Epistemic Practices:
a framework for characterising engineering students' epistemic cognition.

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DECLARATION

This thesis results entirely from my own work, and has not been offered previously for any other degree or diploma. The total word count, including appendices, does not exceed the maximum permitted length.

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ABSTRACT

Solving complex, open-ended problems is frequently characterised as the central activity of engineering. Such problem solving requires a high level of epistemic sophistication, however, few studies have investigated the relationship between epistemic cognition and engineering students' problem solving strategies. While there are several models of epistemic cognition, they consistently characterise approaching knowledge as though there is a single, absolute correct answer as naïve. Higher epistemic sophistication is taken to involve more nuanced beliefs such as perceiving knowledge as relative, contingent, and contextual. However, decades of active research have failed to produce robust quantitative instruments. This thesis exploits a recent conceptual development which posits that selecting an *effective* epistemic approach for a specific knowledge claim is a better measure of sophistication.

By focusing on observable, fine-grained actions to characterise how engineering students approach, justify, and evaluate contexualised scientific knowledge, this study eschews overarching epistemic beliefs in favour of epistemic practices to develop a rich portrait of engineering problem solving. The grounded theory analysis of the think-aloud problem solving protocols and interviews with 30 undergraduate engineering students produced a set of eight epistemic practices, each of which are described at four levels of sophistication.

While the strict separation between epistemic beliefs and actions is distinctive of this project, five of the epistemic practices are coherent with prior models and three are novel and engineering-specific: *equations as imperfect models of reality*, *precision and estimates*, and *answer-checking strategies*. Finally, this study proposes the diversity of students' epistemic practices as a measure of epistemic sophistication, rather than *effectiveness*. Diversity has the dual benefits of being reflective of expert problem solving and attenuating the effects of students' prior knowledge, disciplinary background, and the specific activity. The epistemic practices are presented as a coherent framework that is accessible to engineering teachers and facilitates application in other contexts.

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It has been an exciting, stressful, frustrating, and fulfilling journey. I can hardly believe that it is finally done. But I am very ready for the next chapter of my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

1.1 Epistemic Beliefs and Cognition in Engineering

The importance of developing students' epistemological beliefs isn't something you hear much about around engineering campuses. The central questions of epistemology (How do we know what we know? And why do we believe it?) sound too philosophical to be relevant for engineering problem solving. Yet these questions are absolutely asked, and answered, when engineers work to solve the ill-structured, open-ended problems that are characteristic of professional engineering practice. Indeed, the majority of the biggest problems facing humanity today, such as ensuring access for all people to clean water, food, and healthcare, and finding environmentally-sound mechanisms for transportation, communication and energy generation (United Nations 2016) require the direct and sustained application of engineering problem solving. This means that society in general, and not just engineering educators, are concerned by engineering graduates' abilities to use appropriate disciplinary epistemic skills for creating, interpreting, evaluating, and justifying knowledge.

Engineering schools have increasingly integrated more project work into their curricula to equip their students with skills to tackle authentic engineering problems. Working with teachers to design and facilitate learning experiences that enable students to acquire these skills is a core aspect of my role in the Teaching Support Centre of a Swiss engineering school. While some students thrive when challenged with ill-structured and interdisciplinary problems, others find it difficult and question the value of such experiences. I have heard students say "Don't ask for my ideas: I'm just a student. It's your job to tell me the correct answer", "But which answer is the right answer?", and "This assignment was unfair – it asked us to think, not to show you what we've learned." These responses reflect the naïve epistemic conceptions of these students, and the corresponding focus on correct answers rather than effective answer-finding processes. I was a postgraduate student teaching assistant in chemistry when I first encountered the concept of epistemic beliefs.

While I am still happy with my decision to major in chemistry, I now recognise that my choice was influenced by my epistemic beliefs at the time. Graduating from high school in Canada, I had received the Ethel Kidd award for having the highest marks in both maths and English. I liked maths better – I was confident that I was doing it correctly because my answers exactly matched those at the back of the book. When I learned about epistemic beliefs as a teaching assistant, I was trying to help students overcome similar naïve beliefs that were limiting their ability to reason with uncertainty and multiple constraints.

Encountering the concept of epistemic beliefs in a teaching assistant development workshop ignited a slow burn that ultimately produced this thesis. My primary interest in epistemic beliefs remains quite practical: how do we prepare engineering students to tackle authentic, ill-structured, interdisciplinary problems? Identifying teaching and learning activities that effectively support students' epistemic development was central to my motivation starting this project. However, my investigations and review of the literature led me to focus on developing a more effective way to characterise epistemic cognition in engineering. While the focus of this project is less applied than I initially intended, my contributions to conceptualising epistemic cognition in engineering have addressed some persistent obstacles to measuring epistemic sophistication. My approach has remained quite practical, arising both from my highly contextualised methodology and my desire to support the development of engineering students' epistemic cognition.

Effectively addressing the complex issues currently facing humanity requires that engineering graduates have a high level of epistemic sophistication. It is, therefore, concerning that previous work has identified that engineering students often do not have this. Engineering students' epistemic beliefs[1] have been found to progress over the course of their studies (Culver and Hackos 1982, Marra *et al*. 2000, Felder and Brent 2004, King and Magun-Jackson 2009). Paulsen and Wells (1998) found that, when controlling for other demographic factors, engineering students were more likely to hold unsophisticated epistemic beliefs than students from other fields. Pavelich and Moore (1996) and Wise *et al*. (2004) report that up to three quarters of engineering graduates' epistemic sophistication is insufficient to effectively manage contradictory knowledge claims or to see themselves contributing novel insight to the field. This is completely incompatible with solving the ill-structured problems that are central to professional engineering practice.

While the reasons for engineering students' low epistemic sophistication are likely numerous, the lack of an engineering-specific model is certainly not an asset. Consequently, there is a significant gap between overarching models of epistemic beliefs and specific knowledge practices engineering students apply during problem solving. This gap may also explain persistent inconsistencies and difficulties in measuring epistemic beliefs. This thesis provides a bridge across this separation, taking an epistemic cognition approach to characterise engineering students' actions while solving engineering science problems. The resulting 4-level framework of specific, contextual epistemic practices provides an accessible and robust model of epistemic sophistication in engineering.

1.1.1 Why an Engineering-Specific Characteristation of Epistemic Sophistication is Important

The importance of epistemic sophistication for engineers is ubiquitous in the literature, although it is formulated in terms of students being "more capable of addressing engineering problem-solving in real world contexts because of their ability to see problems from multiple perspectives and recognise that more than one right answer exists" (Wise *et al*., 2004). More prosaically, epistemic

[1] I prefer the term epistemic beliefs, rather than epistemological beliefs. This project focuses on the nature of knowledge and not a more philosophical reflection involving beliefs about how people conceive of the idea of knowledge and knowing implied by the term 'epistemology'.

sophistication is present in the accreditation of engineering programs. For example two of the seven student outcomes required by the US-based Accreditation Board for Engineering and Technology explicitly state that graduates must be able to make informed judgements when confronted with complex situations, and a third outcome includes the ability to navigate potentially contradictory or ambiguous contexts (ABET 2021, pp. 5–6).

Despite their importance, a lack of consensus on the definition of epistemic beliefs has generated a plethora of approaches and nomenclature (Hofer and Pintrich 1997, Briell *et al*. 2011, Sandoval *et al*. 2016). This thesis makes use of Briell *et al*.'s distinction between cognitive structures and cognitive processes models to organise prior models so that their relevant similarities and differences are clear. Cognitive structure models concern themselves with people's mental states that hold conceptions about knowledge and knowing. Cognitive structure models of epistemic beliefs correspond to how beliefs are usually understood, that is as abstract concepts about knowledge and knowing. Models that employ a cognitive processes approach, such as epistemic cognition, focus on how people manipulate, construct, evaluate or justify particular knowledge claims in specific contexts.

While most studies have sought to demonstrate the importance of epistemic beliefs for students' learning (Norton and Crowley 1995, Pavelich and Moore 1996, Marshall *et al*. 1999, Tsai 1999, Burnett *et al*. 2003, Kember *et al*. 2004, Stathopoulou and Vosniadou 2007, Muis and Franco 2009, Montfort *et al*. 2012, Ding 2014, Greene *et al*. 2018, Zhu *et al*. 2019), the continuation of naïve conceptions in professional engineering practice is clearly problematic. For example, naïve epistemic beliefs in practising engineers could be expressed as an unexamined trust in figures of authority or by attempting to find the single true answer to a real world situation of applied engineering. In this context, Pavelich and Moore (1996) and Wise *et al*.'s (2004) findings that the majority of engineering graduates have insufficient epistemic sophistication to operate in the core contexts of professional engineering is highly worrying. This thesis' contributions to an accessible, engineering-specific model of epistemic sophistication are therefore relevant and timely.

1.1.2 A Brief Review of the Literature on Epistemic Beliefs and Cognition

William Perry created the first model of personal epistemology based on his longitudinal interview study with Harvard undergraduates (1970). His developmental, stage-based model described how students' epistemological beliefs influence how they see the world and make decisions. This work sparked a half century of active research in the field, with multiple models seeking to provide a coherent conceptual foundation with solid empirical support.

In addition to Perry's perennially popular model, three particularly influential models were created by Patricia King and Karen Kitchener (1981, 2004), Marlene Schommer-Aikins (Schommer 1990, Schommer-Aikins 2004), and Barbara Hofer and Paul Pintrich (1997). While the general arc of epistemic development is consistent across the models, poor empirical support and persistent measurement problems (Sandoval 2005, Stathopoulou and Vosniadou 2007, Greene *et al*. 2008, Hofer and Bendixen 2012, Rizk *et al*. 2012, Greene and Yu 2014, Lindfors *et al*. 2019) have continued to motivate researchers to address potential underlying issues with the models. A major advance is the recognition that, at least in the current state of understanding, the disciplinary context in which a person perceives themselves and the knowledge under consideration must be considered (Lindfors *et al*. 2019).

While King and Kitchener's reflective judgement model is not cited with nearly the frequency of Hofer or Perry (Sandoval *et al*. 2016), I find opportunity in its focus on epistemic cognition. While beliefs models have dominated the research agenda in the field, Sandoval succinctly identified the power of an epistemic cognition approach to advance the field, noting "One important way to understand the epistemic ideas that people bring to bear is to examine their participation in practices of knowledge evaluation and construction" (2012, p. 350). The richness and contextualisation that an epistemic cognition approach to how knowledge is created, manipulated, and justified is exactly what is needed to overcome the confusion generated by the more common focus on overarching, broad epistemic beliefs. Elby and Hammer (2010), working predominantly on physics problem solving, propose taking a finer-grained approach to epistemic cognition in their epistemological resources model.

The approach taken in this thesis employs an even more fine-grained approach to epistemic cognition that focuses on specific, contextualised actions that students take while solving engineering science problems. Employing a grounded theory approach enabled a tight connection between the empirical observations and the framework of epistemically-relevant problem solving behaviours generated.

This thesis answers Sinatra's (2016) call to explore the use of epistemic beliefs and conceptions of knowledge in settings where problem solving, decision making, and reasoning are occurring. Mason (2016) argues that there have been too few empirical investigations that capture "epistemic beliefs in action."

1.1.3 Study Methodology

This thesis employs an epistemic cognition approach to characterise engineering students' problem solving. This approach does not concern itself with the problem solving method itself but rather with the fine-grained knowledge practices within students' problem solving that are related to how engineering knowledge is created, evaluated, and justified. While the low number of study participants precludes rigorous quantitative analysis, I examined the rich qualitative picture of students' problem solving to characterise the nature, range, and frequency of different knowledge practices. The analysis addresses the following research questions about students' epistemic sophistication during engineering problem solving:

RQ1: What epistemic practices do engineering students use during problem solving?
RQ2: Do a student's epistemic practices cluster at a single level or span several levels of sophistication?
RQ3: What do the epistemic practices profiles of epistemically sophisticated engineering students look like?

The methodological approach of this thesis had two guiding principles. First, to avoid the quagmire of inferring epistemic beliefs from self-reporting surveys (Greene and Yu 2014) by focusing on how students manipulate and evaluate engineering knowledge in a fine-grained manner. Secondly, to develop empirically-based descriptions of engineering students' epistemically-relevant problem solving. Accordingly, engineering science problem-solving tasks were carefully constructed to stimulate students to enact a range of epistemic practices. The think-aloud problem solving protocols were followed by semi-structured interviews and generated rich observations that were analysed with a grounded theory approach.

1.1.4 Main Findings

The epistemically-revealing problem solving practices employed by the 19 engineering student participants were resolved into seven types of epistemic practices and organised into a 4-level framework. Readers acquainted with epistemic beliefs models will recognise elements of several epistemic practices, however my engineering-specific formulations provide some novel facets. For example, sources of knowledge include familiar origins such as experts, but also mathematical derivation and physical experimentation. Additionally, I describe three novel engineering-specific epistemic practices: *equations as imperfect models of reality*, *precision and estimates*, and *answer-checking strategies*.

In my framework, the epistemic progression described across the four levels is not a developmental shift but rather an increasing range of available practices. Practices characterised in the first level, *absolute*, do not seek to justify or validate answers that come from sources deemed expert. *Local coherence* practices, the second level, apply strategies that seek logic and consistency with elements in the immediate vicinity. For example, that the mathematical operations are correct. The third level practices, *coherence*, also seek consistency at a larger scale by drawing on personal experiences and observations of the physical world. Practices at the most sophisticated level, *sceptical reverence*, recognise ambiguity and the need to make judgements. This final level is drawn from Julie Gainsburg's work with professional engineers (2007).

While my practical focus could be interpreted as a step away from the ideal of a robust, overarching theory, it provides new insight into the often identified but continuously discounted/neglected observations that the same student can express beliefs corresponding to both highly sophisticated and very basic epistemic approaches with little temporal separation. Elby and Hammer's under exploited epistemological resources model, where increasing sophistication is characterised by selecting a productive stance to achieve the current goal is a more coherent explanation (Elby and Hammer 2010, Elby *et al.* 2016). However, I propose the refinement that the overall diversity of the epistemic practices that a student employs is a better measure of their epistemic sophistication.

The overall arc of increasing sophistication described in this thesis is coherent with prior models, however the rigorous focus on epistemic cognition and omission of any inference of overarching epistemic beliefs results in a framework that is rich, practical and fine-grained yet sufficiently general to be applied in other contexts.

1.2 Structure of the Thesis

This first chapter has presented the goals and motivations for this doctoral study in terms of how epistemic cognition is relevant to the societal role of engineers.

Chapter 2 provides more detail on the context of the study through an examination of the existing literature. Issues arising from the under-exploitation of models of epistemic cognition, the conflation of overarching epistemic beliefs and specific knowledge practices, and an inadequate attention to context are used to make the case for the epistemic practices approach developed in this thesis.

Chapter 3 reports the research design and methodologies employed in both the qualitative and quantitative studies conducted.

Chapter 4 reports and analyses the empirical observations from the four studies conducted with engineering students. This includes of a set of qualitative interviews conducted in 2015, two sets of qualitative interviews preceded by think-aloud problem solving sessions conducted in 2016 and 2017-18 respectively and the results of the quantitative questionnaire studies conducted in 2015-16.

Chapter 5 critically assesses the observations of the four studies, and situates them with respect to previous work in the field, particularly with reference to the work of King and Kitchener, Julie Gainsburg, and Elby and Hammer.

Chapter 6 concludes the thesis by drawing together key ideas that have emerged across the preceding chapters. Focusing on the epistemic practices framework anddiversity as a measure of epistemic sophistication, this summary highlights the contributions to knowledge of this thesis.

2 Literature Review

2.1 Epistemic Structures and Epistemic Processes

Epistemic beliefs are fascinating yet elusive, as the enduring level of research in the field attests. While a multitude of studies have generated a wide range of approaches, empirically-based, testable models are rare (Muis *et al.* 2006, Bråten 2016, Sandoval *et al.* 2016). An additional weakness is that these models conceptualise epistemology as a "very abstract principle at great remove from practical actions", which Perkins has identified as a key obstacle to theory being applied in, for example, teaching (2003, p. 213). As my research questions have made clear, my objective is to contribute to a robust yet accessible model by taking a fine-grained, practical approach to investigating how knowledge is used and applied during problem solving by engineering students. As this chapter will illustrate, I identified a major lack of attention to the disciplinary epistemology in terms of the engineering-specific ways knowledge is generated, manipulated, and justified. While experts certainly use disciplinary thinking skills, Entwistle states that teachers are unlikely "to teach them explicitly, and may need help in identifying them for their students" (2018, p. 157). To use Perkin's terms (2003), my literature review demonstrates the potential of my research to contribute to the field in terms of both *explanatory theory* relevant to researchers and *action theory* that provides an accessible way for engineering teachers to develop epistemic sophistication in their teaching.

As I argued in the Introduction, sophisticated disciplinary epistemic skills enable an engineer to perform effectively in their field. While engineers mobilise considerable knowledge and numerous skills when they solve the ill-structured problems they encounter as professionals, epistemic sophistication is a key aspect for applying their knowledge in contextually-relevant ways. This chapter therefore starts by identifying several core challenges for solving ill-structured engineering problems, including using models and managing uncertainty. This serves to focus our attention on the knowledge skills that are relevant to engineering yet are absent from current models of epistemic sophistication in engineering.

The second part of this chapter critically reviews the broad field of epistemology with a particular attention to the distinction between cognitive structures approaches and cognitive processes approaches (Briell *et al.* 2011). While Briell *et al.*'s approach is not widely used, it is ideal for illuminating how cognitive structures approaches have monopolised research focus yet have failed to deliver robust, empirically-supported models. Supported by a detailed review of the literature, I critique the focus on overarching epistemic beliefs and argue for a pragmatic cognitive processes approach based on students' contextual, enacted knowledge practices.

The chapter concludes by demonstrating how the research questions of this thesis address persistent issues and contribute to a much-needed model of epistemic sophistication that is contextualised in the discipline of engineering, coherent with empirical observations (both from the current study and the work of other researchers), and incorporates recent theoretical developments in the field.

2.2 Thinking Like an Engineer

2.2.1 Problem Solving is Engineering

Problem solving is often used as a near synonym for engineering (Pawley 2009, Mourtos 2010, Passow and Passow 2017, Zhu *et al.* 2019), an approach that is markedly different from most disciplines which tend to make knowledge itself and not the application central to their disciplinary identity (Case and Marshall 2016). Investigations of engineering problem solving have explored many facets from the types of problems encountered by professionals to problem-based learning, yet few studies have focused on the specific, fine-grained strategies that students use during their problem solving (Litzinger *et al.* 2010, p. 338).

While the problems that students encounter during their studies tend to be well-structured and focus on aspects of engineering science (Dym *et al.* 2005, Sheppard *et al.* 2008, Swenson 2020b), professional engineering work introduces multiple additional challenges related to functioning in complex, dynamic environments. The types of problems encountered by professional engineers are typically characterised as being ill-structured.

The key characteristic of ill-structured problems is that they do not have an established method for solving them (Gainsburg 2007, Crismond and Adams 2012), although recurrent features include: the need to define the problem (King and Kitchener 2004, Gainsburg 2007, Crismond and Adams 2012, Swenson 2020b), deciding what criteria will determine acceptable answers[2] (Dym 1994, Gainsburg 2007), and the collection of relevant information. This is done within a problem space where none of the data is known with complete certainty nor is guaranteed to be constant (King and Kitchener 2004, Swenson *et al.* 2019). The open-ended departure point, the uncertainty of data, and the multiple correct answers that require the engineer to defend their final solution require advanced problem solving skills.

It is therefore unsurprising that significant effort in engineering education has been devoted to developing students' problem solving skills. One common result is that engineering curricula have sought to include more open-ended, authentic projects in order to address the gap between well-structured classroom problems and ill-structured work place problems (Jonassen 2000, Marra *et al.* 2000, Wise *et al.* 2004, Jonassen *et al.* 2006, Yadav *et al.* 2011, Zhu 2017, Swenson *et al.* 2019). Entwistle *et al.* (2005) state that it is important to scaffold engineering students by decreasing their reliance on routine, algorithmic approaches to problem-solving and to support them to adopt more conceptualised strategies towards their studies. For Allie *et al.*, this means that engineering lecturers must make their tacit ways of thinking and interacting in engineering more explicit for students, particularly the "rhetorical patterns underpinning their disciplinary knowledge

[2] Note: more than one answer.

bases" (2009, p. 363). These more open-ended projects have been shown, over time, to improve students' skills when they have sufficient opportunities to practice (Martin *et al.* 2005).

"Unfortunately, relatively little research has specifically examined the strategies students use while solving engineering related problems" (Litzinger *et al.* 2010, p. 338) and therefore not much is known about the specific strategies and approaches that need this careful scaffolding[3]. In their think-aloud study of students working on solving textbook statics problems, Litzinger *et al.* note with concern that "few of the students could reason physically" (2010, p. 337). This suggests that making connections between physical reality and paper-based exercises is an area that requires development. Litzinger *et al.* also found that stronger students generated more problem representations (i.e. models) and used four times more self-explanations than did weaker problem solvers. It is interesting to note that the types of explanations and representations of strong problem solvers spanned all the categories and did not concentrate in any particular category.

The following sections explore the fundamental aspects of open-ended engineering problem solving; in order to situate the contributions of this thesis, careful attention is afforded to how models and equations are used, and how uncertainty and precision are managed.

2.2.2 Using Models and Equations on Paper or Connected to Physical Reality

Modelling is an activity that "involves indirect representation and analysis of real-world phenomena" (Boon and Knuuttila 2009, p. 209) and it is central to the practice of engineering (Gainsburg 2013, Bucciarelli and Kuhn 2018, Swenson 2020a). However modelling is a broad term encompassing a range of different practices: mathematical equations, free body diagrams, schematics, and scale models are all examples of modelling practices used in engineering. Müller says models can be classified either according to what kinds of object they are or

[3] There is a fascinating body of research documenting effective practices for the process of problem solving (ie Polya 1985, Jonassen 2010), not to be conflated with the epistemic strategies targeted by the current work.

according to what they are intended to do, although in practice the boundary is often messy (2009). Weisberg asserts that the common goals of these different practices is a desire to "assess the relationship between the model and the world" (2007, p. 209). However, the prevalence of computers and computational modelling techniques can increase the conceptual separations between the system being modelled, the model, and the calculated values or predicted outcomes. This means that engineers need to be more expert, not less, with models in order "to understand the implicit assumptions built into their software tools to understand where failure points could occur and how to interpret the results" (Swenson 2020a, p. 5).

Boon and Knuuttila (2009, p. 694) report that models are typically understood as "representations of an aspect of the world or a target system" but propose that models should be considered to be epistemic tools. Their approach makes explicit both the importance of the disciplinary context and the focus on the activity of modelling (rather than models as objects). Smit's (2017, p. 56) observation that "modellers can turn constraints (such as simplifying assumptions) into enablers for problem-solving" is consistent with seeing models as epistemic tools and with the centrality of problem solving in engineering. Bucciarelli and Kuhn (2018, p. 212) state that "The engineer's ability to abstract [a model] from a concrete situation… is key to problem solving and to managing complexity" and that it is "one of the crucial skills conveyed as part of disciplinary training" in engineering. The range of types of models listed above illustrates the importance of these epistemic tools in engineering problem solving, and underlines the importance of adequately preparing students to use models in effective ways.

Like Berland and Crucet, this project finds the use of models to be an epistemically-revealing practice as it requires students "to attend to different features of the model and make context-dependent decisions about how best to use and evaluate" the outcome (2016, p. 11). As explored above, many different types of modelling are used in engineering. However, the scope of the current work considers models only in terms of mathematical equations[4] as this is adequate to address the

[4] My use of the term model is less detailed than Michael Weisberg's careful work that distinguishes between the models themselves and the equations or model descriptions used to represent the

research questions.

Mathematical equations employed to make predictions and calculations in engineering may be the result of empirical observations or express relationships that were developed from theory. Either way, these equations represent the general, sometimes abstract or idealised, end of the continuum that engineers must master, with the specific physical reality under consideration at the other end. Blömeke *et al.*'s (2008) study of teachers' epistemological beliefs identified conceptions of maths knowledge ranging from a collection of rules and formulae, a formalist perspective focused on the exact and logical, to a process-related problem solving activity and finally something relevant for society and life. While Blömeke *et al.* report these conceptions in terms of their epistemic sophistication, I find it useful rather to think of them along a continuum that describes the progression from abstract to applied. This organisation makes apparent the necessity that engineers attend to both extremes of this continuum when solving ill-structured problems. A failure to navigate between the two extremes and conducting problem solving as a purely mathematical, and apparently precise, undertaking neglects both the value of physical observations to advance problem solving and the implications of ambiguity and uncertainty present in application contexts. Swenson *et al.* (2020a) identify the need to check modelling assumptions against the real-world application as a key aspect of competent use of models and simultaneously highlight that students are typically assigned only problems that fall within acceptable parameters for the models they should apply. Swenson *et al.*'s (2019) study with high performing engineering students found that all five students were able to see two different approaches from which their models could be evaluated: demonstrating their ability to apply principles from the course and providing an adequate basis for a real-world application. In addition to the overall evaluation, Swenson *et al.* (2019) observed students checking their models by: having used all the course concepts learned up to that point, (same student) personal experience with the weather, (different students) having seen similar objects in the field, finding the model too simple to represent the real world, noting

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models in mathematical form.

that numbers seem unrealistic (too big, too small), calculations are error-free and/or logical, and that the solution satisfies the assignment. Swenson *et al.* argue that these behaviours represent the "productive beginnings of engineering judgement" (2019, p. 4). I will return to the benefits of drawing on a range of epistemic approaches later in this thesis. The following section addresses the importance of ambiguity and uncertainty in engineering problem solving.

