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Critical thinking in the university curriculum – the impact on engineering education

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Critical thinking is a graduate attribute that many courses, including engineering courses, claim to produce in students. As a graduate attribute it is seen by academics as a particularly desirable outcome of student learning and is said by researchers to be a defining characteristic of university education. However, how critical thinking is understood and defined varies quite significantly between disciplines. The paper describes a series of in-depth, semi-structured interviews with academics involved in teaching and learning in a number of disciplines, including engineering. The objective of these interviews is to look at how different disciplines define critical thinking and how they teach critical thinking in their courses. The paper also describes how an analysis of student work and module descriptors has led to the development of a model of critical thinking that can be used across disciplines.

Keywords: creativity; curriculum design; science education; university education; critical thinking

1. Introduction and literature review

Universities are under greater strain to show what the added value of a university education is. Critical thinking is a graduate attribute that a university education claims to instil in students and by many is seen as the defining characteristic of a university education (Phillips and Bond 2004). However, disciplinary understandings, ways of teaching critical thinking, ways of evaluating critical thinking, definitions of critical thinking and the importance placed on critical thinking can differ quite significantly: can critical thinking, therefore, be seen as a discipline specific or generic skill? This is a question that can be seen in much of the literature regarding critical thinking (Barrie 2006, Jones 2007).

In engineering (and also in other degree courses where accreditation from professional bodies is essential; Barrie 2006), it is also important to take account of what employers and accrediting bodies require from graduates. Critical thinking is a graduate attribute that engineering courses try to encourage in students. However, is it a skill that engineering employers need and have

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engineering academics, professional accrediting bodies and engineering employers ensured that their definitions of critical thinking are the same?

This paper describes a research project that examined how academics in an Irish university in a variety of disciplines, including engineering, defined critical thinking. The interviews also looked at whether the importance of critical thinking differed across disciplines and if the academics could identify what they felt were appropriate pedagogical techniques for introducing critical thinking skills to students. Documentary analysis was carried out of module descriptors, course handbooks and student work to help define a model of critical thinking that could be used in the future across disciplines, including engineering, to teach, assess and identify critical thinking.

Section 2 describes the methodology employed in the study, while section 3 describes some of the findings of that process. In particular, this section describes the differences that exist between disciplines in terms of definitions of critical thinking.

Section 4 outlines the model developed as a result of the interview analysis and how this was used to conduct the documentary analysis. Section 5 (the conclusions) outlines how the findings could be used in engineering courses to ensure that students are learning critical thinking skills and to identify critical thinking in student work.

2. Methodology: Interviews with academics

Table 1 outlines what disciplines were interviewed as part of the study.

The initial phase of this study consisted of carrying out interviews with 13 academics from the disciplines as listed in Table 1.

The interviewees were nominated by Heads of Department and the objectives of carrying out the interviews were as follows:

(1) To discover how the academics themselves defined critical thinking.
(2) To find out how the relevant discipline defined critical thinking.
(3) To establish the value and importance of critical thinking in the particular discipline (for students and for graduates).
(4) To discover if there was discussion and debate within the discipline about graduate attributes and critical thinking.
(5) To establish how critical thinking was taught in the discipline and how it might be recognised, assessed and measured in students and their work.

Table 1. Disciplines involved in the study

Discipline	Arts/Science	Professional – Yes/No
Chemistry	Science	No
Agricultural Science	Science	No
Maths	Science	No
Architecture and Civil Engineering	Science	Yes
Physics	Science	No
Mechanical Engineering	Science	Yes
Economics	Arts	No
Sociology	Arts	No
Social Justice	Arts	No
Business	Arts	No
History	Arts	No
English	Arts	No
Law	Arts	Yes

(6) To examine if critical thinking is addressed explicitly or implicitly in each discipline.
(7) To discover the barriers to inducing critical thinking in students.

Each interview lasted for at least an hour. As shown in Table 1, academics from a number of disciplines were interviewed, in addition to engineering academics. This was to examine if critical thinking is a generic graduate attribute or whether some element of critical thinking is discipline-specific.

