford the development of CT, recognize students' ways of CT, and provide students with feedback which support the further development of their ability to think critically.

Åkerlind (2008) suggests that phenomenography is most effectively used to inform teaching design decisions when it is implemented in two stages. The first stage is a phenomenographic investigation to determine how students conceptualize a key concept to be learned (such as in this study). The second stage involves making use of the results of the first stage to design a teaching programme that maximises students' opportunities for discerning the full range of key features of the concept identified in the first stage via the use of what has been called variation theory, a theory of learning which arose out of the phenomenographic research approach (Åkerlind, 2018). This second stage is an avenue for further research in this regard.

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