2.2.3 Authentic Engineering Problems Involve Uncertainty

Uncertainty is an inevitable corollary of the open-ended, ill-structured problems identified above as central to professional engineering practice. The uncertainty arises from two main aspects. First, the available data or information about application contexts may be imprecise, incomplete, ambiguous, or subject to dynamic change (Ang and De Leon 2005). Consequently, many problems cannot feasibly be solved without the use of approximations (Smit 2017, p. 55). Second, the final solution depends on judgements made by the engineer/s about the definition of the problem and the relative importance of the constraints and outcomes (National Academy of Engineering 2004, Ang and De Leon 2005). Managing uncertainty and ambiguity is one of the most cognitively challenging aspects of ill-structured problem solving (National Academy of Engineering 2004, Stevens *et al.* 2008, Atman *et al.* 2010, McNeill *et al.* 2016).

"Engineering decisions are invariably made under substantial uncertainty" (Rockafellar and Royset 2015, p. 1), which is a key way that textbook and school problems are unlike professional engineering practice (Downey and Lucena 2003, McNeill *et al.* 2016). Textbook problems typically provide all the information necessary, such that all students should produce an identical, highly precise answer. McNeill *et al.*'s (2016) study of material science engineering students solving open-ended problems identified that dealing with uncertainty and making assumptions were among the most difficult aspects for students. Students are rarely required to generate approximate value, use estimates to advance their problem solving or to construct an argument to justify decisions taken to establish priorities for the solution. Students' discomfort with ill-defined problems can persist even after they have finished the task, due to an apparent belief that they should obtain a single, unambiguous correct result that is at odds with the contexts they will encounter in their professional careers (Swenson 2020a).

The multiple differences between the textbook problems students train on and the ill-structured problems encountered in professional engineering practice limit students' opportunities to manage both kinds of uncertainty introduced in the first paragraph of this section. Thus, part of the open-ended projects that are increasingly common in engineering curricula is learning that uncertainty is inherent in engineering work. While Dringenberg and Purzer's (2018) study of first year students working on ill-structured problems focused more on the transversal skills related to team projects, they identified the ability to accept ambiguity and ascribe value to multiple perspectives as essential factors for success. Indeed, Leifer and Steinert (2011) have identified that an ability to embrace ambiguity is central to innovation, which is a key goal of engineering.

It is therefore unsurprising that the ability to function and make decisions in the face of uncertainty is present in the accreditation criteria for engineering programs (Crawley *et al.* 2011, Commission des titres d'ingénieur 2020). In fact, the ability to function with ambiguity is referenced three times in the *conceive design implement and operate* (CDIO) syllabus: decision analysis with uncertainty (ref. 2.1.4), initiative and willingness to make decisions in the face of uncertainty (ref. 2.4.1), and making complex technical decisions with uncertain and incomplete information (ref. 4.7.7). It is clear that an ability to manage imprecision, approximations, and uncertainty are important yet under-developed skills for engineering students.

2.2.4 Thinking like an Engineer is Epistemic

Expert engineers demonstrate more sophisticated epistemic approaches than novice engineers (Felder and Brent 2004), a connection that has been explored by numerous researchers in terms of the development of competent engineers (Marra *et al.* 2000, Felder and Brent 2004, Marra and Palmer 2004, Wise *et al.* 2004). Each discipline has its own epistemology, its own way to create, communicate, and justify knowledge, which means that the problem solving behaviours of experts are necessarily characteristic of the discipline (Voss *et al.* 1983). Donald places a particular emphasis on the way knowledge is verified and evaluated in a discipline, writing that they "differ so much that they are the defining characteristic of the disciplines" (2002, p. 286).

For engineering, the centrality of problem solving makes it an ideal activity for observing disciplinary epistemology and how it is enacted in the various practices required to solve problems ranging from well-structured textbook to ill-structured professional problems. These practices involve managing imprecision and uncertainty, and manipulating models and equations. These engineering-specific aspects serve to embed the observations of this thesis in the discipline and are explored in parallel with general aspects of epistemic cognition identified in prior scholarly work and presented in the following sections.

2.3 Models and Approaches for Characterising Epistemic Beliefs

My focus is on the value and relevance of epistemic sophistication for today's engineering students. However discussions about epistemology (from the Greek study of knowledge) date back to Plato (circa 300 BCE). Then, epistemology was "An area of philosophy concerned with the nature and justification of human knowledge" (Hofer and Pintrich 1997, p. 88). The "tremendous expansion" of research in the field over the past 20 years (Sandoval *et al.* 2016, p. 457) can be attributed to William Perry's work in the 1970s, which took a more practical approach by seeking to understand why students responded differently to the intellectual and social environment of university. Proponents of "naturalised epistemology" (Goldman 1994) recommend using contributions from psychology and other sciences to move away from theorising about knowledge and knowing to exploring the processes people employ in making and evaluating knowledge. This approach has been taken up particularly in disciplinary contexts (Kelly 2016), including engineering. As I illustrate below, a fine-grained, cognitive processes approach is a promising way to address the continued lack of an engineering-specific model of epistemic sophistication.

Contributions from the fields of education and developmental psychology, learning sciences, and disciplinary education have led to a broad range of approaches and conceptualisations. This has predictably generated a diverse range of terminology including: epistemological beliefs (Schommer 1990), epistemic beliefs (Muis and Franco 2009), epistemological resources (Louca *et al.*

2004), epistemic cognition (Kitchener and King 1981, Chinn *et al.* 2011, Sinatra 2016) and an associated lack of consensus on definitions (Hofer and Pintrich 1997, Briell *et al.* 2011). Briell *et al.* illustrate the "plethora of nomenclature" (2011, p. 9) with a table summarising 12 frequently employed terms and 26 less frequently employed terms[5]. Sandoval *et al.* (2016, p. 458) identify this confusion as an obstacle to both the "intellectual effort to model epistemic cognition and to educational efforts to develop it."

Briell *et al.*'s review article cut through a great deal of confusion in the field by proposing a classification of the different models as either cognitive structures or cognitive processes[6], depending on "whether the construct was perceived as something that exists abstractly or something that occurs in thinking and learning situations" (2011, p. 10). Figure 2.1 presents a visual representation of the categories and the related models. Cognitive structures focus on abstract conceptions such as beliefs and includes Baxter-Magolda's work on epistemic assumptions and Schommer-Aikins' on epistemic beliefs. Briell *et al.* classified constructs as cognitive processes if they describe how individuals use and evaluate knowledge (2011), encompassing Kuhn's argumentative reasoning and King and Kitchener's reflective judgment model. Briell *et al.*'s classification is significantly more relevant to the focus on this thesis than the developmental/dimensional division often used and certainly more useful to illustrate the contributions of this thesis. My review does not include work which takes a philosophical approach to personal epistemology (Greene *et al.* 2008), as these approaches are not germane to the argument of the thesis.

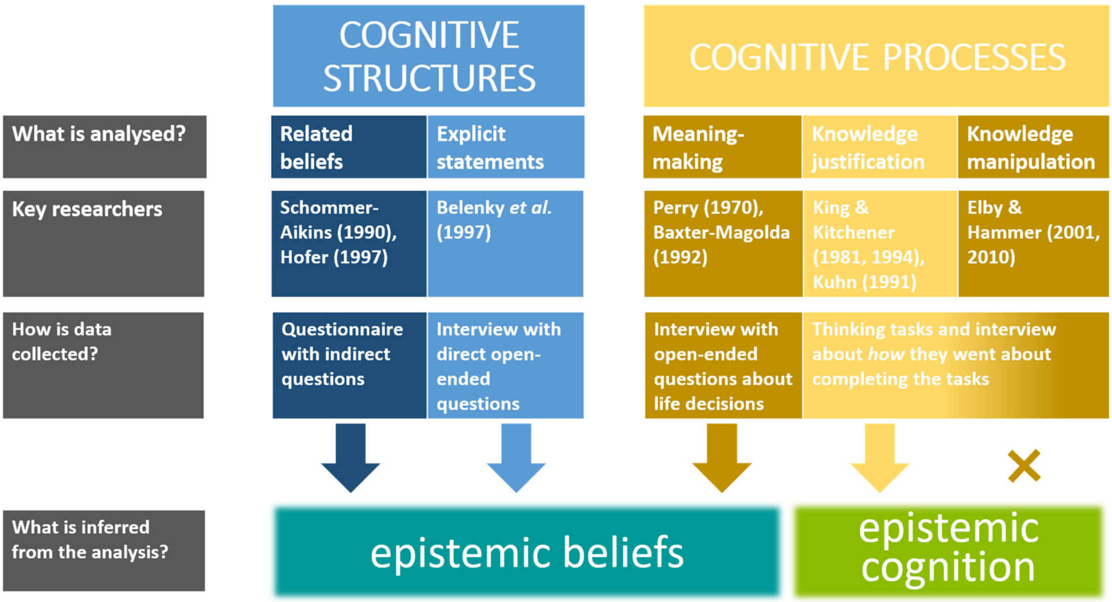
The developmental/dimensional approach to classifying models of epistemic beliefs has a near hegemonic dominance and is used by all of the most cited articles in the field (Sandoval *et al.* 2016, p. 462). Developmental, or stage-based, models characterise increasing epistemic sophistication through a set of sequential phases or stages. Dimensional models posit that epistemic sophistication increases across

[5] *Epistemic cognition* is listed as a frequently employed term but *epistemic practices* does not figure on either list.

[6] And occasionally *both*

several semi-independent beliefs that may evolve at different rates. While this classification prevails in the literature, it focuses on a somewhat superficial aspect that does not elucidate the issues addressed by the current work. I will therefore use Briell *et al.*'s classification (2011). Briell *et al.*'s cognitive structures relate to a general understanding of the word belief, where people's direct or indirect views about the nature of knowledge and knowing are used to infer their epistemic beliefs. These epistemic beliefs are assumed to be stable, overarching constructs which are restricted to the realm of the abstract, where knowledge and knowing are mental concepts rather than enacted, observable phenomena (Kitchener 2011).

Figure 2.1 Epistemic Beliefs Models According to Briell et al.'s Classification (2011)



The current work focuses on the second category of Briell *et al.*'s classification of how epistemic beliefs are conceptualised: cognitive processes focus on how students know and manipulate knowledge in specific contexts (2011). This approach is based on observable actions, from which some researchers have sought to infer epistemic beliefs. The relative benefits and disadvantages of these two conceptualisations of epistemic beliefs are explored in more detail below. The first two sections examine, respectively, the cognitive structures models of Belenky *et al.* and Schommer-Aikins. The final three subsections explore the cognitive processes approaches to epistemic sophistication, where the focus is on the actions or behaviours of the person. This thesis uses this less commonly used cognitive processes approach[7]. While Briell *et al.* (2011) identify two types of cognitive processes models (represented by Perry, and King and Kitchener), my analysis also places Elby and Hammer, who are cited by Briell *et al.* but omitted from their categorisation, in this cluster. Epistemic cognition, a term first used by Karen Kitchener (1983) to describe people's self-monitoring processes when solving ill-structured problems, is commonly used in a broader sense that corresponds to a cognitive processes approach.

2.3.1 Nature of Knowledge and Knowing Via Semi-Structured Interviews

This cluster of models was initiated by Belenky *et al.* (1997) and is one of the many developmental approaches; other works in higher education that employ a similar approach include Brownlee (2004) and Maggioni *et al.* (2006).

The methodological approach underlying these models involves asking participants quite open-ended but direct questions about the nature of knowledge and knowing during semi-structured interviews. Interviews tend to be quite long (2-5 h) and range across a variety of topics including knowledge, truth, experts, and learning. The observations arising from the interviews have either been used to construct developmental models, or have been assessed against developmental models. Common across all the developmental models is the idea of a trajectory from a dualist absolutist view of knowledge provided by experts, to an awareness of the constructed, evolving nature of knowledge and the development of criteria against which to evaluate knowledge claims.

While this approach attempts to directly access participants' explicit beliefs, accounts from researchers suggest that most people are not able to articulate these philosophical ideas in a coherent and well-organised way (Brownlee *et al.* 2001, Chan and Elliott 2002). Further, this approach still requires implicit beliefs be inferred from participants' comments. Finally, developmental psychology has moved away from stage-based models due to their inability to capture the

[7] In their review, Briell *et al.* (2011) report that the majority of the studies (73%) used structure-oriented constructs and an additional 10% combined structure and processes oriented constructs. Thus, only 17% used a purely processes approach, as I have.

"pervasive variability" in how people think and reason (Siegler 1998, p. 81). The cluster of models below has found novel ways to avoid this issue.

2.3.2 Dimensional Beliefs Models via Likert-Type Measures

In 1990, Marlene Schommer-Aikins offered a significant departure from the previous stage-based models (see also Schommer-Aikins, 2004). Merging concepts from Perry's work, from Dweck and Legett on beliefs about the nature of intelligence (1988), and from Schoenfeld's work on beliefs in maths (1988), her epistemological belief system is composed of five semi-independent dimensions. While the names of the dimensions have evolved over time, they are commonly known as simple knowledge, certain knowledge, source of knowledge, ability to learn, and quick learning. These last two are rejected as dimensions of epistemological beliefs by numerous researchers (Hofer and Pintrich 1997, Greene *et al.* 2008, Sandoval 2009) who classify these beliefs as related to learning.

Another novel point of Schommer-Aikins' model is to allow for the asynchronous development of the different dimensions, such that epistemological beliefs are taken as frequency distributions. A more sophisticated learner is thus distinguished by the percentage of knowledge that they conceive of as static or tentative (Schommer *et al.* 1997).

As you would expect from a model grouped in the cognitive structures cluster, Schommer-Aikins' Epistemological Questionnaire (EQ) attempts to target students' beliefs quite directly. The EQ asks students to indicate their (dis)agreement with statements of specific epistemic beliefs, such as *what is true today will be true tomorrow*. This self-report instrument offers the possibility to collect data economically, compared to prior work that primarily used individual interviews. Schommer-Aikins' semi-independent dimensions and use of frequency distribution appeared to better reflect the intricacies of human beliefs, igniting a full order of magnitude increase in research output in the field (Sandoval *et al.* 2016, p. 464), including the creation of numerous variant questionnaires (Kardash and Scholes 1996, Kardash and Wood 2000, Schraw *et al.* 2002), especially for science-related beliefs (for an overview, see Elby *et al.* 2016).

Hofer and Pintrich's (1997) review of epistemic beliefs digested and compared existing work in the field, and proposed a model of four semi-independent dimensions: simple knowledge, certain knowledge, source of knowledge, and justification of knowledge. This model was highly influential: Sandoval *et al.*'s 2016 review (p. 464) identified it as the most cited source in the field, after Perry.

Despite the intense research activity concentrated on dimensional models, establishing a questionnaire that consistently delivered coherent empirical data has proved elusive. Some researchers (Jehng *et al.* 1993, Bendixen *et al.* 1998) have found it difficult to replicate Schommer-Aikins' posited 4-factor structure (Schommer 1993) and others have been unable to separate the allegedly semi-independent dimensions (Hofer 2000, Qian and Alvermann 1995). Condensing justification into a single dimension has also proved problematic (Stathopoulou and Vosniadou 2007, Rizk *et al.* 2011). As Hofer (2010) and Greene *et al.* (2008) have argued, a dichotomous scale cannot capture the full range of data types and reasoning that people employ to assess knowledge claims, from authoritative and experiential accounts to the contextualised evaluation of evidence or expert opinion. Intensive efforts over two decades have been unable to adequately resolve these issues, and I count myself among the many who have attempted to do so.

The persistent measurement issues prompted DeBacker *et al.* (2008) to compare the psychometric properties of three main dimensional models: Schommer-Aikins' Epistemological Questionnaire (1990), Schraw *et al.*'s Epistemological Beliefs Inventory (2002), and Wood and Kardash's Epistemological Beliefs Survey (2002). They identified shortcomings in the psychometric properties of all three instruments. Faber *et al.* (2016) employed a qualitative approach to identifying the source of these recurrent measurement issues by asking students, in addition to their Likert-scale answer, to write a short sentence explaining their answer. Using Yu and Strobel's Hofer-based instrument (Yu and Strobel 2011, 2012), Faber and colleagues found some items where students expressed different levels of agreement yet wrote down the same justification (i.e. for the item *Principles in engineering cannot be argued or changed*) and other items where students expressed the same level of agreement yet wrote down conflicting justifications (i.e. for the item *If your personal experience conflicts with the 'big ideas' in a book, the book is probably right*).

Schommer-Aikins' dimensional approach to characterising epistemic beliefs is, at face value, more reflective of the range and variation of beliefs expressed by humans. However, the pervasive and persistent measurement issues suggest underlying issues of construct validity. My own concerns prompted me to explore and ultimately employ a cognitive processes approach, as described in the following sections.

2.3.3 Salient Meaning Making via Interviews

William Perry's work (1970), which kindled the significant interest this field has enjoyed over the past decades, is the core of this cluster of models that include Marcia Baxter-Magolda's (1992). Perry's longitudinal study comprised of yearly interviews with male Harvard undergraduates asking them to explain how they made important decisions in their lives, or to describe their experience of important situations. His developmental model consists of nine epistemological positions describing how individuals perceive knowledge and their beliefs about knowing. The positions are hierarchically integrated structures describing the progression from a dualistic, absolute view of knowledge where a learner accepts a static, certain truth from the most authoritative source, through multiplicity where students do not seek to reconcile different opinions but rather accept that each person is entitled to their own view, and finally in the latter stages of the model, students begin to conceive of themselves as active generators of their own knowledge and to contextually evaluate knowledge claims. The nine original positions are typically condensed into four levels (Moore 1994). His investigation of how students reasoned in open-ended situations in their lives firmly places Perry's approach in the cognitive process cluster. However, his inference of the students' underlying epistemological positions is more closely related to epistemic beliefs than epistemic cognition.

Baxter-Magolda's longitudinal study with both male and female students also included elements about the nature of learning and the nature of instruction in her model, describing the expected roles of a learner and of a teacher (1992). Both models in this cluster involve asking students about how they think and navigate in the world, and infer overarching epistemic beliefs from their comments.

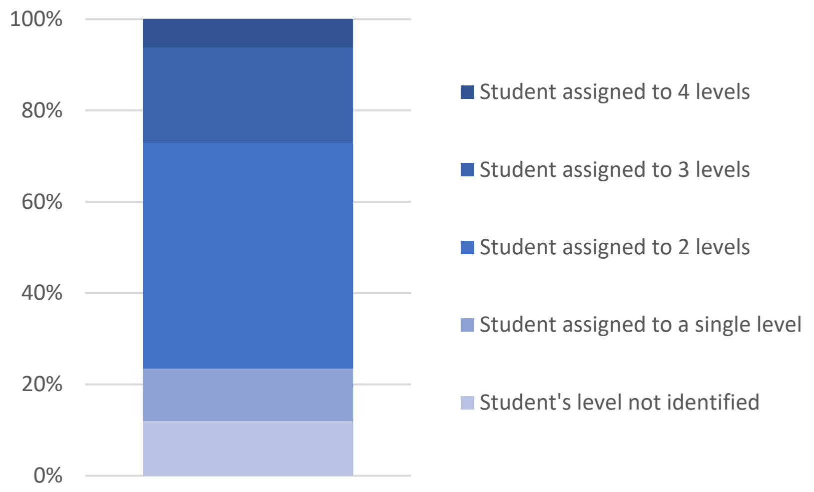
Recent work by Jiabin Zhu and colleagues has sought to develop a questionnaire for engineering students based on Perry's model (Zhu 2017, Zhu *et al.* 2019). The 45 questionnaire items are formulated quite broadly, i.e. "I enjoy working with complex ideas in which experts have no consensus." While the specificity for engineering is referenced in the title and throughout the article, none of the items themselves focus on engineering-specific knowledge or contexts. Rather the opposite in fact, as items refer to "papers", "open-ended essay", and "seminar formats", none of which are core activities in traditional engineering programs. Of the 205 complete data sets collected by Zhu *et al.* (2019), their instrument assigned 11% of participants to a single epistemological position (dualism, multiplicity, commitment, or relativism). As presented in Figure 2.2, the majority of participants were assigned more than one level of sophistication, including 6% of participants who were identified as spanning all four levels. The authors explain that participants whose responses corresponded to more than one level "could suggest that they were going through transitional stages in their epistemological development" (2019, p. 5). Given that 75% of participants who were classified were attributed two or more levels, I find their explanation completely inadequate[8]. Moreover, the assignment of some participants to non-contiguous levels (i.e. dualism-commitment, dualism-relativism-commitment, or dualism-multiplicity-commitment; numbers of participants in each category are not specified) undermines their explanation. Yet again, the "coexistence of lower and advanced levels of thinking" (2019, p. 5) is not taken as an important observation in itself but instead is dismissed as an artefact "of the complexity of students' epistemological development" (2019, p. 4). I will return to this recurring empirical observation in the Analysis Chapter and contribute a novel, coherent explanation.

In my analysis, I make a distinction between this group of models (comprising Perry, Baxter-Magolda, and Zhu) and other cognitive processes models in terms of what is inferred from the observations. While these models employ a cognitive processes approach in their data collection, they then use their observations to infer overarching epistemic beliefs. In contrast, King and Kitchener, and Elby and Hammer maintain the cognitive processes approach by focusing on epistemic

[8] I am curious about why ~12% of participants were not assigned to any epistemic level at all but this is unfortunately omitted from the article.

cognition rather than beliefs. Perry's model thus falls in a Venn diagram-like area of high overlap, which is likely a product of being the foundational work in the area and also an important factor in its continued influence in the field. Given the importance of the cognitive processes in answering my research questions, the nuances and distinctions of the models in this cluster are explored in detail.

Figure 2.2 Zhu et al.'s Perry-level Classification of 205 Chinese Engineering Students[9]



2.3.4 Reflective Judgements and Argumentative Reasoning via Interviews

This grouping contains Patricia King and Karen Kitchener's reflective judgement model (Kitchener and King 1981, King and Kitchener 1994, 2004, Kitchener 2011) and Deanna Kuhn's *argumentative reasoning* (1991). While the latter model has been used more broadly (Briell *et al.* 2011), King and Kitchener's focus on epistemic cognition, rather than conceptions of knowledge, is more relevant for the current work. While these models employ qualitative methods to investigate how students went about actually reasoning, they lose their contextualisation by then inferring a student's level of sophistication from the distribution or occurrence of certain behaviours or opinions. Another criticism that I have of these models is their discipline-general approach, which neglects the influence of the type of problem and knowledge practices that are representative of a particular discipline.

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[9] Chart represents my analysis of data reported by Zhu *et al.* (2019); values may not be exact.

Patricia King and Karen Kitchener began with the questions "How do people decide what they believe about vexing problems?" and "How do people arrive at their judgments about complex and controversial problems?" While their approach was initially from a critical thinking perspective, the nature of their enquiries lead them to epistemology. Their methodological approach involved semi-structured interviews with older adolescents and adults about how they reasoned through the poorly-structured problems posed to them. Specifically, participants needed to make judgments about competing assertions on issues "about which 'reasonable people reasonably disagree'" (King and Kitchener 2004, p. 5). For example, the issues in the original interview included the safety of chemical additives in foods and the accuracy of news reporting, and posed questions such as "…is it the case that one opinion is right and one is wrong?" and "Can you ever know for sure your position on this issue is correct?" (King and Kitchener 1994, p. 102). Deanna Kuhn's *argumentative reasoning model* (1991) employed a similar methodology, where older adolescents through to senior citizens were interviewed about their conceptions of expertise and knowledge after confronting ill-structured, real-life social problems such as unemployment. The issues covered by others employing the model range from highly controversial (Should drugs be legalized?; Angeli and Valanides 2005, p. 318) to non-controversial (Do those clouds mean rain?; Mansfield and Clinchy 2002, p. 232).

The reflective judgement model is composed of seven substages organised into three stages: pre-reflective thinking, quasi-reflective thinking, and reflective thinking. The model describes a developmental progression of the "ways that people understand the process of knowing and the certainty of knowledge claims and in the corresponding ways that they justify their beliefs" (King 2000, p. 16). Less sophisticated judgements rely more on authority or direct observation. More sophisticated judgements are characterised as more nuanced, with a more explicit and salient "relationship between evidence and judgment" (King 2000, p. 19). King *et al.* (1989) report a sequential movement through the substages at a rate of about one per six years, and report that regression in people's reflective judgement is very rare.