3. Results

The interviews showed that definitions of critical thinking across disciplines are broadly similar. However, there are significant differences in how well formulated disciplinary definitions of critical thinking are and how the definitions have been reached. An interesting finding was the difference between how well formed the definitions of critical thinking held by non-technical disciplines were compared to disciplines like engineering. For academics in the non-technical disciplines, a real effort had been made to become acquainted with literature and pedagogical research. Discussions had been held about what critical thinking really was and what it might mean to students:

> 'In terms of my own understanding of critical thinking, it is just absolutely the centre of everything that either myself or my colleagues would have done over the years in terms of trying to get people to not just take things at face value. Always thinking is that true? What is the evidence? What are the counter possibilities? If you were looking for a way of substantiating it, how would you do it? If you were looking for a way of disproving it, how would you go about it? Examining if somebody says something, find somebody who criticizes and evaluate the counter positions and so on. I mean that seems to me to be what I have been doing since I became an academic 35 years ago.' (Academic from Humanities)

In contrast, in engineering, academics had clear ideas about the importance of critical thinking but found it difficult to verbalise what it actually meant, falling more into the 'I know it when I see it' division. It is hard to understand how the term 'critical thinking' can be explained to students and how they can be encouraged to learn this skill if engineering academics are still vague about what it means and how it can be recognised.

In the technical disciplines examined in this study, critical thinking appeared quite often in module descriptors and task descriptors without any real definition of what it was. However, what is interesting is that careful probing of interviewees, in an attempt to get them to think about critical thinking and what they felt it meant, interviewees stated that they equated critical thinking with problem solving, creative thinking and something a little more abstract and conceptual than simply learning facts, which is very similar, although less expertly or adroitly expressed, to those in the non-technical disciplines.

Academics in all disciplines were also questioned about the things that they felt helped or hindered students from becoming critical thinkers. Across all disciplines, the second level system of education was considered to be the most significant barrier to critical thinking. This system, interviewees felt, led to knowledge of facts without understanding and thus students lacked the ability to be independent thinkers.

It was felt by interviewees that the second level system was failing students in another way too and this was particularly relevant to those in the sciences and engineering-related disciplines: students were lacking in basic mathematical skills and scientific skills. They could learn formulae off by heart but had no real understanding of mathematics or science so significant time in engineering courses was spent on ensuring that students had basic mathematical and scientific skills:

> '…the big hurdle that we have to get over is a more basic one and that is the numeracy skills. Mathematical skills and statistical skills for our students are things we have to invest a huge amount of time and effort in. And therefore to that extent the critical side gets shoved to one side by the shear technical demands of the subject.'

Interviewees felt that subjects like engineering, economics and chemistry are so content driven in the early years that the space for introducing critical thinking was minimal. This was less of a problem in courses in the humanities. Does this indicate that students are badly prepared in these technical subjects at second level? Does this mean that universities are doing the jobs that should be done at second level and therefore cannot engage in what should be done at third level – that is, encouraging critical thinking, independent learning and questioning? This should be something that professionals in engineering should be concerned about. In particular, in a time when governments are placing greater emphasis on the need for graduates with technical, mathematical and scientific skills, it is worrying that academics feel that the second level system in Ireland is not preparing students adequately to face into degrees in these disciplines and that the students in these disciplines come later to learning critical thinking, questioning and independent thinking skills than those in humanities.

In terms of logistics, it was also felt that large class sizes made teaching critical thinking skills harder. This is because academics felt that non-traditional approaches such as problem-based learning and cooperative learning were better methods to encourage critical thinking but that the methods were harder to use in large classes.

As part of the interviews, academics were asked about the pedagogical approaches that might be used to engender critical thinking in students. Again, differences were noted between disciplines in how they taught critical thinking. In engineering, and other professional disciplines, content is very important so academics wanted to teach critical thinking from an early stage but admitted that they did not do this explicitly. In the humanities, there was a much more concerted effort to ensure that critical thinking was addressed very early on and that it was explicitly addressed in the curriculum and across modules. There may be lessons that can be learnt by engineering from the humanities in terms of academics themselves becoming more aware of what critical thinking is. Once they have this awareness themselves, it will be easier to communicate to students what they want from them and what critical thinking really is, rather than just using the term in module descriptors and course objectives.

For most graduates, in these disciplines, critical thinking was still seen as an important attribute that universities can engender in graduates and it was acknowledged that progress in these disciplines and successful careers in these disciplines would usually require some level of critical thinking.