By attending to how people justify knowledge claims, rather than their beliefs about the nature of knowledge, King and Kitchener are credited with creating the concept of epistemic cognition. While King and Kitchener used the term to describe the process people "invoke[s] to monitor the epistemic nature of problems and the truth value of alternative solutions" (1994, p. 12), it is currently used in a broader sense to denote a cognitive processes perspective on epistemic beliefs, where the focus is on the actions of the person. Studies addressing epistemic cognition are typically attentive to the influence of context, make fewer inferences, and posit fewer generalisations of their findings. For Greene *et al.* (2016), epistemic cognition describes how people think about knowledge, how knowledge can be used and how they know that they know. For Nancy Sinatra, epistemic cognition is cognition related to epistemic matters; that is, it is the dynamic process of constructing and making sense of knowledge which "invokes or draws upon learners' beliefs, schemas, mental models, resources, frameworks, or other contents of their cognition" (2016, p. 480). She characterises epistemic cognition as the behavioural response to a particular situation, and states that it is not directly equivalent to epistemic beliefs (2016). Chinn *et al.*'s (2011) framework for epistemic cognition, which involves determining "epistemic aims, standards and ideals" takes a fine-grained, context-specific approach while employing a dimensional, cognitive structures approach. They argue that students' epistemic aims are key for contextualising and understanding their actual epistemic cognition, as the aims inform how students interact with knowledge to either gain a deep understanding or to simply address the current problem. It has also been suggested that epistemic cognition may have metacognitive, in addition to cognitive, aspects (Hofer and Sinatra 2010, Sinatra 2016).

In my analysis of the literature, I see that epistemic cognition, focusing on how people are manipulating and evaluating knowledge, rather than on overarching beliefs, is the approach which has the most promise to advance the field. Further, King and Kitchener's methodological approach with specific tasks is an effective way to generate relevant activity to discuss during the interview, rather than overly broad or hypothetical situations. However, there are important discipline-specific aspects regarding how to evaluate knowledge claims and convincingly defend decisions (Voss *et al.* 1983, King 2000). Inspired and grounded by King and Kitchener's work, I employ a different type of task and look for how students work with engineering and science knowledge in order to develop a better description of epistemic cognition in engineering.

In general, studying students' epistemic cognition involves investigating how people use knowledge. Appropriate methodologies for this approach include observation and think-aloud studies (Litzinger *et al.* 2010, Mason 2016) with semi-structured interviews to better understand and interpret the observations (Sandoval *et al.* 2016). Multiple researchers (Lising and Elby 2005, Muis and Gierus 2014, Sinatra *et al.* 2014, Mason 2016, Sinatra 2016, Lindfors *et al.* 2019) have called for more investigation of the contexts in which the dynamic process of epistemic cognition functions. Similarly, Lindfors *et al.* (2017, p. 4) say that "It is necessary to observe how these beliefs are expressed in an individual's practice" in order to acquire a deep understanding of the beliefs themselves.

Epistemic practices is Kelly's (2016) term for epistemically-revealing behaviours which can be observed and captured in order to characterise how a person approaches, justifies, and evaluates scientific knowledge within a given context. This approach assumes that epistemic practices arise from the dynamic process of epistemic cognition and must be studied *in situ* as they are "situated in time, space, social practices, and cultural norms" (Kelly 2016, p. 397). This reflects the increasing importance (Sandoval *et al.* 2016) placed on using observations of students' thinking and behaviour to better understand what constitutes epistemic sophistication.

2.3.5 Epistemological Resources Model via Contextualised Observations

Andrew Elby and David Hammer initiated a departure from both the developmental and dimensional models which have dominated studies of epistemic beliefs (Elby and Hammer 2001, 2010, Hammer and Elby 2002, Louca *et al.* 2004, Elby *et al.* 2016). Their epistemological resources model recommends taking a fine-grained approach to how students go about thinking, so I have classified it as a cognitive processes approach. As noted by Briell *et al.* "little emphasis is given to differentiating conception-oriented constructs and process-oriented constructs" (Briell *et al.* 2011, p. 11) and consequentially the two are frequently conflated or combined without regard. Thus, while epistemological resources have been referred to as "fine-grained cognitive structures" (Sandoval *et al.* 2016, p. 471, Lindfors *et al. 2017)*, this thesis argues that the cognitive resource model is more useful and effective as a fine-grained cognitive processes approach. This means that Elby and Hammer's suggestion that repeated use of individual cognitive resources can lead to the development of stable epistemic frames, aligning with the cognitive structures models, this aspect of their model will not be employed in the current work which will focus on the processes aspect.

Elby and Hammer identify two major shortfalls of prior models; first that they fail to differentiate between the correctness and productivity of different epistemic beliefs; and secondly, that the units of analysis used in these models are too coarse-grained to capture essential contextual differences in how knowledge is used or evaluated.

Both developmental and dimensional models imply that epistemic sophistication is demonstrated by enacting sophisticated epistemic beliefs, such as not taking scientific knowledge as absolute and static. Elby and Hammer do hold that knowledge is ultimately contextual and tentative, however they stress that this conception is not the most productive approach in every situation. They illustrate this concept with the example that students should be ready to simply accept the notion that the earth is round when it is presented to them but to take a more questioning approach to theories of mass extinctions (Elby and Hammer, 2001). Treating all scientific knowledge as tentative and evolving would not be productive, despite the global correctness of this approach. Several researchers have made the same point, noting that relying on experts for justification of a knowledge claim is the most appropriate approach in certain situations and not simply a naïve response that should be equated with low epistemic sophistication (Greene *et al.* 2008, Chinn *et al.* 2011). Elby and Hammer (2001) define a belief as "productive if it generates behavior, attitudes, and habits that lead to 'progress' as defined by the given person or community" (2001, p. 555). They thus insist on the importance of assessing the appropriateness or effectiveness of students' epistemic practices *in situ*, to avoid the obvious nonsense that a tentative approach to knowledge is always more sophisticated even when considering well-established laws of nature.

This leads into Elby and Hammer's second criticism of developmental and dimensional models, which is that students are expected to hold "certain blanket generalizations about the nature of knowledge and learning, generalizations that do not attend to context. Such blanket assertions, [they] argue, are neither correct nor productive" (2001, p. 555). For example, if a student expresses agreement with Yu and Strobel's item "Principles in engineering are unchanging so that they cannot be argued or changed" (2011), are they thinking about the well-established principles of statics (the causes and effects of stationary forces acting on rigid objects) or the emerging principles of machine learning (using computers to run predictive models that learn from existing data in order to forecast future behaviours, outcomes, and trends)? Elby and Hammer therefore advocate for a fine-grained approach to probing students' epistemic beliefs, concept by concept.

In response to the shortcoming identified above, Elby and Hammer's epistemological resource model posits that people have a set of cognitive resources available to them, from which they choose which resources to bring to bear in each specific, precise context. For Elby and Hammer, epistemic sophistication is adopting an appropriate approach according to the context of the specific knowledge claim. In this model, sophistication is not progressing to a higher stage but rather an improved ability to select and employ productive cognitive resources. While Elby and Hammer tend to formulate their ideas in terms of epistemic beliefs, I avoid the term beliefs in order to emphasise my cognitive processes approach. The cognitive resource model is a considerable departure from the previously discussed models where epistemic cognition is organised into hierarchical phases or dimensional subphases.

The cognitive resources model offers a coherent explanation for previously problematic observations, made by many researchers, where participants expressed conflicting views or acted in highly contradictory ways. Leach *et al.* (2000) probed such contradictions through the use of two different types of items on the same questionnaire: decontextualised, Likert-scale items which prompt rapid responses and items which are deeply contextualised in specific narrative descriptions (i.e. researchers examining experimental data at a superconductivity conference). Leach *et al.* report major variations in the responses of participants on these two different types of items. These data are best explained by the epistemological resources model which posits that the participants were cued in different ways by different items, rather than responding from a coherent, stage-based conception of knowledge. Lin and Tsai (2008) and Tsai (2004) report that while each participant expressed a range of views, one perspective tended to be dominant, although not necessarily the most sophisticated perspective. For me, focusing on the most frequent or most sophisticated beliefs collapses the rich and useful details of the cognitive resource model into a developmental model.

Elby and Hammer use the concept of epistemic framing, inspired by the notion of framing used in anthropology and sociolinguistics (2010). A frame is constituted by a person's expectations of a given situation, expectations which will ultimately influence what the person perceives in the situation, and what actions the person will deem appropriate for themselves. Hutchison and Elby demonstrate how students' expectations about learning activities, i.e. their epistemic framing, can affect their reasoning (2013). Their think-aloud protocol, primed by questions which frame solving physics problems as either a real life "sense-making" or a schoolish "answer-making" activity caused students to approach the problem in different ways. They propose that repeated activation of the fine-grained cognitive resources results in the construction of stable epistemic frames (Elby and Hammer, 2010). Interestingly, Elby and Hammer also cite two examples of an individual (one a teacher, one a student) suggesting switching to a different frame was better suited to making sense of a current problem (2010). These interactions suggest that people believe that it is possible to change an epistemic frame within a given context. Louca *et al.* thus argue that teachers do not need to confront students' beliefs, but rather should help students to recognise productive resources which they already possess and to identify when it is effective to apply such resources (2004). Louca *et al.* further propose that this process also provides a mechanism for the development of epistemic sophistication, the lack of which has been noted as a significant weakness of developmental models (Siegler 1996). This cognitive structures approach is an interesting contribution in terms of how processes and structures may be connected, and for proposing a developmental model. However, these ideas are beyond the scope of the observations undertaken in this thesis and this aspect of their work will not be further explored.

While this thesis is more interested in the more dynamic cognitive processes aspects, Elby and Hammer (2010) also posit three mechanisms which act to stabilise the epistemological resources a student will bring to bear: contextual, deliberate or structural. Contextual stability occurs when the student has repeatedly experienced particular characteristics of a learning environment and will thus continue to be cued to respond in the same way by said characteristics. Deliberate stability occurs when a student intentionally seeks to maintain a particular epistemic stance. For example, Elby and Hammer (2010) describe how an interviewee explicitly changed his approach to studying physics by seeking to follow the advice provided by his physics instructor to imagine explaining each concept to a 10 year old. Louca *et al.* describe how over time and through repeated activation, a particular set of epistemological resources will develop into a stable epistemic structure (2004). This type of stability sounds more like a cognitive structure than a cognitive process and, given the temporal dimension, is beyond the scope of the current work.

The methodological implications of the cognitive resource model are that data must be collected at a fine-grained scale and analysed with careful attention to the context of the knowledge being described. If possible this is supported by triangulation with direct observations and other data. Louca *et al.* state that they are hesitant to infer a belief from a single observation but rather emphasise the need to check for stability across multiple contexts (2004). Further, they question the ability of studies using a single survey or interview to make valid inferences about students' epistemic beliefs.

Studies employing the cognitive resource model have primarily focused on students in physics (e.g. Elby and Hammer) or other science contexts (Gainsburg 2015) with careful attention to context. These studies have provided an ideal situation in which to demonstrate that an unsophisticated epistemic approach will always be most effective (and thus appropriate) in some situations. For example, Lindfors *et al.*'s (2017, p. 123) study of 10th grade students' problem-solving processes for classical mechanics problems "revealed that different sets of epistemic beliefs were conducive to different aspects of students' problem-solving process and outcomes". Similarly, Gottlieb and Wineburg (2012) found that historians alternated between academically and religiously based ways to evaluate claims and evidence, depending on the nature of the documentary material and even within the same text.

Elby and Hammer's cognitive resource model is a major departure from prior models of epistemic beliefs and offers a coherent explanation for apparent inconsistencies observed in empirical studies. They dispute three of the four dimensions of the highly influential yet empirically problematic model proposed by Hofer and Pintrich's 1997 review article, namely certainty, source, and simplicity (2001). They argue that only the dimension justification would be constant across contexts (Elby and Hammer 2001). In contrast to Hofer, who advocates excluding beliefs about learning from epistemic models for "reasons of clarity and parsimony" (Hofer and Bendixen 2012, p. 233), Elby suggests refraining from deciding if beliefs about learning are an integral part of epistemic conceptions until there is better empirical or theoretical support for such a decision (Elby 2009). Hofer presages Elby and Hammer's work both in terms of the specificity of context and also in part about the efficacy of adopting a particular epistemic approach in a particular context with her comment that "more work is needed to address the contextuality of beliefs and the degree to which each of us make epistemic judgments appropriate to context" (Hofer 2000, p. 401). Elby and Hammer similarly called for more investigation into which epistemic beliefs are productive in different situations (Elby *et al.* 2016). This thesis will address this in part, and propose a refinement of how to measure "productive."

2.4 Considering Disciplinary and Cultural Context

The difficulty of establishing consistent general measures of epistemic beliefs led to research which situated students' beliefs in a particular domain or disciplinary context, frequently in the discipline of science (Schoenfeld 1983, 1988, Buerk 1985, Donald 1986, 1990, Lampert 1990, Stodolsky *et al.* 1991, Carey and Smith 1993, Hammer 1994, Roth and Roychoudhury 1994, Tsai 1998, 1999, Marshall *et al*. 1999, Hofer 2000, 2004, Kuhn *et al*. 2000, Buehl and Alexander 2001, Buehl *et al*. 2002, Conley et al. 2004, Reid *et al*. 2005, Muis et al. 2006, Lin and Tsai 2008, 2009, Liang and Tsai 2010, Greene and Yu 2014). A parallel, although less active, approach has been to consider how social and cultural contexts influence epistemic beliefs (Bråten *et al.* 2009, Sulimma 2009, Weinstock 2010, Felbrich *et al.* 2012, Zhu and Cox 2015). For example, Nisbett *et al.* cite the influence of analytical thinking (following Greek philosophy) in the USA versus more holistic thinking (following Confucian philosophy) in Asia (Nisbett *et al.* 2001).

It is therefore unfortunate that the major review articles by Hofer and Pintrich (1997) and Briell *et al.* (2011) focused on domain-general articles, although Briell *et al.* explain their omission of domain-specific articles was based on the sheer number and complexity even though they only considered domain-general articles. The exclusion of domain-specific models is a major limitation as the debate about the generality or specificity of epistemic beliefs has been largely decided in favour of specificity (Sandoval *et al.* 2016, p. 470). Each discipline has its own distinct, intrinsic epistemology (Schwab 1964, 1978, Donald 1995) the practice of which contributes to the identification of an expert of the discipline (Donald 1990, Langer *et al.* 1993, Schoenfeld 2016). The importance of disciplinary epistemic cognition was demonstrated by Herrenkohl and Cornelius (2013) who showed that evidence in science and history looks different and Voss *et al.* (1983) observed that expert chemists behaved as novices when solving ill-structured social science problems.

Students' abilities to adopt and employ appropriate discipline-specific epistemic approaches is essential to their performance in the discipline (Goldman, 2011; Greene 2016). The connections between disciplinary practices and epistemic cognition have been explored in reviews focusing on the nature of science (Elby *et al.* 2016) and mathematics (teachers: Depaepe *et al.* 2016, students: Muis 2004). Paulsen and Wells explain the importance of disciplinary contextualisation arises from the fact that "Students' beliefs about the nature of knowledge… are related to the disciplinary contexts in which students select and experience their specialized coursework in college" (1998, p. 365).

Considering science as a monolithic discipline is inadequate to account for differences in disciplinary epistemology; Tsai (2006) has shown students to hold different epistemic beliefs in physics and biology. Brickhouse *et al.* found that how undergraduate students used evidence to justify knowledge claims in science varied depending on the scientific discipline and topic (2000). Leach *et al.* (2000)

found inconsistencies in how undergraduate students responded to general statements on the nature of scientific knowledge and when solving a challenging physics problem. These observations have prompted some topic-focused studies addressing, for example, students' epistemic beliefs about tectonic plates rather than the whole domain of geology (Stahl and Bromme 2007, Trautwein and Lüdtke 2007, Bråten *et al.* 2009). I am more interested in the students' disciplinary epistemic skills and practices, than in their abstract beliefs about engineering knowledge.

I am particularly interested in a recent study by Julie Gainsburg investigating how engineering students use mathematics to solve engineering problems (2015). Her study employed interviews, think-aloud protocols, and classroom observations with ten civil engineering students. Gainsburg based her work on both a Perry-like developmental model and Elby and Hammer's fine-grained epistemological resources model, but did not attempt to distinguish between cognitive structures and cognitive processes. For the most sophisticated level she drew on the posture of sceptical reverence, which she had developed in her prior work on the highly sophisticated epistemic beliefs of practising engineers (2007). *Sceptical reverence* represents the highest level of sophistication in a Perry-like model, as illustrated in Figure 2.3. Her interviews sought to elicit students' epistemic beliefs in specific contexts, such as in a high school maths class or the professional workplace, enriched with her observations of students solving their homework under think-aloud conditions.

In her 2015 paper, Gainsburg presents a four-level developmental model whose descriptions combine both epistemic beliefs and epistemic practices. Gainsburg observed a close connection between the epistemic beliefs professed during the interviews and those enacted by students during think-aloud protocols. She reports students exhibiting a range of levels in different contexts, with every student except one exhibiting Level 3 in at least one context. Level 1 was most prevalent, being seen in all but two students, when doing their homework in a think-aloud protocol.

Overall, Gainsburg combines developmental and fine-grained approaches to create a legible, general profile of epistemic beliefs in engineering. Particularly valuable is her association of some specific epistemic practices, i.e. sense-making using concepts or maths, with specific levels of epistemic sophistication. However, her inclusion of both cognitive structures and cognitive processes in a mix of highly specific actions and quite general "views" creates a somewhat muddled picture.

Figure 2.3 Gainsburg's "Epistemological Views of Engineering Students" (2015, p. 156)

Level 4 – Sceptical reverence

Assesses reasonableness of answers, computer output
Big picture present throughout problem solving
Recognises fallibility of models, need to understand underlying assumptions
Recognises non-routine nature of solving problems and the need for judgement

Level 3 – Relativism

Seeks deep understanding even if it delays resolving the problem at hand
Discusses with peers to learn alternative approaches
Sense-making using real world observations
Verify solution using own experiences (ie moment arm on a wrench)

Level 2 – Integrating

Use of methods other than those modeled by instructor
Discusses with peers to refine understanding
Will step back and look at the overall picture
Sense-making using concepts, math (not real world observations)
Goal for exercises is to train the mind

Level 1 – Dualism

Break problem to be solved into parts, ignore the big picture
Match problems to previously seen examples
Answer key or instructor sole means of verifying solution
Goal for exercises is to get the right answer

The increased recognition of the importance of context in epistemic cognition research "represents the field's better understanding of the problem space and of the complexity of the phenomena under study" (Sandoval *et al.* 2016, p. 485). The methodological implications for the tools, contexts, and disciplinary fluency of researchers is explored in more detail in the following section.

2.5 Methodological Implications of a Cognitive Resource Approach

The issues around obtaining empirical data on epistemic beliefs and cognition have already been introduced during the presentation of the various models earlier in this chapter. However, the persistent methodological issues warrant an explicit discussion. Neither of the two major methods, namely the Likert-type questionnaires used for dimensional models nor the semi-structured interviews for studies using developmental models (Sandoval *et al.* 2016), are adequate for the fine-grained, epistemic process focused approach used in this thesis. This section illustrates how think-aloud protocols using contextualised, disciplinary tasks create opportunities to evoke and observe relevant epistemic practices.

Concerns related to the psychometric properties of the widely-used dimensional questionnaires have been presented above. This lack of clear empirical support may point to conceptual issues arising from how these instruments require participants to articulate explicit statements of their epistemic beliefs. This conflicts with the widely held view that epistemic beliefs are tacit and contextual for many people (Sinatra and Chinn 2012, Chinn and Rinehart 2016). The main issue for developmental models is assigning people to a given level when the empirical evidence indicates that their actions and expressed views vary greatly. For example, Tsai and colleagues have repeatedly found participants' expressions of their ideas about learning[10] to span more than one category (Tsai 2004, Lin and Tsai 2008, Chiou *et al.* 2012). Like Gainsburg (2015), they found that while each participant typically had one dominant category, it was not necessarily the most sophisticated. Zhu *et al.* (2019) also observed a lack of coherency in engineering students' apparent level of epistemic sophistication.

Muis *et al.* (2006) have called for more studies using qualitative methods to better assess the domain-specificity of epistemic sophistication through greater

[10] Note: Beliefs about learning were not differentiated from epistemic beliefs.

attention to context. Examples of compatible methods include: semi-structured interviews (e.g. Gainsburg 2007, 2015), cognitive interviewing (e.g. Greene *et al.* 2010, Muis and Gierus 2014) and stimulated reflection (e.g. Ferguson *et al.* 2012, Berland and Crucet 2016). These approaches recognise that epistemic cognition is typically tacit (Sinatra and Chinn 2012, Chinn and Rinehart 2016). Kelly argues that measurement must occur while people are enacting epistemic cognition (2016), a conclusion shared by several researchers who focus on disciplinary contexts (Sandoval 2005, Elby and Hammer 2010).

Concurrent think-aloud protocols (Ericsson and Simon 1984) are a revealing way to observe epistemic cognition in action (e.g. Hofer 2004, Mason *et al.* 2010, 2011, Ferguson *et al.* 2012, Greene *et al.* 2014). Some researchers have argued that the addition of retrospective interviews to these protocols can lead to more informed understanding of people's epistemic cognition (Sandoval 2005, Chinn *et al.* 2011). For example, Pluta *et al.* (2011) assessed epistemic cognition by first asking middle school students to engage in scientific inquiry and then prompting them to reflect on their epistemic practices. Hammer and Elby have studied their epistemological resources model by triangulating across observational studies of activity and cognitive interview studies (2010).

One methodological benefit of think-aloud protocols is that observations can be collected data with minimal interference with the student's actions. The ideal think-aloud narration involves a minimum of explanation and interpretation on the part of the student and a minimum of interference on the part of the interviewer. However, researchers often seek to infer what people are thinking but not verbalising from the think-aloud data (Sandoval *et al.* 2016). Mason *et al.* (2011) caution that participants can only verbalise thinking processes that they are aware of, which highlights a major difficulty in attempting to use observations to infer beliefs that are generally assumed to be tacit (Sinatra and Chinn 2012, Chinn and Rinehart 2016). Another constraint is that the researchers must be fluent themselves in the epistemic practices of the discipline.

An unfortunate limitation of many think-aloud studies is that the data is "often context-specific and interpreted solely within a single model of epistemic cognition" (Sandoval, 2005), thus limiting the scope and generalisability of the results of the study. For example, Ferguson *et al.* (2012) and Mason *et al.* (2011) use a dimensional epistemic beliefs model to code the resulting transcripts, causing Mason *et al.* to state that their "results cannot be extended beyond the context in which they were produced. An in-depth investigation that takes into account both instructional variables, such as topic and task, and learner characteristics, would permit issues to be generalized further" (Mason *et al.* 2011, p. 149). If research in the field continues to be bound by the topic, task, and learner characteristics, we are a long way from the teacher-ready model called for by Sandoval *et al.* (2016) and Bråten (2016).

2.6 Path and Mechanism for Epistemic Development During Engineering Studies

Despite the criticism levelled against the models and methods used to characterise epistemic beliefs enumerated in the preceding sections, it is nevertheless useful to report some of the findings. One important point is that there is a broad consensus, regardless of the model used, that students become more sophisticated over the course of their studies (Culver and Hackos 1982, Baxter-Magolda 1992, Jehng *et al.* 1993, Schommer 1993, Pavelich and Moore 1996, Paulsen and Wells 1998, Marra *et al.* 2000, Felder and Brent 2004, Wise *et al.* 2004, King and Magun-Jackson 2009). However, observations that engineering students (when controlling for other demographic factors) were more likely to hold less sophisticated beliefs than students in other fields is concerning (Schommer 1993, Paulsen and Wells 1998). In their study of engineering students, Marra and Palmer (2004) state that a high level of epistemic sophistication (corresponding to Perry level 5) is required for graduates to operate as professional engineers. It is therefore highly worrying that Wise *et al.* found few graduating engineering students in their study demonstrated a sufficiently high level of epistemic sophistication (2004)[11]. This slow development of engineering students' epistemic cognition is a key motivation for starting the current work. This section examines the literature with respect to two questions: First, what stimulates the development of engineering students' epistemic cognition? And second, what is

[11] Qualitiative study with 21 students; mean Perry level of 4.

the mechanism of change?

2.6.1 Supporting the Development of Epistemic Cognition

Descriptions of the situations or experiences that stimulate the development of epistemic cognition abound in the literature. In his foundational work, Perry proposed that students' epistemological beliefs change when they are confronted by multiple authoritative sources and must find ways to reconcile the differences (1970). Recommendations for how to encourage students to develop their epistemic cognition consistently focus on deliberately challenging less sophisticated views and creating opportunities for students to reflect on how they think about their disciplinary knowledge (Perry 1970, Culver and Hackos 1982, Finster 1991, Lynch *et al.* 1994, Felder and Brent 2004).

Thus, engineering programs must create learning situations that prompt students to interact with engineering knowledge in sophisticated ways. Yet several researchers have noted that experiences which directly challenge students' less sophisticated epistemic beliefs occur infrequently in engineering programs (Frye *et al.* 2012, Danielak *et al.* 2014). Gainsburg notes that "undergraduate engineering courses may rarely confront students with the kinds of epistemic challenges which push liberal arts students towards relativism" (2015, p. 142). Kuhn addressed this theme in his description of contrasts in disciplinary epistemologies of science and engineering students versus the humanities (1962). He notes that a paradigm shift in science is complete and irreversible, such as the appearance of the germ theory of disease. After a period of debate and testing, the new, correct paradigm becomes the sole lens through which the world is observed. In contrast, when faced with a problem, the humanities permit a student to select a perspective or stance, for example feminist or deconstructivist, from which to critique and analyse the situation. While a particular stance may wax and wane in fashion, it does not become invalid or obsolete. Thus, students in the humanities work within a plurality of valid yet divergent perspectives, a situation incompatible with maintaining a dualistic view of knowledge.