4. Critical thinking model and documentary analysis

When the interviews had been analysed, a model of critical thinking was established to help with the analysis of the module descriptors and the student work. This model draws upon the work of Maton (2009a,b) and the interviews themselves. There are two terms that Maton (2009a,b) defines in his work and that must be described before giving the definitions of critical thinking used in the documentary analysis. These terms are semantic density (SD) and semantic gravity (SG; Maton 2009a,b).These terms represent opposite ends of a continuum and are inversely proportional. SD is more closely bound to what most academics typically view as critical thinking. It implies that a lot of meaning is packed into symbols and words and represents abstraction. SG, on the other hand, denotes work that is context dependent and needs examples. Most academics, as stated, would probably view a high level of SD (the ability to abstract and rise above concrete examples) as being required for critical thinking and this is true. However, in this paper, it is argued that movement between SG and SG is what characterises the critical thinker. The critical thinking student is someone who can take the empirical and rise above this with abstraction and theory but they can also use the concrete and context to ground their theory. Critical thinking is a movement backwards and forwards between the real and the abstract, the narrow context and the broader generalities.

In the next stage of this project, all interviewees provided the interviewers with the details of two modules that they felt required critical thinking in their students. For these modules, handbooks, descriptors and assessment tasks were provided. In addition, with the consent of students, pieces of course work where students were meant to demonstrate a level of critical thinking were also provided. These documents were all uploaded to NVivo for coding.

The model that was developed above, where critical thinking is dynamic movement back and forth between the concrete and the abstract, was used as the basis for coding the course work. Strong SG, which is context dependent and evidence based, is related to learning practical skills and knowing how to do something – whether this is knowing how to conduct an experiment in a laboratory or how to write an essay. It can be represented by the question: 'how do I do this?'. Strong SD is the student's ability to start to question why certain things are done – so in a laboratory to be able to question the methods used, the data and the results and to use this to be able to produce better experiments or to make recommendations (moving back again from abstract to concrete). This strong SD may be represented by the question: 'why do I do this?'.

Each module descriptor, module handbook and assessment task was examined to identify words, phrases or tasks that would direct students towards SD and towards SG. In the learning objectives, the analysis looked at whether the objectives included both objectives regarding up-skilling students in how they might perform tasks and also objectives that might direct students towards more abstraction and reflection. Assessment tasks were examined in conjunction with the accompanying course work to examine what types of tasks were most successful in bringing about a display of critical thinking in the students' work and what language or terminology in assessment tasks was successful in bringing about critical thinking.

Critical thinking is the ability to perform a task, to reflect and question and to ground abstraction and reflection in the reality. In the module descriptors and assessment tasks from some disciplines, evidence was found of movement from SG to SD and back again. Much of this evidence was found in non-technical disciplines and it was apparent that much can be learnt in engineering and technical disciplines about how to evoke critical thinking in students. The greater awareness held by those academics in the humanities and other non-technical disciplines lead to very good and clear examples of learning objectives and assessment tasks, where students were given the directions they required to become critical thinkers. This was less evident in the technical disciplines and perhaps relates to the fact that those academics interviewed from technical disciplines had less sure or well-verbalised definitions of critical thinking and so found it harder to articulate in tasks and learning objectives what they were seeking from students.

This paper includes two good examples of where students were helped to become critical thinkers: one is an assessment task from Law and the other is a set of learning objectives for students of Architecture. These examples of teaching approaches are included in this paper to demonstrate how engineering learning objectives and assessment tasks might be structured to elicit critical thinking.

In both examples, clear directions were given to students about how particular tasks should be structured. In both examples, students were asked to use concrete, real information to examine, construct and question more abstract theories and ideas. They were then asked to relate these theories and ideas back to new examples and to analyse empirical evidence, using the abstract concepts they had discovered.

Here is the example from Law:

> 'Each student will be assigned a charity as their adoptee for the coming semester and over the course of the semester each student must develop a written charity portfolio, relating the issues discussed in class to their individual charity. The portfolio would thus contain chapters relating to the charitable purpose advanced by the charity and how it meets the public benefit test; the governance structure of the charity; the challenges facing the charity in the context of the new statutory regulations on accountability and financial reporting; its fundraising procedures; its interactions with the state (through advocacy) and the market (through trading); the organization's tax treatment; whether cross-border regulatory issues are of concern to the charity and how it is facing up to the challenges of the 21st century. Based on a

review of its legal framework and its operations, the portfolio should identify the biggest regulatory challenges facing the chosen charity and examine whether a strong case could be mounted that it deserves better funding. The portfolio should also advise the charity of any weakness in its current structures and procedures and make recommendations for tackling those shortcomings.'