Real-world engineering experiences, such as internships, projects, and other opportunities to encounter ill-structured problems, have been shown to be important for developing more sophisticated epistemic skills (e.g. Baxter-Magolda

1992, Felder and Brent 2004, Marra and Palmer 2004, Gainsburg 2015). Marra *et al.* (2000) found that engineering students who participated in a first-year design course had significantly more sophisticated epistemic beliefs than their peers who had not taken the course. In follow up work, Marra and Palmer (2004) found that students' ability to solve ill-structured problems was positively correlated with their epistemic beliefs. These findings support curricular reforms in engineering education to increase students' opportunities to engage in experiences that better mirror the real world by incorporating complexity and situations beyond the assumptions of simplistic models.

Scaffolded progress towards more sophisticated disciplinary practices appears to be important (Sandoval *et al.* 2016). Finster (1991) recommends that students be encouraged to stretch to employ strategies just beyond their current abilities, which he calls "n+1". It appears that students should not be challenged to stretch too far at once, as Lynch and Kitchener (1994, p. 149) found that students may not be able to engage with approaches that are more than one level above their current functioning.

While there is good evidence that ill-structured problem solving can develop engineering students' epistemic cognition, not enough is known about the fine-grained practices that constitute "a level" and therefore enable the application of recommendations to challenge students to employ "n+1" strategies. This thesis provides insight into the types of actions relevant to epistemic cognition in engineering and investigates how these actions manifest at different levels.

2.6.2 Mechanism of Development of Epistemic Cognition

The mechanisms for epistemic development have not been rigorously theorised in either the developmental or the dimensional models. Elby and Hammer have proposed one of the rare mechanisms for development, as part of their epistemological resources model, positing that students become aware of more sophisticated practices and thus increase their range of potential strategies. Gainsburg further refined their proposal by decomposing the transition to more sophisticated beliefs into two parts: capacity and selection (2015). She defines capacity as the range of epistemological resources that the student is aware of, and selection as the skill to identify when to employ a specific cognitive resource. The mechanisms of developing epistemic cognition are important and deserve more research attention than they have received. However, it will not be the focus of the current work.

While identifying teaching strategies effective for developing engineering students' epistemic cognition was the original motivation for this project, a lack of adequate assessment tools to measure epistemic sophistication made such goals unachievable. Consequently, the focus of this thesis became contributing to a robust model able to characterise epistemic sophistication in engineering. I develop this concept further in the following section.

2.7 Towards a Rigorous and Exploitable Model of Epistemic Cognition in Engineering

The preceding sections have made a clear case for the importance of managing uncertainty, using models, and justifying knowledge claims as relevant for epistemic cognition in engineering problem solving. Equally clear is the lack of a model to observe and record how engineering students enact these sense-making and justification of knowledge behaviours *in situ* in their own contexts. This concluding section summarises my arguments and how they have informed my approach.

2.7.1 The Fine-Grained Cognitive Processes Approach of the Thesis

Informed by the literature above, this thesis will use a fine-grained approach to observing engineering students' epistemic cognition. I join Sandoval *et al.* in their assessment of Elby and Hammer's cognitive resource model as "the theoretical framework best aligned with the discipline-specific, situated view" which is required for the current project (2016, p. 474). Given the importance of problem solving and the occurrence of epistemically relevant practices related to how engineering knowledge is manipulated and justified, this thesis will characterise students' contextualised problem solving using a think-aloud protocol. This matches Bråten's (2016) call for more suitable measures of epistemic sophistication and his recommendation to focus on the behaviours that reveal a person's epistemic cognition.

I have argued that it is this enactment of epistemic beliefs, rather than the beliefs themselves, that should be the target of efforts to develop models of epistemic cognition. As outlined earlier in this chapter, the distinction I make between the fine-grained observable epistemic practices that students employ during their problem solving and broader epistemic beliefs has not been adequately exploited in prior work. Some researchers have proposed that there may be two types of epistemic beliefs as a way to explain observed inconsistencies in people's expressed opinions and behaviours. For example, Sandoval (2005) suggested that students have both a formal epistemology that describes their overarching set of ideas about scientific knowledge and also a practical epistemology that applies to their own science activities. Louca *et al.* use the term professed epistemology to identify a teacher's "stated views about knowledge and learning" in the calm of clinical interviews which they say "can differ substantially from that person's enacted epistemology, the views about knowledge and learning an observer would infer from classroom behavior" (2004, p. 59). Hogan (2000) uses distal epistemology and proximal epistemology to describe the sometimes contradictory ways that students describe and go about learning.

Most research effort has focused on characterising epistemic beliefs at an overarching level. But, as illustrated by the distinctions between formal and applied beliefs made by Sandoval, Louca *et al.*, and Hogan, many researchers think that these overarching beliefs are not the same as the applied beliefs (Hogan 2000, Louca *et al.* 2004, Sandoval 2005). Sinatra explicitly states (2016) that epistemic cognition is not directly equivalent to epistemic beliefs. Sandoval suggests that this separation "at least partially explains why students' formal epistemological ideas seem so difficult to change through instruction" (2005, p. 636).

From my perspective, measuring formal epistemology (the most common target of research in the field) has little value if these observations have little relevance and are not representative of how engineering students will approach their problem solving. Accordingly, I focus my attention on engineering students' *in situ* practices to observe and characterise epistemic sophistication. This is coherent with Sandoval *et al.*'s (2016) recommendation that observing students' behaviours while engaging in specific contexts can provide important insights about the productiveness of epistemic beliefs and what constitutes successful epistemic practices. I am opposed to Briell *et al.*'s position (2011) that process-oriented constructs lack a clear articulation of what makes them epistemological. While I can appreciate the desire to access the underlying beliefs, I would argue that the thinking process itself is the most effective way to do this. By focusing on the detailed observation of a student's knowledge justification and reasoning during problem solving, I am able to discern a richer, more accurate picture of a student's epistemic approach than from decontextualised declarative statements. This thesis implements this approach by focusing on students' observable actions rather than their declarations, direct or indirect, specific or general, of their epistemic beliefs.

2.7.2 The Engineering Context of this Thesis

The fine-grained cognitive resource model employed in this thesis focuses on how engineering students reason and manipulate knowledge as they perform problem-solving tasks. A major factor motivating my approach is that it avoids persistent issues with evaluating epistemic beliefs, outlined above, in favour of a more applied strategy that also makes the connections to engineering problem solving more evident. Further, my approach is consistent with Sandoval *et al.*'s observation that many studies are not attentive to the epistemic norms and practices of each discipline (2016). They propose that for the building of "theory bottom-up from such research, a first step could be to produce more local models applicable to a limited range of learners and contexts. In turn, such models might be combined to produce more overarching frameworks for epistemic cognition that are better grounded in actual knowledge construction and evaluation within the disciplines" (2016, p. 475).

The approach of this thesis focuses on the observable, contextualised actions of engineering students during problem solving. A key aspect underpinning my focus is that, for example, students' belief that engineering problems can have multiple potential correct answers is irrelevant compared to their propensity to enact sense-making and verification behaviours which are consistent with seeking multiple answers. I call these fine-grained behaviours epistemic practices, with the further precision of *enacted* if I observe them directly and *professed* if the student relates the behaviour. It is essential to note my tight focus on behaviours and the exclusion of students' pronouncements about their beliefs. This focus is highly coherent with Sinatra's (2016) characterisation of epistemic cognition as the behavioural response to a particular situation and, very importantly, provides disciplinary context in which to elicit and observe epistemic cognition. Further, this thesis will avoid attempting to infer or generalise epistemic beliefs from the observed epistemic practices. While such inferences are ubiquitous in the field, I would argue that this is a contributing factor to the persistent issues in establishing a stable construct. This thesis avoids these issues and contributes to the development of a model that is accessible to engineering teachers by focusing directly on epistemic practices.

In order to support engineering programs' ability to prepare graduating engineers to competently assess knowledge claims and to problem-solve in the complex situations expected of them, the research questions of this thesis are coherent with the multiple calls for empirically-based, contextual, and testable models (Muis *et al.* 2006, Bråten 2016, Sandoval *et al.* 2016). The next chapter, Research Design, describes the approach and methods I employed to collect and analyse the empirical observations of this thesis.

3 Research Design

3.1 Introduction

The particular approach to epistemic cognition in engineering taken in this thesis has informed the methodological decisions underpinning the work. Starting with the theoretical perspective, this chapter demonstrates the coherence between the research questions and the research design. It also acknowledges how the fine-grained, contextualised qualitative methodology of the *approaches to learning* work contributed to the methods employed to answer my research questions. While qualitative methods are employed less frequently in engineering education (Case and Light 2011), think-aloud protocols and grounded theory analysis were chosen for their ability to address the research questions. The chapter also relates the implementation of the methods, both qualitative and quantitative, and the approach taken during the data analysis.

While the dialectic relationship between the research questions and methodology (Case and Light 2011) means that they evolved through interaction with each other, for simplicity I will state the final formulation of my research questions:

RQ1: What epistemic practices do engineering students use during problem solving?

RQ2: Do a student's epistemic practices cluster at a single level or span several levels of sophistication?

RQ3: What do the epistemic practices profiles of epistemically sophisticated engineering students look like?

3.2 Methodology

3.2.1 Research Paradigm

My own background and my understanding of how science and engineering disciplines tend to value quantitative data initially led me to impose a rather positivistic research approach on this project. My research training in the physical sciences was built on the assumption that we are able to directly observe reality and to identify causal relationships that can be generalised for other situations. However, the research questions driving this project proved to be inconsistent with such a positivistic ontological approach. The knowledge that this thesis seeks relates to how engineering students see engineering knowledge, and does not make claims about the authentic nature or ideal state of engineering knowledge. Accordingly, I adopted an interpretive ontological approach that allows for multiple interpretations of a phenomenon. That is, this thesis proceeds with the assumption that each participant's actions during problem solving arise from their own subjective views of engineering knowledge. This is consistent with Bryman's description of interpretivism (2016, pp. 12–13) and the importance Saunders *et al.* (2009) place on the perceptions and experiences of the research participants.

An interpretive approach takes reality to be a multi-dimensional construct that is dependant both on the individual person and on their current frame of reference (Brundrett and Rhodes 2013). Thus, a complete description of a phenomenon should include the full range of perceptions existing in the study population. The methodological approach of this thesis was one of discovery, using an inductive approach that allowed findings about students' cognitive processes "to emerge throughout the data collection and analysis process" (Case and Light 2011, p. 188). The need for "natural" settings for data collection, to respect and capture subjective meanings (Brundrett and Rhodes 2013), was my major motivation for selecting think-aloud protocols. These protocols generated the rich, dense data that was needed for theory generation.

Recognising the subjective nature of the phenomena under consideration, I sought to be attentive to how my own ontological assumptions affected my perceptions and decisions throughout the research project. This study does not address the pedagogical implication of the phenomena described. Coming from the physical sciences, I would describe the current work as 'fundamental research' rather than 'applied research' that brings concepts and ideas into interaction with society. Given the massive influence of educational systems on society and the current context of post-truth and the mistrust of experts, developing students' epistemic sophistication has only increased in importance. Despite my concern for these issues, the scope of this study precluded further exploration in this direction. I have restrained myself to the interpretivist approach, as it is both coherent and adequate to address my research questions.

3.2.2 Developing the Research Design

The initial motivation for this research project was to provide university science and engineering teachers with a relatively easy to administer instrument which would allow them to get a snapshot of their students' epistemic beliefs and perhaps even to measure the impact of certain interventions on these beliefs. The original research output was envisioned as a quantitative study that would produce a diagnostic questionnaire, enriched and illustrated by qualitative interviews. While this goal provided clear motivation for using quantitative methods, the methodological incoherence ultimately meant that the quantitative data contributed little to addressing my research questions.

As my research questions coalesced around exploring and describing students' epistemic practices, it became necessary to prioritise qualitative research methods (Eriksson and Kovalainen 2021). Consistent with the ontological approach described above, the research questions assume that different students, having different personal and educational experiences, will implement a different set of epistemic practices in their problem solving. Creating a context that stimulates observable enactment of these differences motivated my choice of qualitative research methods, which seek to describe the range of ways that students use and justify engineering knowledge and the factors that allow students to develop and implement these different epistemic practices.

Accordingly, I employed a purposeful selection of participants to increase opportunities to capture the existing breadth of perspectives. The main data collection method was semi-structured interviews preceded by think-aloud problem solving tasks. The think-aloud tasks prompted students to produce physical and audio artefacts of their thinking and problem solving in an engineering context. Reviewing the physical artefacts served as a stimulus for the subsequent recall portion of the interview, enabling students to describe their approach and strategies.

In quantitative work, the unlikelihood of an observed event occurring due to random variation (rather than a correlation between variables) is commonly used as a measure of the validity of the work. In qualitative studies, the small samples typically preclude the use of statistics and different mechanisms must be used to assess the integrity of the findings. As is coherent with an interpretivist approach, these mechanisms do not rest on measures of objectiveness but rather "trustworthiness". Denzin and Lincoln (1994) identify four factors related to establishing the trustworthiness of qualitative research findings: credibility, transferability, dependability, and confirmability. Credibility is an assessment of confidence in the truth of the findings and is strengthened by triangulation from multiple data sources and methods, such as interviews, observations, and document reviews (Bowen 2009). Transferability is an assessment of how the findings in the current study can be applied in other contexts and is strengthened by rich, contextualised descriptions of the phenomena. Dependability is an assessment of "the stability of the findings over time, and confirmability relates to the internal coherence of the data in relation to the findings, interpretations, and recommendations" (Bowen 2009, p. 306). While the choices made in the current section ultimately determine the trustworthiness of the findings, my discussion of the limitations of this project is reserved for the conclusion where considerations related to the analysis and the findings themselves can be addressed.

As the reasoning behind my approach is described and illustrated in the Literature Review and Research Findings chapters, this chapter will focus on the methods used to collect the quantitative and qualitative observations. Section 3.3 presents my methodology for developing, collecting, and analysing several iterations of a questionnaire with a dimensional beliefs approach. My qualitative methods for structuring, collecting, and analysing the qualitative data from the interview and think-aloud sessions are presented in section 3.4. The result is a mixed-methods approach, although the contributions to the findings from the quantitative aspect are minor, they did serve to significantly develop my thinking about epistemic cognition. The schedule of data collected is presented in Table 3.1.

Table 3.1 Schedule of Data Collection

Data	Date range	Duration of sessions	Usable data sets
Semi-structured interviews	April – May 2015	45-60 minutes	11
Questionnaire distribution	November 2015 – May 2016	N/A	338
Think-aloud protocols and interviews	March – April 2017	60-90 minutes	8
Think-aloud protocols and interviews	October 2017 – December 2018	60-80 minutes	11

3.2.3 Methodological Inspiration from Approaches to Learning *Research*

The *approaches to learning* research introduced novel methodologies for research into academic performance, which until the 1960s had been dominated by psychological tests and questionnaires (Entwistle 2018). A rigorous investigation of learning was generally understood to require highly controlled conditions and focused on how well students performed in recall or other tasks with a single correct answer. An important opening towards qualitative methods was prompted by some interview studies, including Perry's (1970), which explored how students' thinking developed during their time at university (Entwistle, 2018). These early investigations of *approaches to learning* used quite open interview questions to collect students' experiences of learning (i.e. Ramsden 1992, Vermunt 1996). Vermunt's interview study (1996) is particularly relevant to me in its categorisation of several types of cognitive (relating, applying, memorising, etc.) and regulative activity (testing, evaluating, planning, etc.). Setting aside the issue of how beliefs about learning are related to epistemic beliefs, Vermunt's three mental models of learning (intake of knowledge, use of knowledge, construction of knowledge) have clear implications for how students can be expected to go about their learning tasks. These interview studies, however, were concerned with learning experiences on quite a large scale, as is evident from the one-year gap between interviews in Perry's longitudinal study.

Marton initiated an important new methodological approach by investigating learning using naturalistic experiments where students engaged in activities similar to those in their university course (1975). For example, Marton and Säljö (1976) had students read a text and then questioned them about the author's objective and how they had approached reading the text. In their analysis, Marton and Säljö looked for qualitative differences in students' perceptions of the text. Similarly, Pask's methodology involved setting tasks for students (1976, 1988), asking them to understand the material and then explain it to a researcher. The approach of these studies is a significant departure from contemporary work that assessed learning in terms of the word count and precision of students' recollection of what they had read (Entwistle 2018). These studies demonstrated both the value of qualitative studies of students' learning and modelled a rigorous method that sought out differences between students' approaches.

My methodology owes a debt to these *approaches to learning* studies for initiating a focus "on students themselves, as they carried out tasks similar to those they experienced in their everyday studying" (Entwistle 2018, p. 61). The work on *approaches to learning* provided an early example of how to investigate the breadth of students' actions and interactions with knowledge. Their approach also modelled attention to context and used tasks similar to those that students perform during their studies. The importance of disciplinary ways of thinking have been highlighted by several authors (Ramsden 1988, Vander Stoep *et al.* 1996, Entwistle 1997, 2018), with Entwistle noting that "Learning at university is always highly contextualised, dependent on… the nature of the knowledge within a specific discipline" (2018, p. 7). While attention to context is a central element in the *approaches to learning* methodology, Case and Marshall (2004) note that the focus on understanding and the tasks used in many studies omit the procedural or algorithmic skills that are important in engineering problem solving.

In addition to the task-specific thinking and the attention to context of *approaches to learning*, my methodology adopted the focus on the student's own interpretation of their situation (Haggis 2003) and the holistic approach that allows for multiple perceptions and objectives to be simultaneously present (Prosser and Trigwell 1999). The following sections will illustrate how I have incorporated these core ideas into some more recent methods to generate data relevant to my research questions.

3.2.4 Grounded Theory Approach for Data Analysis

The grounded theory approach seeks to generate theory "from the data at hand, rather than already existing theory being used in the analysis as is generally common in education research" (Case and Light 2011, p. 193). Grounded theory, which first emerged in the field of sociology in 1967, departs from traditional research approaches in that it does not begin with a theory or hypothesis to test. This methodological approach was activated during the analysis phase of my research, which as the name suggests, sought to remain "grounded in the words and actions of those individuals under study" (Goulding 2005, p. 296). In grounded theory, data collection is undertaken early and the formulation of hypotheses is typically performed retrospectively by analysing the data. While noting that the use of existing constructs is common in education research, Case and Light highlight the power of grounded theory to "challeng[e] preconceptions and allow[ing] for alternative conceptualizations" (2011, p. 193). Given the cacophony of approaches to epistemic beliefs, I chose grounded theory to ensure that my analysis retained a close connection to my data without undue exterior interference.

Grounded theory is ideal for the current project due to its capacity to support the development of "a well-integrated set of concepts" (Corbin and Strauss 1990) and its sensitivity to the specifics of the context under study. The current study is not a pure application of grounded theory, which is defined as an "iterative, inductive and interactional process of data collection, simultaneous analysis, and emergent interpretation" (Goulding 2005, p. 296). The current study violates the first canon of grounded theory research as formulated by Corbin and Strauss (1990) in that the data were largely collected before any analysis occurred. However, given the experimental set-up of the data collection with audio recording, it was possible to review the audio from the think-aloud sessions and interviews retroactively in light of ideas arising during the analysis. A limitation of this approach was that it was not possible to pose additional questions to participants to pursue themes that arose during the analysis.

While the current project began with a literature review, the observations emerging from the analysis of the qualitative studies sent me on a significantly different path than I originally intended. The iterative process of the data analysis submerged me in the developing themes and effectively separated me from prior models. As I emerged with my nascent ideas, I then re-engaged with the literature from a completely different perspective. I would not have written the literature review in Chapter 2 as it is before analysing my own data.

According to Corbin and Strauss, the aim of a grounded theory approach "is ultimately to build a theoretical explanation by specifying phenomena in terms of conditions that give rise to them, how they are expressed through action/interaction, the consequences that result from them, and variations of these qualifiers" (1990, p. 9). In this approach, it is assumed that people make decisions in response to their perception of the conditions presented to them (Corbin and Strauss 1990) and thus by observing the decisions we can reconstruct their underlying ideas. The specificity of conditions that give rise to certain phenomena is a challenge in all grounded theory work, and particularly in this project which is precisely interested in the specificity of these conditions with respect to engineering knowledge. For Corbin and Strauss (1990), catching the interplay between people's responses to "changing conditions and to the consequences of their actions" is the responsibility of the researcher. The think-aloud protocols described in section 3.4.2 were essential for generating relevant observations. Section 3.4.8 presents further detail on how grounded theory was implemented during the coding of the interview and think-aloud data.

3.2.5 Procedures for Ethical Conduct of the Research

Approval for this research project was granted from Lancaster University (March 6, 2015) and EPFL (April 4, 2015); these decisions can be consulted in Appendix A. All students approached to complete the quantitative instruments were provided with the information sheet (Appendix A) and their consent was taken implicitly if they chose to complete the questionnaire. All interview and think-aloud protocol participants were provided with the information sheet in advance and gave written informed consent at the start of the interview (Appendix A), including for their anonymised views to be shared in scientific publications and meetings. Pseudonyms, mostly chosen by the students themselves, are used throughout this manuscript to identify participants in a way that allows for the range of practices and thoughts of a student to be visible. However, I have taken care to avoid including information that would allow a specific student to be identified.

3.3 Methods for Quantitative Data Acquisition

3.3.1 Motivation for Quantitative Methods

Questionnaires, and the quantitative data that they produce, are attractive for multiple reasons. In addition to the coherence between quantitative data and the disciplinary epistemology of engineering education, the capacity of quantitative methods to survey the large student populations that are typically found in engineering is an important consideration. With adequate sample sizes, the observations carry statistically relevant measures that further add to their perceived value. In this context, this thesis set out to produce the elusive quantitative instrument that would make the intriguing concept of epistemic cognition more relevant and accessible to engineering teachers. The sections below outline the development of items, piloting with focus groups, and three administrations of the questionnaire.

3.3.2 Questionnaire Design and Development of Items

The questionnaire developed in this thesis had a four-part structure, corresponding to the three types of questions plus demographic items. Part I contained items designed to investigate epistemic beliefs in engineering. Items in Part II addressed students' in-class activities. Part III contained two items about the characteristics of a "really good professor" and a "really good student" and Part IV contained demographic items.

The items in Part I were constructed to target the four core dimensions of Hofer and Pintrich's (1997) dimensional model of epistemic beliefs. Due to the relative paucity of quantitative studies in epistemic beliefs in engineering, there were few items from the existing literature that I could incorporate into this study. Items from previous studies were used verbatim where possible or adapted as appropriate. In total, 23 items from Kardash and Wood (2000), Yu and Strobel

(2011), and Schraw *et al.* (2002) were used. Items were contextualised as "in engineering studies" and students were asked to respond on a five-point Likert scale of agreement.

Part II contains entirely new items that drew from the 2015 interviews of in-class actions described by students, formulated with the phrasing and vocabulary used by students. Students were asked to respond on a Likert five-point frequency scale contextualised as "in your favourite course". Questions were intended to focus on a single element, avoiding double-barrelled items such as "I am well organised and keep detailed notes of each class."

The two items in Part III, created by me, strayed into learning beliefs by asking students about their conceptions of excellent learners and teachers.

The three editions of the questionnaire, as distributed, are presented in Appendix B. The first edition of the questionnaire is in French; I translated the items myself. The fidelity of the translation was tested by having a bilingual native English speaker who had never seen the original English items translate the French items back into English (Bracken and Barona 1991). When comparing the original English version and the back-translated version, four small changes were made and two more significant reformulations, in order to ensure coherence between the two languages.

3.3.3 Questionnaire Layout and Data Processing

All three versions of the questionnaire administered had the same four-part format, with small variations in the individual items in Parts I and II. Part I contained 28-37 items, depending on the version, designed to investigate epistemic beliefs. Part II had 11-18 items addressing students' in-class activities. The order of presentation of the items was distributed in order to separate similar items or those that appeared contradictory. A final open question allowed respondents to provide feedback or comments about the questionnaire. The three disseminated versions of the questionnaire contained 48, 46, and 46 items, respectively.

The questionnaires were distributed with an accompanying participant information sheet. A representative example is presented in Appendix A. A student filling out and returning the questionnaire was taken as consent, thereby avoiding the use of signed consent forms that would have identified participants and prevented the data from being anonymous at source. All data was collected on paper questionnaires, which were scanned and read into OMR optical reading software (version 8.4), and marked answers verified through the checking features available in the software by the researcher. The raw data was exported to a csv file and imported into SPSS (version 22, IBM). Reverse scored items were recoded directly in SPSS using the transform function. For the items in Parts I and II, responses were collected on five point Likert scales. The scale for epistemic beliefs was one of agreement (strongly agree, agree, neutral, disagree or strongly disagree) and of frequency for in-class actions (always, often, sometimes, rarely, never). This data was treated as interval data by attributing a numerical value to each response. The data from Part III was treated as ordinal and Part IV as nominal.