Students are not only being told what needs to be done and how it should be done, but also to apply the abstract principles and concepts that are being discussed in class to a specific concrete example– they are being directed to move from SG to SD and thus to become critical thinkers.

In an Architecture module, students were given the following learning outcomes:

On completion of this module students should be able to:

- describe the physical form of significant buildings, settlements, cities and designed landscapes in a predominately European context;
- analyse how buildings, settlements, cities and designed landscapes over this period responded to functional, aesthetic and structural criteria;
- discuss the way in which societies and cultures convey meaning through the artefacts of the designed environment;
- reflect on how architecture, settlements and landscapes have evolved over time borrowing from tradition to solve problems and create new forms.

Table 2. Critical thinking assessment

SG – How do I do this?	Movement from SG to SD – Terms and tasks that enable critical thinking FLOW – this is the 'cognitive shuttling' from SG to SD and back again.	SD – Why do I do this?
Principles	Apply →	Skills
Perspectives	← Reflect	Know-how
Constructs	Synopsise →	Practical
Ideas	Produce a clear and structured argument →	Knowledge
Models	Summarise →	Framework
Concepts	Explain →	Real world
Assumptions	← Understand	Employability
Theory	Real life →	Demonstrate
Incomplete information	Begin (early stage – keeps them stuck!)	Example
Meanings	Identify →	Particular
Inferences	← Devise	Plan
Forces and factors	← Formulate	Problems
Underlying	← Form your own opinions	Goal
Meanings	Contextualise →	Dictionary definitions
Interpretations	← Contrast →	Definitions
Immaterial/Figurative	← Compare →	Poor reflection
Reflection	Previous knowledge →	
	Justify →	
	Resonate	
	Synthesise →	
	← Judge	
	← Assess	
	← Evaluate	
	← Discriminate	
	← Eliminate	

SG = semantic gravity; SD = semantic density.

Again, this demonstrates that a movement from the context dependent (describing physical form) to the more abstract (reflections on architecture and landscapes) while grounding those reflections in reality.

Based on this analysis of the modules, the language that can be used to demonstrate SG, SD and movement between SG and SD was identified, and is outlined in Table 2.

5. Conclusions

A key finding is that critical thinking is not a static attribute that all students should aspire to as the ultimate destination in their education. Instead, it is a dynamic concept that requires academics to guide students through engagement with context-bound knowledge and the empirical, on the one hand, and knowledge that is abstract and reflective, on the other. It is the movement back and forward between these two states that represents critical thinking.

From the analysis of the interviews with academics and the analysis of students' work, it is apparent that critical thinking is important to most disciplines. However, the clarity of understanding of the term 'critical thinking' varies quite significantly, with disciplines in the humanities having very clear definitions of critical thinking, whereas technical disciplines are less clear on what they mean when they ask students to be critical thinkers. However, in engineering and other technical disciplines, investigation and close analysis of what academics were saying show that many of the ideas and perceptions that academics from a range of disciplines have of critical thinking are similar. All seem to agree that it involves students being more questioning, less accepting of facts as given to them and that it generally is a skill that students attain as they move from lower years to higher years.

There are differences in approach to teaching critical thinking across disciplines. The greatest difference is that in technical and engineering disciplines, where academics are less sure of their own definitions of critical thinking. There is less explanation of the term to students and students are not told quite so explicitly what is expected of them. In disciplines in the humanities, students are given guidance on how to become critical thinkers and of what is expected from them as they move through the university system. In the present authors' opinion, if universities claim to produce critical thinkers, they need to be more explicit about what it is and how it is realised and how it can be recognised. It is with this in mind that this paper describes a structure that outlines what the present authors feel critical thinking 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.

In engineering, there is a need to engage more closely with educational literature to understand critical thinking. It is only through understanding critical thinking that engineering academics can describe it to their students. Engineering can learn from the humanities and professional disciplines such as law and architecture, where critical thinking is more explicitly addressed and students are given clearer guidelines of how to become critical thinkers. By using the ideas described in this paper (that critical thinking is a movement from the contextual to the abstract and back again), it should be possible to design learning objectives and tasks that enable engineering students to become critical thinkers. It is hoped that future research can test the use of this model in designing learning objectives. Future research will also focus on examining how employers define and value critical thinking.

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