3.3.4 Initial Piloting of the Questionnaire with Focus Groups

Two focus groups were conducted on the first version (2015) of the questionnaire, which was in French. Together, these focus groups comprised 13 students between first year Bachelor and final year Master from nine disciplines across the school. They responded to all the items on paper copies of the questionnaire, recorded the time elapsed, and then engaged in a group discussion of items they judged to be unclear. This review process resulted in five items being revised to ensure that the intended message was immediately clear. Further, a quantitative analysis of their responses resulted in nine items being removed since essentially all students had indicated that they agreed with the statement or would 'always' employ a particular action during their classes. The lack of discrimination of these items meant that they were unable to identify interesting variation in the population.

3.3.5 Questionnaire Administration and Respondents' Demographic Profile

In total, three versions of the questionnaire were administered. Version 1 was administered in November 2015, predominantly to students studying in the library individually or in small groups. In February 2016, version 1 was administered to a class composed of Master students from several different study concentrations. In total, 157 students completed version 1 and 121 useable data sets were obtained. Verbal comments from students during distribution of the first version, predominantly from Masters students, revealed that the French language was preventing some students from participating. In order to allow all Masters students to participate, I made subsequent iterations of the questionnaire in English.

Versions 2 and 3 were administered in May 2016 exclusively in classes, through the generous cooperation of instructors. For these versions, 220 and 144 completed questionnaires, respectively, were obtained and 216 and 142 useable data sets, respectively. The administration information is summarised in Table 3.2. While care was taken to ensure an overall broad distribution of respondents from across the five years of study, gender, and engineering discipline, there were clear correlations between the demographic characteristics of respondents due to the logistics of my administration. For instance, the first year Bachelor respondents for versions 2 and 3 are almost exclusively from three departments and almost all female respondents are from a single study concentration. This unequal distribution renders the data set unsuitable for most analyses involving correlations with demographic information.

Table 3.2 Administration of the Three Versions of the Questionnaire

Version	Date	Useable data sets	Site	% women
1	November 2015 and February 2016	121	Library	31
2	May 2016	216	Classes	37
3	May 2016	142	Classes	48

3.3.6 Winnowing Items for Parts I and II of Questionnaire

For each of the three versions of the questionnaire, an initial selection of items was conducted by evaluating each item on three criteria. First, that each item was within acceptable statistical ranges for skewness, kurtosis, and standard deviation (Tabachnick and Fidell 2007). Next, each item was assessed for its ability to discriminate effectively between respondents in the sample. The key issue here was ensuring that the item elicited a diversity of responses, rather than virtually all respondents agreeing with it. Non-discriminatory items were eliminated from each round of analysis, but generally reformulated for the subsequent iteration of the questionnaire. Finally, two-tailed inter-item Spearman correlations were calculated for the remaining items. This measure was chosen as appropriate for ordinal data with analogous properties at both ends.

The results of this analysis are reported in Table 3.3. Overall, 22 items were eliminated from Part I and seven items from Part II. For each version, the Kaiser-Meyer-Olkin's statistic for sampling adequacy and Bartlett's Test of Sphericity were calculated to ensure that the data met the basic criteria to allow for structural analysis with maximum likelihood estimation (MLE). This procedure is described in the following section.

Table 3.3 Summary of Items Eliminated from Parts I and II

Criteria not met	**PART I, version**			**PART II, version**		
	1	**2**	**3**	**1**	**2**	**3**
Skewness, kurtosis[12]	0	(1)	(1)	(2)	(2)	(2)
Discrimination	5	4	3	1	1	1

3.3.7 Part III

The final two items of the questionnaire asked about characteristics of "really good" students and teachers, as shown in Table 3.4, with response options relating to different levels of epistemic sophistication. These data were treated as ordinal, with the least sophisticated response (i.e. providing complete information) representing one end of the scale and the most sophisticated (challenges students to explore difficult areas, and challenges students to explore open-ended problems) the other end.

[12] Slightly platykuric items were nevertheless kept.

Table 3.4 Part III Items: Characteristics of Good Professors and Students

What is the one characteristic that marks out a really good professor?	**What is the one characteristic that marks out a really good student?**
Providing complete, clear information	Being attentive and taking complete notes
Showing students how to solve problems	Being able to solve all the exercises
Demonstrating the relevance and connections between different aspects of the material	Applying the concepts in novel contexts, such as projects
Challenging students to explore difficult, novel areas	Developing their own ideas
Challenging students to explore unclear, open-ended problems	

3.4 Methods for Qualitative Data Acquistion

3.4.1 Semi-structured Interviews

The dialectic interaction and opportunity to pursue specific themes arising from the experiences of an individual student make semi-structured interviews an appropriate methodological approach for my research questions. The successful conduct of this type of interview requires the interviewer to rely on their own experience, intuition, and subject knowledge to respond dynamically to the unique context of each interview. In this thesis, the relevant subject area knowledge includes fundamental concepts from engineering science and the nature of engineering work.

Semi-structured interviews typically draw their structure from an outline, developed by the researcher, which lists some possible questions to explore the relevant topics. This places semi-structured interviews between the rigidity of an exchange that follows a static, scripted set of questions and a completely open conversation. The less-structured part of a semi-structured interview arises from the researcher exploring emergent themes and asking clarifying questions to check the meaning or interpretation of the experiences described by the interviewee. Effective use of such clarifying questions during the interview greatly facilitates *post hoc* analysis (Brinkmann and Kvale 2015, p. 116).

A key advantage of an unstructured flow is that it produces more spontaneous and lively answers, whereas a more structured outline facilitates later analysis (Brinkmann and Kvale 2015, p. 156). Additionally, the outline needs to balance thematic questions that explore the target areas with dynamic questions that build rapport and maintain a comfortable flow during the interview. It is essential to establish a relationship between the interviewer and interviewee that facilitates an open accounting of the students' approaches to problem solving and to their studies, but too much intimacy can cause students to attempt to provide the answers they anticipate will match the researcher's expectations (Lee 2008). The organisation of the room and the initial interactions should facilitate the desired dynamic during the interview.

In order to generate observations germane to my research questions, the interviews explored specific, contextualised experiences and did not seek the participants' general ideas about engineering and problem solving. Thus, Brinkmann and Kvale's advice to ensure the validity of the interview data by asking for a free and detailed narrative of a specific and recent memory, providing prompts such as 'last time you were in class' and allowing for sufficient time for the interviewee to recount the details of their experiences, was determined to be highly relevant (2015, p. 52). In practice, this meant that either a paper copy of the students' class schedule or their answers to the think-aloud tasks were used to anchor the interviews in a specific and authentic context.

3.4.2 Think-aloud Protocols to Observe Problem Solving in Action

A think-aloud protocol sets a task and requests the interviewee to narrate their actions and thoughts during their attempts to accomplish the task. Olson *et al.* (2018) argue that a think-aloud protocol is the most effective way to observe complex thinking processes and that it is well suited to studying the different ways that the same task can be approached. This method is a good fit for the current study, but care must be taken when constructing the tasks and the instructions given to students to ensure coherence with the research questions.

The think-aloud protocol was created in the 1980s in the field of cognitive processing in psychology (Ericsson and Simon 1998) and has since been used to explore thinking during a range of different tasks, including the strategies and approaches used by engineering students during problem solving (Christiaans and

Dorst 1992, Atman and Bursic 1998, Pintrich *et al.* 2000, Atman *et al.* 2005, Taraban *et al.* 2007, Litzinger *et al.* 2010).

The accuracy of the narration with respect to the person's thinking is a question of obvious importance and some divergence of opinion. A primary limitation of this method is that a student may not be aware of, or able to articulate, each thought or idea that crosses their mind. Ericsson and Simon insist that narration is an accurate report of the student's thinking, as the student would be too occupied by advancing the task and maintaining their verbal narration to have sufficient capacity to intentionally adjust their cognitive processes (1984, p. 16). Jäskeläinen (2010), however, cautions that this high cognitive load will result in only a fraction of the student's cognitive processing being narrated. This concern contradicts the findings of Van Someren *et al.* (1994) that think-aloud narration does not affect students' performance more than a typical tutorial-like setting. Similarly, Ericsson and Simon note, "Participants do not appear to monitor their overt verbalizations of thoughts, as they are observed to mostly generate incomplete sentences and phrases, and rarely correct their verbalizations including speech errors" (1998, p. 181). Nevertheless, some students have recounted that their narration was unable to keep pace with their thoughts (Someren *et al.* 1994) or that the complexity of their cognitive processes were too difficult to accurately verbalise (Nielsen and Yssing 2002). Overall, it seems that while a student may not be able to narrate absolutely everything passing through their mind, an audio record can be taken as a "thoroughly reliable" sample of their thinking (Ericsson and Simon 1998, p. 247).

Ericsson and Simon (1998, p. 181) state that "Perhaps the single most important precondition for successful direct expression of thinking is that the participants are allowed to maintain undisrupted focus on the completion of the presented tasks. Hence, participants are explicitly instructed to focus on the task while thinking aloud and merely to verbalize their thoughts rather than describe or explain them to anyone else." In the current project, my instructions were brief and explicit, requesting the student to narrate their thoughts and actions as they occurred. Care was taken to follow the advice of Baker and Cerro (2000) around how questions and comments are phrased to avoid cueing participants about how to respond. For example, avoiding phrases such as 'Tell me what you think' because they imply that the student should form an opinion or analysis of their own thinking. Students may then be less likely to report thoughts that may first appear random (Someren *et al.* 1994, p. 43). For example, a question such as "Why did you do X?" could lead a student into metacognitive reflection which would not have occurred spontaneously and could influence the student's problem-solving practices. Increased interaction between researcher and student may also reveal more about the researcher's goals and result in increased attempts by the student to meet, or avoid meeting, perceived expectations. While I was present throughout the think-aloud protocols in this project, I sought to minimise distractions and interruptions in order to reduce interference with students' train of thought (Someren *et al.* 1994).

The research questions of this thesis required detailed and contextualised observations of students' problem solving. Despite being constrained both by cognitive load limits and the self-awareness of the students (Baker and Cerro 2000), the think-aloud protocols allowed for the observation of epistemically revealing practices through the verbalisation of their thought processes. This capacity for the think-aloud method to provide details about the range and prevalence of strategies employed by students was ideal. To decrease inference during analysis, and to enrich the observations, I conducted a stimulated recall interview immediately after each think-aloud protocol. The focus on descriptive, rather than explicative (why), accounts was maintained. The following section provides detail about the methods I employed.

3.4.3 Conducting the Think-aloud Sessions

Kuusela and Paul (2000) identified two types of think-aloud protocols: (1) concurrent think-aloud, where the student's narration is collected directly during their problem solving, and (2) retrospective think-aloud, where the participants reflect *a posteriori* on their problem solving. I choose to employ concurrent think-aloud as it generally provides more information about the students' problem solving approach and decision-making (Kuusela and Paul 2000).

As recommended by Van Someren *et al.* (1994), an *a posteriori* interview was conducted with each student immediately after their problem solving session to obtain additional details and observations about their approach. This was done with a stimulated recall approach (Lyle 2003), using the student's own written work on each particular task as a prompt to ask how they had started, the origin of the equations they wrote, and how they had verified their answers. Using the students' own notes meant that the stimulated recall could occur immediately after the think-aloud problem solving, thereby keeping the temporal separation brief, as per Lyle (2003) and Charter's (2003) recommendations. Maintaining a temporal separation between the (uninterrupted, audio-recorded) think-aloud and the *a posteriori* recall also served to minimise the impact of the researcher on students' behaviour. A distinction between the two phases was maintained in the analysis, where actions performed by students during the think-aloud problem solving were designated as 'enacted' and comments recounting actions undertaken in other contexts as 'professed'. This terminology is consistent with both Julie Gainsburg's work (2015) and Van Someren *et al.*'s (1994) recommendation.

3.4.4 Designing Tasks for Think-aloud Problem Solving

Creating opportunities for students to exhibit epistemically-revealing problem solving practices, such as reasoning with personal experience or with formulae, was the key objective in designing the think-aloud tasks. These tasks were the central element in providing the engineering context for the data collection, an essential aspect for generating relevant observations. For each set of think-aloud sessions, a series of tasks were designed to invoke diverse problem solving strategies without requiring knowledge beyond a typical first year science or engineering programme. As noted by Baker and Cerro (2000), tasks needed to be difficult, complex, and sufficiently novel to require some metacognitive skill, yet avoid inducing excessive cognitive load (Charters 2003). Chemistry was often chosen as the disciplinary context due to my background; however, I informed students that the problems did not require particular knowledge beyond basic stoichiometry and that they should go about solving the tasks as they would a set of assigned exercises. Each task was presented in a contextualised format to provide opportunities for students to verify the plausibility of answers or to leverage real-life observations. For example, the task involving heat capacity in the first set of tasks involved an *in situ* dental filling. How the think-aloud tasks are contextualised is clearly important, as the presentation of both the tasks and the instructions themselves will influence students' perceptions of how they should approach the activity (Laurillard 1997). Each student was offered the choice to participate in French or English, and were provided with the set of tasks and asked questions according to their choice. The analysis from the first round of think-aloud protocols was leveraged to design the next set of tasks. The complete set of tasks for both the 2017 and 2018 think-aloud protocols, for which I provided one per page during the experimental protocol, are available in Appendix C.

3.4.5 Experimental Conditions for Interviews and/or Think-aloud Protocols

Following Bowen's advice (1994), I mentally divided the sessions with students into several phases: greeting, think-aloud set up, data collection, and wrap up. The greeting phase is important to set up the atmosphere for the rest of the session, and despite needing to reserve sufficient time for data collection, initiating a brief, informal conversation can allow students to adjust to the setting. Think-aloud sessions and/or interviews were conducted with individual students, in either a classroom or meeting room on campus, but not in buildings that they would often have cause to visit. Schoenfeld recommends conducting think-aloud protocols individually in order to reduce the effects of social dynamics present with groups of students, and to select an environment that is comfortable and associated with the desired type of cognition (1985). The other objective of the greeting phase is to tell the students a bit about the study; Bowen recommends providing general yet honest information. For the think-aloud sessions, I said I was interested in how the participants went about solving the problems and not in the answers that they obtained. As they started the problem solving, I would remind them again of this and specify that I had intentionally selected tasks that would pose some difficulty for them to solve.

The think-aloud set-up consisted of a warm-up task similar to the experimental tasks (Bowen 1994, Someren *et al.* 1994) that served to familiarise students with the nature of the narration expected of them. This provided an opportunity for me to provide feedback if a student was explaining or interpreting their thoughts as opposed to simply narrating them. If a student was not speaking, I reminded them to keep speaking as though they had removed the filter that usually (appropriately) prevents us from saying everything that crosses our mind. I took particular care, both during the warm up and the subsequent interview, to ask students about *what* they did and not *why* they did it, to avoid prompting students to artificially exhibit metacognitive behaviours (Bowen 1994). The warm-up task for each set involved a stoichiometric calculation. This simple task allowed students to practice the think-aloud component under a lighter cognitive load and also for me to offer feedback without interrupting the experimental conditions.

In the data collection phase, students were given one task at a time and asked to proceed as though they were completing a set of assigned homework exercises. Students were instructed to go about problem solving as they usually would, but to shut off the filter that usually keeps us from saying everything that passes through our minds. That is, that they should not explain their thinking but simply narrate their actions and observations, starting by reading the task aloud. Having the tasks read aloud provided me with useful information when transcribing the sessions and also appeared to help students launch into narrating their actions.

Students were left to work without interruption until they reported they had finished the task, or were ready to abandon the task, or 15 minutes had elapsed. After 15 minutes, I would ask if the student would like to continue for another few minutes or if they were ready to move on. The 15-minute period was judged sufficient time for the student to have enacted several different problem solving practices; finding the correct answer was not germane to the goals of this research project.

Schoenfeld identified that the materials available and the intervention of the researcher are important variables in think-aloud protocols (1985). Reflecting Schoenfeld's opinion that the materials provided to students, such as a formulae sheet, scrap paper, or a calculator can affect how a student proceeds, all students were provided with identical materials: a basic calculator, a pencil, an eraser, and scrap paper. Similarly, I attempted to provide an equivalent level of intervention with each participant. While I remained in the room during the problem solving, engaged in reading or editing an unrelated article, I refrained from interrupting except during the warm-up exercise.

Sessions with participants were between 60 and 90 minutes long, largely dependent on students' facility and determination to persist in solving the exercises. The whole session was recorded, including the semi-structured interview and stimulated recall that followed. Students' written work was kept and used to supplement the analysis where appropriate.

3.4.6 Purposeful Sampling for Rich Observations

To meet the goals of the rich qualitative approach employed in this project, the selected sample sought to explore the full range of variations in the experiences under study (Booth 1997). Purposive sampling was used in both the qualitative and quantitative studies to assemble observations that reflected the demographic diversity of the population, which increased the opportunity to investigate the widest range of student experiences. This meant attending to the demographic profile of respondents and then targeting classes or locations where students from different study programmes or years of study could be found.

Each of the qualitative studies involved a rather small number of students, reflecting my goal of generating a detailed and thorough exploration of students' behaviours and their descriptions of their experiences (Brinkmann 2012). Prioritising the depth of the observations collected, over quantitative indicators such as number of participants is coherent with my research questions. From the cohort of students responding to an online recruitment notice, in return for 15 Swiss francs compensation, study participants were selected to achieve maximum variation in demographic features. The criteria considered were gender, year of study, and study programme. Other criteria that could influence students' epistemic cognition but were not used in purposive sampling include students' educational history (Swiss *maturité*, French *baccalauréat*, French *école préparatoire*…) and grade point average (as a proxy for having a study approach adapted to the school's expectations).

Recruitment of participants, for each set of think-aloud protocols, continued until conceptual saturation was obtained. This indicated that the diversity of students' behaviours had been captured (Strauss and Corbin 1998). In practice, conceptual saturation was defined as the point at which further data collection and analysis did not yield any new observations.

3.4.7 Transcription and Coding for Interviews and Think-aloud Protocols

The transcription and coding of the interviews and think-aloud protocols involved pragmatic choices related to the technology and more complex conceptual decisions to pilot an approach that was coherent with the methodology.

Pragmatically, I selected the NVivo qualitative data analysis software for its multiple features for grouping and visualising themes across several data sources. The recordings of the interviews and think-aloud protocols were imported as audio files into the NVivo software. The more challenging decisions related to transcription and coding are discussed below. Once these laborious tasks had been completed, the framework feature in NVivo was used to extract the portions of the transcriptions that I had assigned the same code. I reviewed the extracted data in tabular format on A3 sheets.

Generating the transcriptions was not a trivial process. My intention was to transcribe the audio files as faithfully as possible, with a minimum of interpretation, but this was quite difficult with the think-aloud component of the protocol. Van Someren *et al.* address how the nature of the think-aloud narration makes it complex to transcribe accurately, as the utterings are frequently incomplete, interrupted, or muttered (1994, pp. 45–46) and Bowen warns that a one-hour session can take up to six hours to transcribe (1994). I transcribed the interviews in the same language they were conducted to reduce the numbers of manipulations of the students' comments; the resulting bilingual data set may appear unwieldly for many people but is in fact typical in my context. This is illustrated by many participants switching between English and French, even for just a brief section, during their interviews. Non-verbal utterances, such as pauses, sighs, and grunts of frustration, were included as faithfully as possible in the transcription, as they appeared to be an integral part of many students' problem solving. Recognisable pauses were recorded as an ellipse (…) as per convention and a prolonged silence as 'silence'. While the distinction between a pause and a silence remains a matter of interpretation by the researcher, the human ear is well trained for detecting unusual pauses between words in a sentence (Van Someren *et al.*, 1994). These non-verbal markers are central to the literature of discourse and framing (Tannen 1993). The current analysis makes no claim to such analysis and ultimately only the words were analysed. Van Someren *et al.* (1994) underline that it is important not to give one's own interpretation to a sentence through the addition of punctuation, and recommends omitting punctuation entirely and simply starting a new line for each new sentence. I did not find it feasible to follow this advice with the incomplete sentences generated during the think-aloud protocols.

Once each transcript was completed, I annotated it with a short description of what each participant was "doing" at that particular point (e.g. solving task 2, debriefing task 3). The transcripts were reviewed in detail and annotated with descriptive tags designed to avoid inferring meaning. This resulted in some sentences being coded with multiple tags. The unit of analysis was approximately the sentence, although there were many incomplete sentences, particularly in the think-aloud protocols. Students' responses to standard questions in the interview guide were identified to enable comparison in subsequent steps. This analysis did not ultimately prove to be useful. Instead, a grounded approach based on an initial open coding strategy of students' narrated problem solving and subsequent interview was pursued; the conceptual approach to the coding is detailed in the following section.

3.4.8 Qualitative Data Analysis Approach

My goal with the analysis was to capture the broadest range of students' problem solving activities and approaches to engineering knowledge. In using grounded theory for the analytical approach, the first stage of the analysis was "open coding". This involved identifying recurrent, salient, or puzzling incidents. I undertook the analysis in an iterative manner, minutely reviewing the audio files and transcripts and then reviewing them again as new themes arose. The incomplete format of many of the utterances during the think-aloud protocols meant that their meaning was ambiguous (Charters 2003, Olson *et al.* 2018) and contributed to making the data difficult to score (Baker and Cerro 2000). I whole-heartedly agree with Atman and Bursic's observation that the think-aloud protocols are rich but time consuming (1998). Brinkmann and Kvale (2015) caution that even with interviews, where the sentences tend to be more complete and where clarification questions can be asked, the researcher must make inferences about meaning. It is also important to note that the aspects of the task and the situations that a student recounts during the interview do not necessarily represent the extent of their conceptions but only those evoked by the current context (Trigwell and Ashwin 2006). The researcher's analysis, therefore, should take care when making assumptions about the absence of ideas or behaviours.

This "constant comparative method" is central to the grounded theory approach and accompanies each step of the analysis (Case and Light 2011, p. 193), where connections and overlaps should be investigated. In the next stage of analysis, themes were grouped together with axial coding in order to allow a more general picture to emerge. As the codes are nascent theory and the coding process itself the start of theory development, it is important to avoid trying to fit data into prior categories (Bowen 2009). Spiggle (1994) cautions that the connections to the original data should remain clear. This is a key point, as the quality of the grounded theory analysis is characterised by a strong internal coherence. Collecting rich data and detailed contextual information is also important, as these elements will support the transfer of the emerging theory to other situations.

Table 3.5 Coding structure for selected practices

Interview response	Open code	Axial code	Selective code
During tutorials, we have the solutions. Cédric	Solutions	Answer Checking	Level 1 = External expert or pure maths
To check the limits, the extreme cases in the equation, for example if the mass goes to zero or infinity. Baptiste	Logical		
And then the units too. Here it is clear that I wanted Kelvin. Dimitri	Units		Level 2 = Conceptual
I didn't use the mass anywhere. Um. Which is normal because I have just been dealing with acceleration…. And the acceleration doesn't depend on mass. Bart	Concept		
I tried to think about the last time that my parents changed a tyre. Carmen	Observation from life		Level 3 = Connecting to physical reality
I remember quite well the professor explaining it. And I just believed her... Ernest	Book, teacher	Source and Validity of Equations	Level 1 = External expert or pure maths
I was able to remember the formula, and then I checked by reviewing the units. Boris	Units		Level 2 = Conceptual
I'm guessing, but a big part of creating something like this would be working out which properties were important. And what needs to be defined, like the momentum. Bart	Physical reality		Level 3 = Connecting to physical reality

As the conceptual categories arising from my analysis of the data coalesced, I reviewed the work of other researchers to identify commonalities and differences with my data set. The result was that the structure of the final codes was orthogonal to the axial codes and resulted in the generation of a tabular format that aligned open codes across several axial codes, rather than the branching tree-like structure typically produced. The columns in Table 3.5 present the coding structure for a sample of open codes and can be used to illustrate the timeline of this process, as the information was generated from left to right. To reduce readers' cognitive load, the tables in the Analysis chapter are structured by the selective codes. This analysis was conducted across both languages simultaneously and only the specific quotations used for illustrative purposes in this document were translated to English, if necessary, at the final stages.

The decision to stop collecting and analysing data should be made when a point of conceptual saturation has been reached such that further observations or analysis do not contribute new insight (Strauss and Corbin 1998). While more data can increase the trustworthiness of a study, enhancing transferability by developing richer descriptions and confirmability by providing more points to verify the internal coherence, conceptual saturation indicates that the ultimate goal of capturing the diversity of students' practices was achieved in the current study. In a rigorous grounded theory approach, it would only be at this stage that the emerging ideas would be assessed against existing theories, and the areas of agreement, dissent, and extension would be elaborated in communicating the results (Goulding 2005, p. 297).

3.5 Participants and Experimental Conditions of the 3 Qualitative Studies

3.5.1 Interviews 2015

This set of semi-structured interviews first addressed students' intentions and actions when attending their favourite class in the current term, then secondly the course in which they judged their actions were most different from their favourite class. Each student brought a physical copy of their class schedule for the current term, which assisted in making the discussion concrete and specific. This set of interviews took place in April and May 2015, and did not include any think-aloud problem solving.

3.5.2 Participants 2015

The demographic characteristics of the eleven students who participated in this study are presented in Table 3.6 below, in order of advancement in their studies. The pseudonyms chosen by students are reported in the final column; however these participants are identified in subsequent chapters by the pseudonyms in the first column. I revised these students' pseudonyms in order to be consistent with the nomenclature adopted after this set of interviews, while seeking to respect the linguistic origin of their original choice. An updated pseudonym beginning with an *A* indicates a first year student and a *C* a third year student. The Bachelors students were between 19 and 21 years of age, Masters students between 23 and 26 years old.

Table 3.6 Student Participants for Spring 2015 Interviews

Pseudo	Year	Study program	Previous studies	Chosen pseudo
Augustin	First	Civil engineering	France	Paul
Arthur	First	Micro engineering	France	Patrick
Albert	First	Computer science	Switzerland	Sylvain
Bonnie	Second	Life sciences engineering	France	Marie
Beatrice	Second	Computer science	France	Mathilde
Csongor	Third	Communication systems	Switzerland	Arpad
Destiny	Master1	Chemical engineering	Switzerland	Cannelle
Diane	Master1	Materials engineering	France	Caroline
Drew	Master1	Life sciences engineering	Other	George
Durak	Master1	Technology entrepreneurship	Other	Ogeday
Ellie	Master2	Electrical engineering	Other	Ellie

3.5.3 Interviews with Think-aloud Protocol Spring 2017

This second set of semi-structured interviews, held in March and April 2017, were the first to include think-aloud problem-solving tasks. Each session began with the think-aloud tasks; the physical record generated by the student during their problem solving then served as a concrete and contextual anchor for the interview which followed immediately. The sessions lasted between 50 and 85 minutes, with the average being about 65 minutes. The duration was determined by the students' ease in problem solving, their perseverance in continuing in the face of a difficulty, and to a lesser extent their answers to the interview questions.

3.5.4 Think-aloud Problem Solving Tasks Spring 2017

I designed a series of four tasks to invoke problem-solving strategies without requiring knowledge beyond what a typical first year chemistry course would provide. Two tasks involved calculations (rate of reaction, heat capacity) and two tasks asked for predictions and justifications of observed phenomena. Each task was presented in a contextualised format to offer opportunities for students to verify the plausibility of answers or to employ real-life observations. For example, the task about heat capacity involved an *in situ* dental filling. The session started with a warm-up task that involved a simple stoichiometric calculation.

3.5.5 Participants Spring 2017

Eight students from a range of different study programs, presented in Table 3.7, were interviewed for this study. I employed purposeful sampling to increase diversity in year of study and study program. The Bachelors students were between 18 and 22 years of age, Masters students between 22 and 25 years old.

Table 3.7 Student Participants for Spring 2017 Interviews

Pseudo	Year	Study Program	Previous studies
Amandine	First	Computer engineering	France
Anna	First	Electrical engineering	France
Antoine	First	Life Science engineering	Switzerland
Benoît	Second	Microengineering	Switzerland
Boris	Second	Mechanical engineering	Switzerland
Clément	Third	Microengineering	Switzerland
Damien	Master1	Technology Entrepreneurship (B.Eng electrical)	France
Ernest	Master2	Environmental engineering (B.Eng civil)	Other

3.5.6 Interviews with Think-aloud Protocol Fall 2017-2018

The second set of semi-structured interviews with think-aloud problem-solving followed the same format as the first set. I developed new tasks and a revised focus for the interview questions to deepen or broaden observations made during the first set of think-aloud protocols. The first three interviews were conducted in October or November 2017 and the remaining seven between November and December 2018. The interviews were between 59 and 80 minutes long; the average length was 70 minutes.

3.5.7 Think-aloud Problem Solving Tasks 2017-2018

The three tasks for this set of interviews were designed to pose sufficiently challenging problems to require that students employ a variety of problem solving strategies, including making connections to their lived experiences and creating opportunities to use multiple strategies for checking answers. The first problem was a thermodynamics question involving the equation for heat capacity and the second a ballistics question involving the equations of movement. The intention for the first two problems was to prompt students to recall and use fundamental equations. The final problem was quite different; it simply asked, "How far can a car drive before wearing off a single molecular layer of rubber from its tyres?" The objective of presenting students with this task was to confront them with a problem that did not have a clear correct answer and where making progress would require students to make decisions, assumptions, and estimations. The complete set of tasks, which were provided consecutively one per page during the experimental protocol, is available in Appendix C.

3.5.8 Participants in the 2017-2018 Interviews

Eleven students from a range of different study programs, presented in Table 3.8, were interviewed for this study. Students are identified by a pseudonym of their own choosing, where a name beginning with A indicates a first year student and a name beginning with C a third year student. Purposeful sampling was employed to obtain some diversity in year of study and study program. Bachelors students were between 20 and 21 years of age and Masters students between 22 and 24 years.

Table 3.8 Student Participants for 2017-2018 Interviews

Pseudo	Year	Study program	Previous studies
Baptiste	Ba3	Bioengineering	France
Bart	Ba3	Electrical engineering	France
Bernard	Ba3	Math	France
Carmen	Ba5	Bio engineering	Swiss
Cedric	Ba5	Math	Swiss
Daniel	Ma1	Mechanical engineering	Other
Delphi	Ma1	Civil engineering	Swiss
Didier	Ma1	Environmental engineering	Swiss
Dimitri	Ma1	Communication systems	Swiss
Elise	Ma3	Micro engineering	France
Guillaume	Ma3	Electrical engineering	France

3.6 Chapter Three Conclusion

This chapter has outlined the methodological approach undertaken in answering the research questions of this thesis. While considerable effort was expended in gathering, analysing, and describing the methods used for the quantitative data, these efforts ultimately contributed little to this project. It is the qualitative data from the students' think-aloud problem solving and subsequent semi-structured interviews, collected through a grounded theory approach, that provide the observations that underpin the central contributions of this thesis.

As the analysis presented in the following chapter will make clear, these detailed and contextualised observations allowed me to develop a rich characterisation of engineering students' epistemically-relevant practices. The arguments against inferring overarching epistemic beliefs, which I made in the previous chapter, will also be revisited in light of the unsatisfactory structure in the epistemic beliefs items in the questionnaire.

4 Research Findings

4.1 INTRODUCTION

This chapter presents my empirical observations arising from the four studies that constitute the data collection of this thesis, listed in Table 3.1, in an integrated manner to coherently address my research questions. The main focus is on my first two research questions, about the nature and distribution of students' epistemic practices. For this I take a fine-grained, cognitive processes approach (Briell *et al*. 2011) to develop a detailed profile of students' epistemic practices during engineering problem solving. Answering my final research question, about how to characterise and model epistemic sophistication in engineering, requires contributions both from my observations and from prior work in the field. This chapter will introduce my relevant empirical data; however, I will provide a more complete answer to these questions in Chapter 5.

While my cognitive processes approach rejects categorising students by their level of epistemic sophistication, I find that the categorisation of students' behaviours or actions is a useful analytic tool. As was explored in detail in Chapter 2, there is broad agreement on what constitutes epistemic sophistication, despite measurement and terminology issues. The consensus is that the arc of increasing epistemic sophistication proceeds from naïve conceptions that knowledge is absolute and comes from experts, to more sophisticated conceptions that knowledge is evolving and that an individual must make context-dependant judgements.

The descriptions of naïve epistemic conceptions proposed by prior models, such as Perry (1970) and Hofer and Pintrich (1997), have generally been found to be relevant for engineering knowledge. Additionally, Julie Gainsburg has made important contributions to the most sophisticated end of the scale by describing the practices of professional engineers (2007). However, in order to operationalise Elby and Hammer's epistemological resources model at their intended fine-grained level (Elby and Hammer 2001, 2010), it is essential to develop rich characterisations of discipline-specific practices. The key contributions of this study are about intermediate epistemic sophistication, representing an essential area in terms of students' development during their university studies. As outlined in Chapter 2, some of the key epistemic practices for engineering involve navigating between representations and real-world complexity, managing uncertainty, and justifying the problem solving approach taken.

Table 4.1 Categorisation of Epistemic Problem Solving Practices

Increasing epistemic sophistication

Level One Absolute	**Two Local coherence**	**Three Coherence**	**Four Sceptical Reverence**
Engineering thinking leads to single, exact correct answers.	Engineering thinking is internally coherent, precise, and mathematically based. However, different approaches can give different good answers.	Engineering thinking makes connections between physical reality and models, where all answers that meet or exceed the constraints are acceptable.	Engineering thinking involves judgement.

The main approach I employed in parsing and analysing the qualitative data is grounded theory, which yielded 10, 11, and 14 axial codes respectively, for each of the three qualitative studies. The practices identified were next grouped into themes, for example answer-checking or models, and used to construct descriptions of specific practices at multiple levels of epistemic sophistication. I developed the levels described in Table 4.1 from my analysis of the empirical observations presented in this chapter, however, I present them here in advance of the observations themselves as I have used them to structure the epistemic practices throughout the chapter. The four levels describe practices from a naïve, precise, and absolute Level 1 approach to engineering knowledge, to sophisticated, context-dependant Level 4 practices. In the following sections, the individual epistemic practices are introduced and illustrated with extracts from my interviews with students. The chapter concludes by summarising how the empirical results address my research questions, in preparation for the discussion of these observations in relation to prior work presented in Chapter Five.

4.2 EPISTEMIC PRACTICES

4.2.1 Engineering Students' Epistemic Problem Solving Practices

Epistemic practices are observable, epistemically revealing practices enacted when a student approaches, justifies, and evaluates specific, contextualised knowledge (Sandoval *et al*. 2000). Think-aloud protocols of problem solving tasks provide an effective way to elicit and observe these practices in engineering students (Litzinger *et al*. 2010).

This section presents the epistemic practices of 30 engineering students, who were predominantly directly observed during think-aloud tasks. I investigated students' practices under as contextualised and specific conditions as was experimentally possible. The observations presented here are grouped by the type of epistemic practice; how students work with their peers, their approach to correct answers, how they verify their answers, and how they use estimation and mathematical models. An analytical approach following a student's path in solving each problem did not generate interesting observations for the tasks employed. Rather, a fine-grained approach where each action or sentence was coded proved more relevant. Some of the think-aloud tasks which produced the richest practices on the part of the participants required students to reconstitute or recall a formula from memory and involved several steps that provided opportunities for conceptual reasoning and real-life contextualisation.

4.2.2 Working with Peers

One of the core aspects of epistemic beliefs models is the source of knowledge. Are experts the only reliable source of knowledge? Who do students think are competent to answer their questions and to what degree do they see themselves or their peers as capable of contributing to knowledge? While the experimental conditions of this research project did not allow for the direct observation of peer interactions, students' descriptions of their behaviour in exercise sessions did produce instances of professed interactions with peers.

Table 4.2 Students' Practices for Working with Peers[13]

	Level 1 Absolute	**2 Local coherence**	**3 Coherence**
	Avoids soliciting knowledge from peers, direct questions to experts	**Discusses with peers to refine own understanding**	**Discusses with peers to learn from peers' ideas, even if imperfect**
Representative Quotations	I ask my questions directly to the TA who can answer properly. Bonnie	When I haven't understood, I will ask my neighbour to see if he has. He does the same. Csongor	We started by telling [each other] what we already understood and then we realised maybe we didn't understand well enough to do the exercise. And so we started to explain to each other what we had understood. And then one person had an idea but when she started to test it, didn't work very well. But another person had an idea to improve it, and we kept doing that. Beatrice
Adam	2	2	
Augustin	1		
Arthur	3		
Beatrice			4
Bernard		1	
Bonnie	1		
Csongor		1	
Destiny		2	
Diane		1	
Drew		1	1
Durak		1	
Ellie		1	
SUM	7	10	5

[13] Only students who exhibited or discussed the current theme are listed in each table. Thus, the omission of a student from a table indicates that this theme was not observed for this student.

Students' comments pertaining to their interactions with peers were identified during the grounded theory analysis, and then positioned in order of relative epistemic sophistication, as illustrated in Table 4.2. The first set of practices are naïve in perspective, seeking knowledge only from experts. Moving towards the right across the table, epistemic sophistication increases, students increasingly see their peers and themselves as agents of knowledge creation and justification.

Each student's report of working with their peers tended to be stable across the 2-3 different courses discussed during the 2015 interviews, and only two students (Adam and Drew) reported practices that spanned two categories. This contradicts the caveat, expressed by some students, that contextual factors such as the ratio of teaching staff to students influenced their behaviour. By the second year, all students except Bonnie had come to appreciate the potential value of discussion with their peers. The perceived value of discussion with their peers does not show a clear progression in relation to year of study in the limit of the small sample size consisting mainly of Bachelor students. I observed this non-trend across multiple epistemic practices. Beatrice's sophisticated approach is unusual for a second year student and, in her comments, was associated with her experiences of collaboration with large-scale interdisciplinary group projects and a class where in-class group work was the central activity.

4.2.3 Strategies Used by Students to Assess Their Own Understanding of Course Material

How students assess their own understanding of course material is one of a number of epistemic practices observed in this study that relates to how students justify knowledge. Students were asked how they would know, at the conclusion of an hour of their favourite class, if they had understood the material. In addition to the responses summarised in Table 4.3, two students said they would not have understood anything as they would have been focused on the mechanical aspects of note taking. The least sophisticated practice for checking understanding relies on the professor or outside expert, where students feel that they have understood if they have retained what they have been told. Using their ability to do the exercises assigned by the professor was the most frequently reported practice for checking their own understanding.

Assessing their ability to use the material in a novel or authentic context was described by four students, including three Masters students and Beatrice, with her significant experience with large interdisciplinary projects. These practices were observed more directly in the think-aloud tasks in 2017 and 2018.

Table 4.3 Students' Practices for Self-Assessment of Understanding

	Level 1 Absolute	**2 Local coherence**	**3 Coherence**
Assess own understanding by ability to…	retain information and to know the correct answer	apply knowledge to get the correct answer	apply knowledge in novel contexts or to explain reality
Representative Quotations	I have the impression to have been able to follow what happened. Diane	We always think we have understood because it seems clear but it is at the exercises when we really know if we have understood or not. Bonnie Before doing the exercises? Csongor	I try to imagine [a] part of the body, see how it is connected, how the signals are transported. If there is kind of disorder, how that [body] part is affected? Drew
Adam		3	
Augustin		1	
Bonnie		1	
Beatrice		2	2
Arthur		3	
Csongor		3	
Destiny	2	1	
Diane	2		
Drew		2	2
Durak			1
Ellie	1	1	1
SUM	5	17	6

4.2.4 *Existence and Number of Correct Answers*

The belief in a single correct answer to any question is a core aspect of naïve epistemic beliefs and the awareness of the role of judgement in determining better answers is a reflection of higher epistemic sophistication. Students' practices around correct answers in engineering are presented in Table 4.4.

Table 4.4 Students' Practices Around the Existence and Number of Correct Answers

	Level 1 Absolute	**Level 2 Local coherence**	**Level 3 Coherence**	**Level 4 Sceptical reverence**
	Exercises like this, school exercises always have one solution. Boris For scientific problems, there will always be one single answer. But if the data is wrong, then the answer will be wrong. Clément In school, school problems do [have answers] because profs don't amuse themselves by giving us problems without solutions. But there are lots of problems that haven't been solved yet. Damien	If we don't see the problem with the same view, there can be very big variations. It depends on the point of view of the engineer. [But is it possible that they are both good?] Absolutely. Didier If we say, if we want to say that […] it isn't possible to remove a single molecular layer, that we remove a lot more, then we will reason differently. I think that as long as we can justify what we were thinking, then it works. Elise	Although some [answers] may be better than others, but I think that a lot are good. Overall, what matters is if it meets the constraints. Baptiste I see it as threshold that we need to reach. For example, we have several indicators or ways of identifying if our solution is correct or not. And above a certain threshold, several answers are acceptable. Guillaume	There isn't *necessarily a best answer* because there are so many dimensions and parameters that are in play, where a single pa rameter can be more important than 10 others. For example, cost, or energy consumption, pure performance. And so I see it more as a panel of responses to propose to other people who will then decide what is the most important. Guillaume **italics added*
Anna		1		
Antoine	1	1		
Baptiste			1	
Bart		1	2	
Bernard	2	2		
Carmen		1		
Clément	1			
Damien	1			
Daniel	3			
Delphi		2		
Didier		1	1	
Dimitri		2		
Elise		2	1	
Ernest		1		
Guillaume			1	1
SUM	8	14	6	1

Clément's dualistic comment about a single correct answer known to experts is very far from Guillaume's incorporation of the contextual and subjective nature of problem solving in engineering resulting in good (rather than correct) answers. While the overall arc of students' comments about the existence of correct or better answers in engineering are coherent with general models, the specificity of the engineering context emerges in Level 3 practices. At Level 3, students behave with the awareness that multiple correct answers exist and that the most appropriate one can be determined by external constraints or criteria. Guillaume's two comments in Table 4.4 imply that he is aware that evaluation by external criteria is key to a final decision and that, while he sees the need for judgement in making this decision, he does not deem himself competent or authorised to exercise such judgement.

Paper-based exercises are a common way to provide engineering students with an opportunity to practice and apply course material. Whenever the nature of the problems which students encountered as part of their studies was discussed, students unanimously stated that the exercises they were assigned consistently had a single correct answer. Boris's comment in Table 4.4 is a typical example. Project-based courses, which occur more frequently in upper years, were cited most frequently as the occasions when students encountered tasks with more than one answer. Several students felt that they were not often challenged to critically examine their learning or presented with "real-world" problems during their studies. The only non-project school work that students discussed having "better answers" were programming tasks.

4.2.5 Managing Precision, Uncertainty, and Estimation

The set of practices related to Precision and estimation, see Table 4.5, describes a trajectory from the unsophisticated requirement for precision in all things to the more sophisticated use of estimates to advance problem solving. While these practices are often linked to models and equations, they are distinct in that seeking precision or employing estimates can occur independently. For example, one think-aloud task described projected particles in terms of their average size and average density, and in the ill-structured tyre question, some students generated values for average daily distance travelled without recourse to a model.

Table 4.5 Students' Practices for Managing Precision and Estimation

	Level 1 Absolute		**Level 2 Local coherence**		**Level 3 Coherence**	
	Seeks precision as a key criterion in problem solving.		Attributes little value to imprecise calculations.		Employs estimates to advance problem solving when necessary.	
	Actually we need the exact values of the parameters, like the speed, like the characteristics of the road, of the tyre, materials of the tyre. Daniel		No, it applies in basically no context. Because it is not sufficiently complex. It can be used for a quick initial estimation, but not in industry or in other important areas like research. We cannot limit ourselves to such simple calculations. Didier		And we will suppose that it is in Angstroms, if we suppose that rubber is a complex material like it seems, it will be at least 10 Angstroms. Didier	
	Professed	**Enacted**	**Professed**	**Enacted**	**Professed**	**Enacted**
Baptiste					1	4
Bart		1			1	4
Bernard		2				
Benoît			1			1
Carmen			2		1	5
Cédric		1				1
Daniel	1					
Delphi					2	3
Didier			1		1	3
Dimitri		1				
Elise	1				1	2
Guillaume						1
Subtotal	2	5	4		7	24
SUM	7		4		31	

Daniel's comment in Table 4.5 exemplifies an unsophisticated approach for the tyre question, when he states that it is not possible to answer without precise values for several parameters. Didier recognises that imprecise values can be useful, however, he incorrectly supposes that estimates or order of magnitude calculations would be not valuable, or even sufficient, in professional engineering practice. The unsophisticated practices articulated by Daniel are typically adequate for the simplified situations commonly proposed in paper-based exercises. The connections between these practices and seeking single correct answers, using models as exact representations, and a failure to connect to physical reality are evident. It is unsurprising that some students ascribed little value to imprecise calculations, as they reported rarely encountering problems where such approaches were necessary during their studies. This illustrates the discrepancy between engineering studies and the on-the-ground practice of working engineers, who are often confronted with situations where data is not available or where precise data would be more expensive to collect than the benefit that it would provide.

Didier ascribes more value to, and therefore makes more use of, estimates. Despite the lack of precision, he mobilises a wide range of knowledge to make plausible estimates and advance towards producing an answer with a plausible order of magnitude. These practices are more representative of professional engineering, showing a stronger connection with physical reality and a recognition that precision is often not essential. No instances of epistemic practices above Level 3 were observed.

4.2.6 Answer-Checking Practices

Answer-checking strategies are related to students' sense-making and knowledge justification practices. The think-aloud tasks provided the opportunity to observe such practices directly; unsurprisingly, answer-checking practices were a major source of epistemically-relevant practices. Answer-checking practices exhibited by students during the think-aloud problem solving portion of the interview are termed "enacted" practices, while those that students described during the interviews are termed "professed" following Van Someren *et al.*'s recommendation (1994). I associated the ten different answer-checking strategies I observed with the four levels of epistemic sophistication used to structure this chapter. The different strategies are presented in Table 4.6, illustrated with representative quotations. *None* refers to instances where students reported that there was no possible means to check their answer. Frequency data for professed answer-checking practices is presented in Table 4.7 and for enacted practices in Table 4.8.

Answer-checking strategies associated with relying on experts and abstract mathematical approaches are categorised at Level 1. Strategies that involve assessing the local coherence of the concepts are Level 2. Answer-checking strategies at the highest end of sophistication observed (Level 3) involve making connections to real world experiences, either in the participants' personal lives or via scientific experiments.

By comparing Table 4.7 and Table 4.8, we see that students were more prolific in their descriptions of answer-checking practices, in response to specific interview prompts, than in their narration of their enacted practices. I observed 131 instances of professed answer-checking practices and 50 instances of enacted answer-checking practices. The frequency of enacted answer-checking strategies, which occurred without any prompting, is likely more representative of students' actual problem-solving practice. The constraints of the session eliminated many professed practices from being enacted during the think-aloud (i.e. peers, solutions), however, all five of the professed practices available to students were also enacted by students during the think-aloud problem solving. Further, the relative frequency of the three accessible Level 2 practices are consistent across the professed (Table 4.7) and enacted (Table 4.8) observations, although Level 1 practices were enacted less frequently than they were professed. This suggests that students are reliably able to self-report what answer-checking strategies they use, if not the absolute frequency.

For professed answer-checking Level 1 strategies, relying on external experts and uncontextualised mathematics were most commonly cited by students (68 times). Level 2 practices were professed by 15 students and represent about one third of the instances of answer-checking observed. Level 3 practices were least frequent yet were still professed by 12 students. On average, students professed seven instances of answer-checking practices. All four students who declared that it was impossible to verify an answer also professed answer-checking practices during their interview. Notable outliers are Guillaume who did not profess any checking practices, Bart who mentioned eight different practices, and Baptiste and Cédric who each professed a total of 13 instances across several practices. While there is no clear correlation between epistemic sophistication and year of study, participants certainly exhibited very different levels of sophistication.

Table 4.6 Answer-Checking Practices with Representative Quotations

None
Mmmm... nah, there isn't really a way to check. Delphi

Level 1 = Using an external expert or pure maths to find a single, precise correct answer.

Solutions	**Assistants**	**Reference**	**Peers**	**Logical**
During tutorials, we have the solutions. Or we ask a friend sitting beside. Or ask the assistants. Yes, we usually work a few together on the exercises. Cédric	We ask the friend sitting beside [us]. Or the assistant. Cédric	Or maybe there was an example in class that was kind of the same thing… Carmen I could open the computer and search for these processes, these systems. Daniel	We ask the friend sitting beside [us]. Or the assistant. Cédric	To check the limits, the extreme cases in the equation, for example if the mass goes to zero or infinity. Baptiste

Level 2 = Using concepts, units, and order of magnitude to test internal coherence and degree of precision

Units	**Concept**	**Order of magnitude**
And then the units too. Here it is clear that I wanted Kelvin. Then, yeah, I have to look. Grams. Dimitri	I didn't use the mass anywhere. Um. Which is normal because I have just been dealing with acceleration…. And the acceleration doesn't depend on mass. Bart When air condenses to a solid on the windshield... logically, when it freezes it would lose energy, right? Yeah, because it changes state. The vibrational state is lower. Anna	To already see if the answer is a little coherent, if I have found nanograms, I would have been surprised. With 482 grams, it is a little less than a kilo… Baptiste

Level 3 = Exploiting physical reality and models to find all the solutions that meet or exceed the requirements.

Experiment	**Observation from life**
To heat it up, to do the actual polymerisation procedure. Delphi	I tried to think about the last time that my parents changed a tyre. Carmen I was thinking more like on the street, like I'm walking in the winter. It's the winter, therefore it is cold. I just don't picture myself taking energy from another object. It's just me losing the energy. Ernest

The enacted practices were subject to more constraints than professed answer checking. Students used Level 2 practices most frequently to check their answers (37 times). Uncontextualised maths (Level 1) and real-life application (Level 3) were used equally often. Interestingly, while Guillaume did not profess any checking strategies, he did enact answer-checking four times (three different

Table 4.7 Frequency and Nature of Professed Answer-Checking Practices[14]

	None	Level 1 = External expert or pure maths					Level 2 = Conceptual			Level 3 = Connecting to physical reality	
		Solutions	**Assistants**	**Reference**	**Peers**	**Logical**	**Units**	**Concept**	**Order of magnitude**	**Experiment**	**Observation from life**
Amandine		1			1	2				2	
Anna									1	2	
Antoine		1			1	3	1		2	1	
Baptiste			1	1	2	1	2	2	4		
Bart		1	1		1		1	1	1	2	1
Benoît		2			1	1	2	2	1	1	
Bernard		1	2	1	3	1	1		1		
Boris		3			1						
Carmen		1	1	1					2	3	2
Cédric	1	1	1		2	5		3		1	
Clément	1	1			1	4		1		2	
Damien						1	1			1	
Daniel	1		1	1			1				
Delphi	1					1			1	2	
Didier						1					
Dimitri		1				1	5		1	1	
Elise			3	1	2	2	1	1			
Ernest		1			1		1			2	
Guillaume											
Subtotal		14	10	5	16	23	16	10	14	20	3
SUM 131	4	68					40			23	

[14] All students listed in the table participated in a think-aloud protocol. Values in the top 10% are highlighted.

Table 4.8 Frequency and Nature of Enacted Answer-Checking Practices

		Level 1 = External expert or pure maths					**Level 2 = Conceptual**			**Level 3 = Connecting to physical reality**	
	None	**Solutions**	**Assistants**	**Reference**	**Peers**	**Logical**	**Units**	**Concept**	**Order of magnitude**	**Experiment**	**Observation from life**
Amandine									1		1
Anna							1	1	1		
Antoine						1		1	1		
Baptiste							1		1		1
Bart							3	1	4		1
Benoît						2	2	2			
Bernard											
Boris							1	1			1
Carmen	1										
Cédric						1					1
Clément							3		1		1
Damien											
Daniel							1				
Delphi									1		1
Didier	2						1		1		
Dimitri						1					
Elise	1					1	2		1		
Ernest											
Guillaume							1	1	2		
Subtotal	4	0	0	0	0	6	16	7	14	0	7
SUM	50	6					37			7	

Level 2 strategies). Bernard, Cédric, Dimitri, and Ernest are counter examples, who enacted 0-1 answer-checking practices despite citing several. Bart is once again an outlier, this time enacting nine instances of four different answer-checking practices. These two opposite trends are an excellent illustration of the need for a fine-grained approach to epistemic cognition and also the massive influence of the specific, micro context of the task or knowledge.

It is important to note that fewer students enacted Level 3 answer checking (7) than professed such practices (12). This is despite the intentional construction of the think-aloud tasks to include contextual details that would enable Level 3 practices, such as an acceptable temperature change for an *in situ* dental polymerisation. No instances of Level 4 practices were observed.

4.2.7 Source and Validity of Equations

While the think-aloud tasks were intentionally constructed to not contain any formulae or equations, some problem statements were designed to prompt students to recall and use fundamental equations from Newtonian mechanics and thermodynamics. During the interview, probing students' ideas about the origins of these equations resulted in multiple interesting observations. As illustrated below by the excerpt from Dimitri's interview, it often took quite a bit of questioning to get students to understand what I was asking. A common response from students was to explain the function of the equation. This was true even when I was enquiring about the origin of an equation for the second time in the interview (i.e. with a time lapse of 2-5 minutes). For example, the dialogue with Dimitri quoted below occurred only four minutes after our exchanges about the origin of the thermodynamics equation he had employed in solving the polymerisation task.

> SI: Where does this equation come from?
>
> Dimitri: It is Newton, I think? Mass times acceleration gives the force. It is really the thing… but it wasn't that useful in the end.
>
> SI: Have you seen this equation recently?
>
> Dimitri: I saw it in first year.
>
> SI: And where did it come from?
>
> Dimitri: This, this formula? It is the overall force, the sum of all the forces, which make… it is equal to the mass time the acceleration. For any… How can I say it? The more the object is…
>
> SI: How was the equation created?
>
> Dimitri: In this context here?

SI: No, you said Newton. But what is its origin?

Dimitri: Because I know that it is a sort of physics problem, even if it is a little bit of chemistry. And I know, I know the equation of movement, I know it.

SI: An equation, like the equation of movement, why does it exist?

Dimitri: Because it is useful. It can predict the movement when we know the speed, the acceleration. And the point of origin. It is quite useful to predict movement. It is a function of time, t, of where an object will be at time t.

SI: I see it is useful, but how does it come to exist?

Dimitri: Again, it is history, people, humans who want to understand why. In physics it is more how but it is a bit of this thirst for knowledge.

While not all instances of questioning students regarding the origin of the equations they used resulted in clear responses, four recurrent themes were identified. The first of the two Level 1 origins I identified were that the equation came from school, either via a book or teacher, without reference to any prior source. The second Level 2 practice ascribed the genesis of the equation to sages or experts, without reference to physical reality. At Level 2, some students used the units or mathematical relationships within an equation itself to explain how the equation came to be. At Level 3, students explained how a process of experimentation and observation led to the identification of relationships which could then be formalised by an equation. The three levels are presented in Table 4.9 with representative quotations.

Table 4.10 presents the frequency of the different responses regarding the source of equations given by students, where each origin mentioned by a student was coded. As is coherent with a fine-grained approach, all instances were coded individually. Taking the exchange with Dimitri above as an example, these were coded for both *Sage* for citing Sir Isaac Newton and *Maths derivation* for citing the relationships described in the equation between the mass, acceleration, and the sum of the forces as somehow giving rise to the equation itself. Students ascribed a Level 1 origin most often (24 times by 14 different students) and this was the sole response of four students. This is the least epistemically sophisticated response, but it is certainly efficient. Level 2 sources of *Maths* or *Units* were cited 11 times and Level 3 sources related to a scientific process of observation, hypothesising and simplification into an equation occurred 10 times from seven students. This last explanation makes reference both to the scientific process and also to explicit connections with the physical world, enabling contextualisation

Table 4.9 Source and Validity of Equations Practices with Representative Quotations

Level 1 = Equations come from external experts.		**Level 2 = Equations arise from concepts and mathematics, and are credible when the units are logical.**		**Level 3 = Equations are generated by cognitive activity based on controlled observations and theorising.**
Book, teacher	Sage	Units	Maths derivation	
I remember quite well the professor explaining it. And I just believed her... it was very narrative like telling a story. I knew she was not lying, and you can read about it in the literature. I never tried to challenge that. Ernest Chemistry book. As I remember, the 10th grade. Yes. I remember because it was the worst year of my education. [You met equation in a chemistry book, but where does the equation come from?] From energy, I don't know. Somehow I think, some substances can save energy. Daniel	I don't know. Probably a scientist who thought about it a long time ago. So long ago, maybe even a Greek. Clément Oh la la, it comes from Newton. [He was born with it?] No [laughs]. Frommm... from the laws of Newton. Elise	From a course in thermo[dynamics] that I had last semester. I was able to remember the formula, and then I checked by reviewing the units. Boris Because I always know it, and it is logical with the units. We can easily figure it out again. Even though I know it by heart, we can figure it out quickly. Damien	[I]t comes from the fact that the distance, taking the derivative of the distance gives us the speed. And taking the derivative of the speed, we can get the acceleration. Carmen This, this formula? It is the overall force, the sum of all the forces, which make… it is equal to the mass times the acceleration. For any… How can I say it? Dimitri	They are Newton's laws, so F = ma. [Sounds like Newton came up with them, but where did they come from?] So, well, from lots of different, um. Well he invented, partly invented derivatives and stuff. And I think that he looked at lots of things, like how planets revolve around each other. And how objects move. To see what worked, what proportions happened when. And well I guess a bit, I'm guessing, but a big part of creating something like this would be working out which properties were important. And what needs to be defined, like the momentum. Bart

Table 4.10 Frequency of Practices for Source and Validity of Equations

	Level 1 = They come from external experts.		Level 2 = They arise from concepts and mathematics, and are credible when the units are logical.		Level 3 = They are generated by cognitive activity based on controlled observations and theorising.		
	Book, teacher	**Sage**	**Maths derivation**	**Units**		**Total**	Different types of practices
Amandine				1		1	1
Anna	1					1	1
Antoine	3				1	4	2
Baptiste	3				2	5	2
Bart	1	1			1	3	3
Benoît	2				3	5	2
Boris				3		3	1
Carmen	1					1	1
Cédric	1					1	1
Clément		3		2		5	2
Damien				2		2	1
Daniel	1		1			2	2
Delphi	1				1	2	2
Dimitri	1	1	2		1	5	4
Elise		2			1	3	2
Ernest	1					1	1
Guillaume	1		1			1	1
SUM	17	7	3	8	10	45	29
	24		11		7		

and answer-checking strategies. I did not observe any Level 4 practices.

It is not my intention to imply that some students believe that knowledge simply is and has always been in books. Rather my analysis highlights that, in their typical interactions and manipulations of equations during their problem solving, students do not seek to make connections between an equation and the physical world. Further, ascribing the origin *Sage* implies a remoteness to knowledge generation, not the successful application of a reasoning and thinking process similar to that in which they are currently engaged. The think-aloud tasks were intentionally structured in order to allow students to leverage real life observations. The applied nature of engineering means that navigating between abstract equations and physical reality is an essential aspect of effective problem solving. Thus, the practices described in this section are among the most relevant for how students see engineering problem solving and the knowledge on which such activities are based.

During the interviews, more than half of students (9/17) ascribed two or more different sources to the equations they employed during the think-aloud problem solving. Students who were more familiar with the task were more likely to cite their teacher or a book. Students who were not able to confidently extract an equation from memory were more likely to employ mathematical derivation or units to justify the formulation of the equation. These are all adequate strategies in that they advanced the students' problem solving, however, the interaction between the practices employed by a student and their content knowledge and prior experiences introduces issues with using their behaviour to assess their epistemic sophistication. I return to these observations later, when I consider how to measure epistemic sophistication.

4.2.8 Using Models as Tools and Representations

Equations represent models in abbreviated formats, enabling engineers to make predictions and calculations based on the underlying model. These succinct representations can allow engineers and students to perform rapid calculations that generate apparently precise values. However, their abbreviated format can obscure fundamental assumptions and limitations of the associated model. During the think-aloud sessions, several students produced equations that represent relationships between physical phenomena. For example, most students used the simplified equation for heat capacity, either recalling the equation from memory or reconstructing it from dimensional analysis.

Students' views about models in science and engineering were captured in two ways. First, students were asked about the existence of limitations for the equations that they used during their problem solving. My interview questions intentionally did not use the term model, as the goal was to enquire into students' knowledge practices involving equations as representations of reality and not to pose questions that sounded like they had correct answers. Secondly, spontaneous incidents of students making and checking assumptions during the think-aloud task were coded as "enacted" to distinguish them from incidents students recounted during their interviews (coded as "professed"). While the importance of checking assumptions is frequently emphasised by engineering instructors when presenting models and their associated equations, students rarely encounter situations where the assumptions fail during standard homework exercises. Therefore, it would have been interesting to verify that all students were able to identify an assumption that they should have checked during problem solving.

As illustrated by the representative quotations and frequency data in Table 4.11, the role of empirical observations in model development and checking was not readily apparent to many students. As with most epistemic practices, students' ideas were not consistent across the various equations they encountered during the interview and think-aloud tasks.

Given that the equations used by the students in the think-aloud tasks are simplified models of reality, they result in calculated values that would not exactly match physically measured values. A general awareness of this was expressed by several students, including some examples of specific assumptions contained in the equation at issue. Bernard and Daniel expressed no concerns about potential limits of an equation and appear to make no attempt to relate the equation to a more complex physical reality. It is concerning that Bernard's statement seems to equate higher precision (decimal places in the answer) with higher accuracy of the result. Conflating the precision of a calculated value with the accuracy of the result is an excellent illustration of why models should be taken as epistemic tools rather than faithful representations of reality. The crisp simplicity of black numbers on a white page seems to support students' absolutist, dualistic practices in engineering.

Table 4.11 Practices for Models and Equations

Level 1 **Describes models as exact representations of the world which allow precise calculations**	Level 2 **Identifies, without explaining, discrepancies between models' predicted values and observed values**	Level 3 **Finds models valuable when they are coherent with experiment and observation, despite acknowledged limitations**	Level 4 **Uses computer and mathematical models to catch bad modelling assumptions**
[Are there limitations to using equations?] I haven't seen any up to now, but maybe we should ask chemistry students. Daniel	It is good to know a bit from a theoretical approach but it can be different in practice. Yes, it can be different in practice. Here, it is totally theoretical. We are given a value, but in real life it can be more or less true. The energy generated can... people use numbers to create a model of reality. It is just numbers, especially in a real case with a real machine. Ummm, the difference is ... We try to get it close, but when we say 153 it isn't exactly 153. There can be more digits afterwards, more precise. Bernard	You need to do the experiments to prove the theory. Antoine They observed things in nature. After they deduced the equations. Elise Yes, because we simplify to have this. Otherwise we would have differential equations everywhere. Cédric	Which [equation] to use and what is valid. This is something to clarify in the material, to know the hypothesis underpinning [it]. This is maybe something that I try to be more careful about. Before I was just saying, it was always valid and just use it. Now I try to be more precise about this. Benoît Yeah, yeah, lots of assumptions. Well, that it was a big explosion. I mean, like, there is no relativity, I made the assumption that we are on Earth. Bart

	Professed	Enacted	Professed	Enacted	Professed	Enacted	Professed	Enacted
Antoine	2		1					
Baptiste					1	1		
Bart			1				3	
Bernard			1					
Benoît					1	1	1	
Carmen						1		
Cédric	1			1	1	1		
Daniel	2							
Delphi	1					1		
Didier						2		
Dimitri					1			
Elise			1					
Guillaume					1	2		
Subtotal	4	0	3	1	4	8	3	0
SUM	4		4		12		3	

4.2.9 Epistemic Practices When Confronting an Ill-Structured Problem

As many students reported having rarely been confronted by tasks without a single, precise correct answer, I intentionally created such an opportunity for the final set of interviews. This was accomplished with the think-aloud task "How far can a car drive before wearing off a single molecular layer of rubber from its tyres?" The goal of presenting students with this ill-structured task was to require them to make estimates and take independent decisions.

My analysis examined both students' ability to make progress on the task and their reactions to the task. It is ironic that the most basic answer, where students assumed that a molecular layer of rubber is worn off with each rotation of the tyre, leads to approximately the same answer determined by expert estimators Weinstein and Adam (2008). This means that calculating a reasonable value is not sufficient to designate a good solution. Daniel and Bernard made little progress (see Table 4.12), although they each listed values that (they thought) they would need to calculate an answer. Their approaches focused on calculating a precise answer, i.e. for a specific car and road conditions, and identified parameters that other students more effectively rolled into broader estimates. Others (e.g. Dimitri, Elise) produced basic answers that only required the calculation of the circumference of the tyre from an estimation of the radius of the wheel ($2\pi r$). Four students made good progress leveraging observations from their lives and concepts from class to develop plausible answers.

The task provoked a variety of reactions from students, as reported in Table 4.13. Some expressed appreciation for a task which did not feel entirely synthetic and "useless" (Didier and Baptiste), while others reported that the uncertainty made them feel uncomfortable (Delphi, Cédric, Carmen). Elise reported finding the question easier than the others because there was no precise answer and therefore no wrong answer.

As shown in the heat map in Table 4.14, a trend is suggested when crossing students' progress on the question with their reaction. Most (¾) students with well-developed answers expressed discomfort with the open-endedness and uncertainty of the task. In contrast, students who thought the

Table 4.12 Students' Problem Solving Progress on an Ill-Structured Problem

Progress	Representative examples
None - Students report that there may be an error with the question, as it is not possible to provide any answer with the given information	[Totally blank sheet]. Bernard [List of necessary parameters: weight of car, road condition, rubber, weather]. Daniel
Basic attempt - Make basic attempt to solve it but without making any estimations (apart from the radius of the tyre) or assumptions (apart from one layer worn off each rotation).	$D = \pi r$ Dimitri $r = \tilde{}30$ cm $D = 2\pi r = 6$ m Elise $d = 1.5$ m $\pi d = 4.7$ m Guillaume
Well-developed attempt - Students construct well-reasoned answer, making assumptions and estimations as part of problem solving. Use of contextualisation	And my dad told me that the front tyres are used more, which is logical because they are the wheels that push and pull the car, and also turn. So it is logical. So I need to find out a way to estimate the amount of usage that the tyres get. […] So I'll draw my tyre against the road. Let's say it is 20 cm across. Bart You have to make assumptions. So a wheel is a circle with lots of molecular layers of rubber. So we have an interaction between the atoms. […] What do we have as data? The diameter of the wheel, D. What are we going to say? 60 cm. 70 cm. About that. Then ahhm. ... Coefficient of friction of a tyre. What is it? 08 ... So. ... when a molecular layer is worn off the tyres. It actually means that the molecular layer has come off. What makes it come off? We have the wheel on the ground. What are the forces? We have the weight. F weight. The pulling force of the car. F car. The force of friction. F friction. Baptiste

Table 4.13 Students' Reaction to an Ill-Structured Problem

Approach	**No apparent discomfort at inability to solve.**	**Task is fun because there are few constraints and therefore little risk of being wrong.**	**Task causes hesitation or delay in making decisions.**
Quotations	Yes, there is clearly information missing. We don't know how the wheel reacts, not precisely, with distance travelled. It is an estimation, and even then I have difficulty seeing at what speed a molecular layer will be consumed… You can't answer it at all. Well, actually I think that you can't answer it. Bernard	This one was more entertaining for me. It was up to us to find all the hypotheses, so we were freer. I think it was fun. Baptiste This is funny. [Silence]. And this is all we have. Elise	It threw me off a bit at first, because it isn't the kind we get in tutorials. Well, less often. There (in tutorial) is a correct answer that you get using all the different numbers you put in, and this one is really vague. And also I didn't have an exact idea of how big a single molecular layer is or how much, how much rubber is torn off when you drag it. So it threw me off quite a bit. Bart Ah, I didn't really know. I questioned if I had to… I tried to think about a couple different ways to solve it and I realised that in every case I had to make assumptions. Basically there wasn't any way to even start. Cédric

Table 4.14 Heat Map Presentation of Students' Problem Solving Progress and Reaction to an Ill-Structured Problem

<table>
<tr><th></th><th>No apparent discomfort</th><th>Fun, free</th><th>Hesitation</th></tr>
<tr><td>Impossible</td><td>Bernard Daniel</td><td></td><td rowspan="2">Cédric</td></tr>
<tr><td>Basic attempt</td><td></td><td>Didier Dimitri Elise Guillaume</td></tr>
<tr><td>Well-developed attempt</td><td></td><td>Baptiste</td><td>Bart Carmen Delphi</td></tr>
</table>

task was fun and free made little progress. It appears that a certain level of discomfort was incurred when students made the estimates and judgments required to advance in problem-solving. Students who anticipated a risk-free, fun experience avoided the discomfort and made poor progress.

As was evident from students' comments, making any progress in this task required the students to take decisions about the parameters and values to use. This task offers an interesting window on students' epistemic practices since it required them to assume the position of a person competent to exercise judgment. Both my logical expectations and previous studies (i.e. Belenky *et al*. 1997, Palmer and Marra 2004, Wise *et al*. 2004) predicted that higher year students would be more able to advance on this task than lower year students. However, in the limits of the very small sample size, I observed no correlation with year of study. A potential confounding effect could arise from lower year students feeling obligated to invest more effort in the uncomfortable problem-solving task. In contrast, older students may have calibrated their cognitive investment to the small financial compensation and therefore were less likely to persist through the discomfort.

4.2.10 Using Authentic or Schematic Mind's Eye Images

If drawing on lived experiences and making connections to reality are epistemically sophisticated practices, then students who do this should be more able to solve ill-structured problems. Didier's comment below, about using a mental image, is an excellent example of leveraging one's lived experience in problem solving and led me to investigate if students' mind's eye images reflected their use of real world experiences or personal observations in their problem solving:

> I put myself in the place of an astronaut to see what happens in his space ship and to see what equipment is available in this type of situation. But since I really don't know anything about it, instead I simply put myself in the context of this room, me in the room. I am generating a lot of heat, so it has to be eliminated. How is this being eliminated in this room? And so it was more or less like this that I thought of how it would be done in the space ship.[15] Didier

[15] The first two interviews conducted in 2017 (Didier and Daniel) used a think-aloud task involving heat transfer in a space station, but that was replaced by the polymerisation task in subsequent interviews. This latter task was found to be more effective in eliciting desired problem solving practices.

Each student in the 2017 interview series reported using a range of mind's eye images across the three think-aloud problems, from static and highly schematic (like textbook illustrations) to increasingly authentic (steampunk-style video of a machine). Disappointingly there was no apparent relation between the authenticity of the images and their progress on the ill-structured tyre task. Despite the small sample, these observations suggest that realistic mind's eye images are not a useful indicator of epistemically sophisticated problem solving practices.

4.2.11 Section Conclusion

This section addressed my first research question using think-aloud problem-solving protocols to observe and characterise students' epistemic practices. It reports my identification of novel epistemic practices of engineering problem solving (good/better answers, answer checking, *Source and validity of equations*, and *Using models*) and characterises them at four levels of epistemic sophistication. Together, these practices provide a rich, contextualised description of epistemic practices in engineering.

Each student's epistemic practices ranged across different levels. This observation supports my argument against characterising students, rather than their practices, in terms of level of sophistication. A more in-depth investigation of the frequency and distribution of epistemic practices is undertaken in section 4.4 to answer my second research question.

4.3 EPISTEMIC BELIEFS

In addition to the rich observations arising from the think-aloud problem-solving sessions, I also collected data with a cognitive structures or epistemic beliefs approach. This distinction between the highly contextualised epistemic practices reported in the previous section and the broader, general beliefs reported in this section reflects the arguments I made in Chapter 2. The observations reported in this section were collected by students' Likert agreement scale responses to questionnaire items about their epistemic beliefs or beliefs about learning. A more thorough explanation of the arguments for differentiating or combining these beliefs is presented in Chapter 2.

Table 4.15 Students' Responses and Correlation with Study Year

Item	Strongly disagree ---> Strongly agree	Correlation with year	N	Author
Principles in engineering cannot be argued or changed.			281	YuStrobel-Certainty
All engineering experts understand engineering problems in the same way.			154	YuStrobel-Certainty
Most engineering problems have only one right answer.			154	YuStrobel-Certainty
Engineering knowledge should be accepted as an unquestionable truth.			283	YuStrobel-Certainty
There is one universal engineering method.			151	YuStrobel-Certainty
If you read something in a book for engineering, you can be sure it is true.			282	YuStrobel
When I study, I look for the specific facts.			153	Kardash-Structure
It is difficult to learn from a textbook unless you start at the beginning and master one section at a time.			152	Kardash-Structure
Engineering knowledge is an accumulation of facts.			151	YuStrobel-Simplicity
What is true today will be true tomorrow.			283	Schraw-Certainty
Even advice from experts should be questioned.			283	Kardash-Constructed
Forming your own ideas is more important than learning what the textbooks say			152	Kardash-Constructed
I like thinking about issues that experts can't agree on.			154	Kardash-Constructed‡
The most important part of scientific work is original thinking			152	Kardash-Constructed
The only thing that is certain is uncertainty itself			151	Kardash-Constructed
Correct solutions in the field of engineering are more a matter of opinion than fact.			281	YuStrobel-Source
A theory in engineering is accepted as correct if engineering experts reach consensus.			151	YuStrobel-Source
First-hand experience is the best way to know something.		-.215**	282	Hofer2000-Justification
I am more likely to accept the ideas of someone with first-hand experience than the ideas of researchers.		.171*	280	Hofer2000-Justification

Correlation is significant to the * = .01 and ** = .001 level (2 tailed)
‡-I made a small modification in formulation

4.3.1 Epistemic Beliefs about "Favourite Classes"

Attempts to construct a robust quantitative instrument did not meet acceptable parameters for factor construction, as presented in detail in Chapter 3. Students' responses to some of the individual survey items are nevertheless interesting. Table 4.15 presents students' responses to 19 items selected from previously published science or engineering focused studies of epistemic beliefs. These items were presented to students with the additional contextualisation of "in the context of your favourite class" to induce students to situate their responses in a particular context likely to be coherent with their beliefs. The number of responses per item ranges from 151 to 283, depending on the version(s) of the questionnaire where the item appeared. This data provides quantitative support (N = 151 -> 283) for the lack of epistemic development observed in my qualitative epistemic practices data.

4.3.2 Taking Beliefs about Teaching and Learning as Epistemic Beliefs

This section investigates students' approaches to engineering studies through the lens of the activities that students state are valuable to help them learn. While there are disparate opinions on the inclusion of beliefs about teaching and learning in the construct of epistemic beliefs, the responses presented here are useful to support my argument about the inadequacy of current cognitive structures approaches to epistemic sophistication. I created two survey items addressing students' beliefs about the value of ill-structured and well-structured problems of learning. Students' responses to the items are reported in Table 4.16[16]. The persistence of the belief in Masters students that they "learn the most from exercises with a single clear answer" (N = 277) supports my qualitative data that students do not have effective epistemic practices to manage multiple correct answers. The interaction between students' quite positive responses to "I enjoy the challenge of open ended problems" (N = 277) and my qualitative observations that discomfort (rather than enjoyment – see Table 4.13) is an excellent illustration of the inadequacy of a broad epistemic beliefs approach to capture how students actually interact with engineering knowledge. The implications for models of epistemic cognition, related to my final research question, will be developed in the following chapter.

Students' beliefs about teaching and learning in engineering were also addressed by the final section of the questionnaire. Students' responses about the characteristics of really excellent professors and students are presented in Figures 4.1 and 4.2 respectively. The response options are organised with the least

[16] For graphical simplicity, students' responses are presented as a 3 level scale. Statistical tests were run with the full 5 level scale and found no correlation with year of study.

epistemically sophisticated response (providing complete information, being attentive and taking complete notes) at the bottom of the figures and the most sophisticated (challenges students to explore open-ended problems, developing their own ideas) at the top. The combined frequencies for the two most epistemically complex responses for a really excellent professor were <15% (48 responses, N = 322) and were constant across year of study. While the epistemically unsophisticated belief that professors should provide clear and complete information was more common in first year students compared to other students, no clear trend towards a more sophisticated conception of good teachers with increasing year of study was observed.

Table 4.16 Heat Map of Students' Beliefs about Open-Ended Problems by Year of Study[17]

I learn most from exercises with a single clear answer.

Year	Bachlors1	Bachlors2	Bachlors3	Masters1	Masters2	Total
Never-Rarely	0.14	0.00	0.27	0.19	0.00	38
Sometimes	0.30	0.21	0.17	0.39	0.45	85
Often-Always	0.55	0.79	0.57	0.41	0.55	117
SUM	**147**	**24**	**30**	**54**	**22**	**277**

I enjoy the challenge of open-ended problems with several possible solutions.

Year	Bachlors1	Bachlors2	Bachlors3	Masters1	Masters2	Total
Never-Rarely	0.26	0.58	0.17	0.17	0.23	71
Sometimes	0.35	0.21	0.37	0.28	0.32	89
Often-Always	0.39	0.21	0.47	0.56	0.45	81
SUM	**147**	**24**	**30**	**54**	**22**	**277**

Students' expectations of really excellent students were more epistemically sophisticated than for teachers. As shown in Figure 4.2, the decreasing frequency of the response in the following list: apply concepts in novel contexts, develop their own ideas, solve all the exercises and take complete notes. These data also showed a weak correlation with year of study ($p<.01$, Cramer's v = .162). The effect size of the correlation between students' responses to really excellent professor and

[17] Light shading indicates values between 0.25 and 0.49 and darker shading indicates values above 0.5.

really excellent student was also weak (p<.000, Cramer's v = .202). The lack of correlation between sophisticated beliefs and year of study is coherent with my qualitative observations. However, the lack of correlations between really excellent teaching and learning suggests that the data is of poor quality, with too many factors contributing to how students responded to these low-context, cognitive structure items.

Figure 4.1 What is the one characteristic that marks out a really excellent professor?

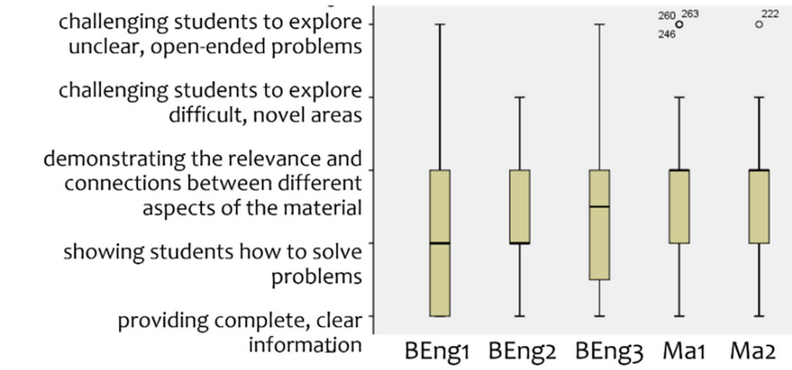
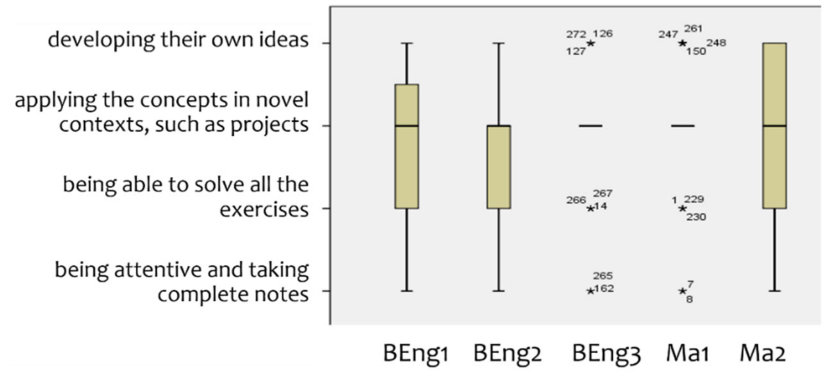


Figure 4.2 What is the one characteristic that marks out a really excellent student?



4.3.3 Section Conclusion

This section reported observations related to students' overarching epistemic beliefs and approaches to becoming an engineer. It should be noted that students' responses do not necessarily mean they view such approaches as the most effective for learning to be professional engineers, rather these are their perceptions of what is expected of engineering students and professors. It is important to note that this broad approach appears to have flattened many of the rich, salient details of epistemic practices observed in context during the think-aloud problem solving.

For me, an approach centred on overarching beliefs that obscures students' specific epistemic practices is not an appropriate base for a robust and meaningful measurement of epistemic sophistication. The implications of these findings will be analysed further in Chapter 5, in order to answer my final research question.

4.4 Using Epistemic Practices to Evaluate Epistemic Sophistication

Effective use of sophisticated epistemic practices is clearly a sign of epistemic sophistication, however, using naïve practices does not necessarily correspond to a lack of epistemic sophistication. This section returns with a more quantitative approach to the observations of students' epistemic practices to address my final research question about how to characterise engineering students' epistemic sophistication in a *cognitive processes approach*. Despite their value, rich contextualised descriptions typically require considerable research effort to collect and are difficult to transpose or compare across situations. It is one advantage of the micro scale of my epistemic practices that they reduce some issues around transfer to new situations. In this section, I introduce my argument that the *diversity* of a student's epistemic practices is an appropriate way to characterise their epistemic sophistication.

4.4.1 Assessing the Frequency and Range of Students' Epistemic Practices

This section takes a quantitative approach to the observations reported in the previous sections. On average, 191 episodes from the transcript of each student who participated in the qualitative studies were coded (minimum 31, maximum 313 episodes). This represents an average of 44 codes per student (minimum 25, maximum 54 codes per student). It is important to note that the observed practices are diverse in nature, ranging from students enacting memorised manipulations despite not being sure what the current task is asking (Level 1) to reporting that the solutions provided by their instructor are the only way to check their homework (Level 1). Further, the think-aloud tasks provided only a short period to observe students' problem-solving and may have elicited some practices more often than others. It is thus simplistic to report which practices occurred most frequently, as though each practice is of equal importance, but it nevertheless provides a crude measure of how students approached their problem solving.

As shown in Figure 4.3[18], every student except Csongor† exhibited practices spanning at least two levels. The think-aloud tasks prompted students to exhibit a wider range of practices than the interview alone: four of the five students who neither enacted nor professed Level 1 practices were interview-only students. Ellie† was unique to exhibit practices spanning three levels despite not participating in think-aloud problem-solving. All students exhibited at least one instance of a Level 2 epistemic practice and typically several different Level 2 practices. Delphi's practices were heavily weighted towards Level 3 but only three students demonstrated Level 4 practices (Bart, Benoît, and Guillaume). While the small sample size and broad range of disciplinary backgrounds preclude any analysis by discipline, the topics of the think-aloud tasks make it relevant to note that no chemistry nor physics majors participated in the think-aloud protocols.

Figure 4.4 reports each instance of students' epistemic practices, giving the overall frequency of their practices across my session with them. An interesting observation facilitated by the alphabetical nomenclature of participants' pseudonyms in these two figures is that there does not appear to be a correlation between year of study and the sophistication of their epistemic practices. While the small sample size sharply reduces my ability to generalise this observation, it is nevertheless consistent with my quantitative data.

The increased number of practices elicited from think-aloud protocol participants is even more evident in Figure 4.4 than in the previous figure. Except for Carmen and Delphi, all students exhibited practices below their highest level more often than peak-level practices. Level 2 practices were used most frequently, although the distribution of an individual student's practices across the levels is often quite homogeneous. This means that a decision to assign a student (rather than their practices) to a specific level of sophistication would necessitate a considerable amount of judgement from the researcher. Such a decision would require the researcher to designate some practices as more representative of epistemic sophistication than others, or determine what ratio of Level 1:2 practices is necessary to classify a student as belonging to the higher level. While I

[18] Students who did not participate in a think-aloud protocol are marked with a dagger.

Figure 4.3 Range of Students' Epistemic Practices, professed and enacted

Figure 4.4 Frequency of Students' Epistemic Practices, professed and enacted

appreciate the value of having a measure of epistemic sophistication, collapsing the richness of range of observed practices into a single level increases the separation with students' actual behaviours and therefore reduces potential opportunities for theory development and pedagogical feedback.

The richness of the frequency data is illustrated by how the nearly identical profiles of Carmen and Cédric in Figure 4.3 diverge significantly in Figure 4.4. My observations of students' epistemic practices occurred while they solved several different tasks, most of which were well-structured problems. Measuring the range of students' epistemic practices, Figure 4.3, is adequate to evaluate their overall awareness or ability. However, the frequency data is richer, capturing each time an epistemic practice was used and therefore potentially multiple contexts when a student judged the action to be relevant. This latter measure is therefore a better indicator of the overall diversity of a student's problem solving practices. I develop the importance of these different profiles in the following section.

4.4.2 Diversity of Epistemic Practices as a Measure of Sophistication

In my analysis of the think-aloud problem solving, the range and frequency of the epistemic practices caused me to reflect on how researchers have assessed an individual's current level of epistemic sophistication. The result is my proposal to use the diversity of students' epistemic practices. I present my argument conceptually, with the example of students' practices around equations, in this section and with a more quantitative approach in the following section.

More than half of students who participated in the think-aloud protocols (9/17) ascribed two or more different sources to the equations they employed when solving the tasks. Students who were more familiar with the task were more likely to cite their teacher or a book. Students who were not able to confidently extract an equation from memory were more likely to employ a mathematical derivation or units to justify the formulation of the equation. These are all appropriate or effective strategies in that they served to advance the student's problem solving. However, a disciplinary expert would identify some practices are more contextually appropriate. This is problematic since each student's approach to a task depends on their content knowledge and prior experiences with similar tasks in addition to their epistemic sophistication. Using a disciplinary expert's practices to calibrate the appropriateness of students' practices does not, therefore, seem like a good approach to evaluate a student's epistemic sophistication. It also exacerbates the context-specificity of each study, thereby making comparisons harder.

My analysis makes use of both the fine-grained model by counting each instance of an epistemic practice (professed or enacted) and my four level framework to group practices that employ a similar epistemic perspective in order to make the diversity of practices more visible. I propose that the breadth or diversity of students' practices is a more accurate measure of epistemic sophistication in the cognitive resource model. With my proposal, a student using multiple strategies to triangulate to a higher level of confidence and thereby demonstrating a more integrated view of knowledge would be characterised as epistemically sophisticated irrespective of the particular strategies used.

4.4.3 Using an Ill-Structured Problem to Identify Sophisticated Epistemic Practices Profiles

The "tyre task" is ill-structured and therefore quite different from both the other tasks posed during the 2017-2018 think-aloud problem solving. Typical features of ill-structured problems include requiring students to develop a novel (to them) approach and managing uncertainty. This task calls on several more epistemically sophisticated practices and is therefore more representative of the type of problem solving encountered by professional engineers. In Figures 4.5 and 4.6, the data is organised by students' progress on the ill-structured problem. This allows us to see the epistemic practices profiles of students who found the task impossible, made a basic attempt, or produced a well-developed attempt. My analysis explored possible correlations between students' epistemic sophistication, characterised by their epistemic practices, and their progress on this ill-structured problem.

From Figure 4.5, it appears that students must be able to use some Level 3 practices in order to make a reasonable start. Level 3 practices are characterised by making connections between calculations, theory, and real-world contexts, specifically experiment and observation from life. Yet using several different Level 3 practices, or even one Level 4 practice, is not a reliable indicator of a student's ability to produce a well-developed answer. Further, the range of practice present in this figure does not elucidate why Elise produced only a basic attempt yet Carmen generated a well-developed answer. They each used five different Level 3 practices, but Carmen used more Level 1 practices and fewer Level 2 practices.

The frequency, or diversity, data in Figure 4.6 creates profiles that are distinct for the three types of answer to the ill-structured task. Here, the profiles of students with well-developed answers have epistemic practices distributed across at least 3 levels and a relatively high portion of Level 3 practices. My observations of these 11 students solving one ill-structured task provides only a limited perspective but are consistent with using the diversity of epistemic practices as a measure of epistemic sophistication.

Figure 4.5 Students' Epistemic Practices Range Profiles by Progress on an Ill-Structured Task

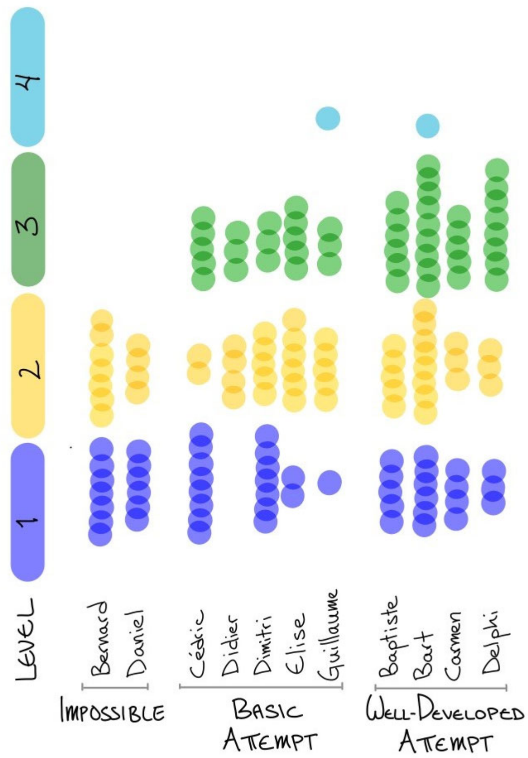
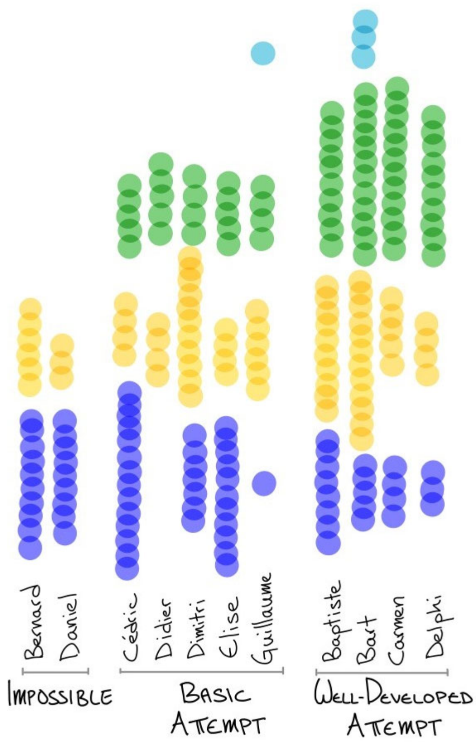


Figure 4.6 Students' Epistemic Practices Frequency Profiles by Progress on an Ill-Structured Task



4.4.4 *Section Conclusion*

The epistemological resources model posits that as students become more epistemically sophisticated, they increase their range of epistemic practices and also their ability to select an appropriate practice. However, my analysis raises questions about how appropriateness is determined. I found the approach a student takes for a specific task depends on that student's prior knowledge and experiences with similar tasks. My analysis led me to posit that diversity, rather than appropriateness, is a more robust measure of epistemic sophistication in the cognitive resource model. By using the diversity of epistemic practices, both the effect of a student's prior knowledge and the disciplinary perspective of the researcher are attenuated. Tracking the diversity of the strategies used also provides a richer description of the range of strategies that a student possesses. In Chapter 5, I return to these ideas to situate my proposal in terms of current models of epistemic cognition.

4.5 CHAPTER FOUR CONCLUSION

My analysis presented in this chapter provides clear evidence that a cognitive processes approach based on epistemic practices is a rich and robust way to characterise epistemic sophistication. Six sets of epistemically-relevant practices I identified during students' problem solving answers my first research question and are summarised in Table 4.17. These include the characterisation of two novel engineering-specific epistemic practices: managing uncertainty and using models. The first row of the table contains a brief description of the approach of the level, and the cells below describe how that epistemic practice is implemented at each level of sophistication. Each set is comprised of four practices that fulfil a similar function in engineering problem solving, yet are distinct in terms of the sophistication of their approach. Like many previous studies, both the quantitative and qualitative data of this thesis fail to definitively either support or contradict inclusion of learning beliefs in epistemic beliefs. I will thus follow Elby's suggestion to await better empirical or theoretical support to determine if learning beliefs should be included or excluded from models of epistemic practices (2009). Consequently, I omit practices for *Working with peers* from Table 4.17.

The practices at each of the four levels share common characteristics. Level 1 Absolute practices seek single, exact correct answers and are not concerned with anything beyond the core task. Level 2 Local cCherence practices rely on logic and mathematics. Mathematics is, obviously, central to quantitative problem-solving.

However, seeing problem-solving as exclusively mathematical is an unproductive belief for engineering which, in its practice, is a highly applied field. Level 3 Coherence practices also use logic, however, these practices extend to making connections between physical reality and models, and anticipate that multiple acceptable solutions that exceed the requirements can exist. Level 4 Sceptical Reverence is the most sophisticated level and includes practices that recognise that the complexity, ambiguity, and uncertainty of engineering practice requires engineers to exercise their own judgment based on the specific context. The tabular organisation allowed me to also answer my second research question about the distribution of practices used by students: each student uses a range of epistemic practices, mixing naïve Level 1 and more sophisticated practices.

I used my empirical data to introduce my novel argument that the diversity of epistemic practices, rather than their effectiveness, is a more appropriate way to assess epistemic sophistication in the epistemological resources model. This is relevant to my third research question about the epistemic practices profiles of sophisticated students. In the preceding section, I have used students' ability to generate a well-developed answer to an ill-structured task as an indicator of engineering-specific epistemic sophistication. These sophisticated students responded to the set of think-aloud tasks, which included one ill-structured problem, by using practices spanning at least 2 levels and used Level 3 practices more often than students with basic answers. These observations are consistent, without providing definitive support, of using the diversity of students' epistemic practices to characterise their engineering-specific sophistication. I return to these analyses in Chapter 5 to address the implications of my findings for models of epistemic cognition.

Table 4.17 Epistemic Practices for Engineering Problem Solving

Level	One Absolute	Two Local Coherence	Three Coherence	Four Sceptical Reverence
	[Engineering] thinking leads to a single, precise correct answer.	Engineering thinking is internally coherent, precise and mathematically sound. However, a well-argued approach can give a different good answer.	Engineering thinking makes connections between physical reality and models to find all the solutions that meet or exceed the requirements.	Engineering thinking tolerates uncertainty and requires making judgements based on the specific context and perspective.
Source and validity of equations	Identifies books, sages, or teachers as the source of scientific equations. Conflates confidence in such equations with trustworthiness of the source.	Describes scientific equations as arising from concepts and mathematics, and that the equations are credible when their units are logical.	Describes equations as the product of cognitive activity based on controlled observations and theorising. Judges equations that are able to predict experimental outcomes as credible.	Manages inherent imprecision in both experimental and predicted values.
Using models as tools and representations	Describes models as exact representations of the world that allow precise calculations.	Identifies, but cannot explain, discrepancies between model-predicted and observed values.	Finds models to be valuable when they are coherent with experiment and observation, despite acknowledged limitations and simplifications.	Uses mathematical and computer methods to catch bad modelling assumptions.
Precision and estimation	Seeks precision as a key criterion in problem solving.	Attributes little value to imprecise calculations.	Employs estimates to advance problem solving when necessary.	Leverages estimates to advance or verify problem solving.
Strategies for reasoning and verifying answers	Uses surface cues, adherence to method or an expert to verify answers. May report that it is not possible to verify an answer without an expert.	Employs units, order of magnitude, and concepts to verify answers.	Makes connections to physical reality and personal experience to verify answers.	Employs mathematics in post hoc, justificatory way to verify problem solving

Existence and number of correct answers	Seeks the single correct answer that is known to experts or will be in the future.	Accepts multiple answers as good, ascribing their existence to different perspectives.	Expects multiple good answers to exist which each meet the external criteria.	Exercises own judgement to determine the most appropriate answer for a given context, allowing for that new evidence may cause it to change.
Self-assessment of understanding	Assesses own understanding by ability to retain information and to know the correct answer.	Assesses own understanding by ability to apply knowledge to obtain the correct answer.	Assesses own understanding by ability to use knowledge in novel contexts or to explain reality.	Acknowledges the consequences of alternative judgements and the risks of poor conclusions.

5 Discussion

5.1 Introduction

The main focus of this chapter is how my epistemic practices approach advances the conceptualisation and measurement of epistemic sophistication. Thus I first argue how the epistemic practices I identified (RQ1) provide a novel and highly pertinent approach to epistemic sophistication in engineering. This discussion also demonstrates the coherence of the epistemic practices at each level of my 4-level framework and the value of considering the distribution of engineering students' epistemic practices (RQ2). Secondly, I argue how adopting the epistemic practices approach developed in this thesis advances our ability to characterise and measure epistemic sophistication in engineering (RQ3). Finally, I describe how my approach addresses several issues that plague prior models of epistemic beliefs in engineering. In each of these three sections, points of consensus and disagreement with prior work are used to situate the contributions of the current work.

5.2 Epistemic Practices are Pertinent for Characterising Epistemic Sophistication in Engineering

5.2.1 Cognitive Processes Approach to Epistemic Sophistication

Prior work characterising epistemic sophistication has employed a variety of different models. As summarised in the Literature Review, cognitive structure models focusing on beliefs are prevalent in the literature yet suffer from persistent weaknesses of empirical support as well as fundamental conceptual issues. My practical epistemic practices approach avoids many of these issues by focusing on the specific, contextualised behaviours that students use while solving engineering science problems. In my analysis I identified six sets of epistemic practices, including the three novel sets, summarised in Table 4.17 at the end of the preceding chapter. While some of these practises are similar to observations from prior work, they are consistently conflated with beliefs. In addition, my formulation attends to ways of constructing and justifying knowledge that are common in engineering, such as how models and equations are used. The following sections examine each of the three novel sets of epistemic practices identified in this study, then how the perennial standards of epistemic beliefs become more salient and concrete when formulated as engineering-specific epistemic practices. These elements all contribute to my argument that cognitive processes approach is an under-exploited but highly pertinent way to characterise epistemic sophistication in engineering.

5.2.2 Practices for Source and Validity of Equations

The prevalence of mathematics in engineering (Kent and Noss 2000) introduces an interesting novel aspect to students' practices which is not described in general models of epistemic beliefs. The set of epistemic practices around equations in *Source and validity* describe a trajectory from the unsophisticated direct acceptance of equations as absolutely true to the more sophisticated explicit management of the discrepancies between calculated values and physical reality. These practices represent a specific, action-focused formulation of Julie Gainsburg's distinction between using an exclusively mathematical or logical approach and making connections to physical reality. Again from a beliefs' perspective, Blömeke *et al.*'s (2008) four part characterisation of teachers' beliefs about the nature of mathematics sketch a comparable trajectory from (1) maths as a collection of rules and formulae to be acquired, (2) a focus on the exact and logical, (3) maths as a problem-solving science, and finally (4) as relevant for society and life.

One limitation of the current study is that the equations used by participants during their problem solving were predominantly empirically-derived, such as heat capacity and the equation of movement, and all tasks were well within the valid parameters for standard assumptions. It is therefore possible that my observations would not apply to how students manipulate equations and models in other situations.

5.2.3 Practices for Models as Tools and Representations

Models are important in engineering, and serve as tools that help "to explain, predict or optimise the behaviour of devices or the properties of diverse materials" (Boon and Knuuttila 2009, p. 687). Thus the ability to work in highly sophisticated ways with models is an essential skill to develop in engineering, particularly with the ever increasing use of computational tools (Kent and Noss 2000) and machine learning (Reich and Barai 1999). As argued by Boon and Knuuttila (2009), models can be employed as epistemic tools that provide valuable exchanges between abstract, general knowledge and specific physical reality. The set of epistemic practices in *Models as tools and representations* describes a trajectory from the epistemically unsophisticated practice of taking models as exact representations to the more sophisticated use of models, despite their acknowledged limitations, to advance problem solving.

While Julie Gainsburg's 2015 work on engineering students' epistemic beliefs identified the use of mathematical models as its focus, only one practice directly related to the use of models is presented. The Level 4 practice *Appreciates models' ability to advance problem solving, despite acknowledged limitations and simplifications* is actually from her 2007 work with professional engineers. The three less sophisticated epistemic practices related to using models identified in the current work provide a richness and detail for a ubiquitous element of engineering problem solving.

5.2.4 Practices for Precision and Estimation

A particularly relevant and engineering-specific set of epistemic practices focuses on the perceived value of precision and the use of estimates. Engineering must often work with incomplete or tentative data (Ang and De Leon 2005), making this set of practices important for engineers (e.g. Commission des titres d'ingénieur 2020). These practices are closely linked to practices around models and equations, however they are distinct in that not all instances of precise or imprecise values are connected to models.

The set of practices related to *Precision and estimation* describe a trajectory from the unsophisticated requirement for precision in all things to the more sophisticated use of estimates to advance problem solving. These practices are fundamental to managing the uncertainty and dynamic situations of applied engineering, but are not present in either general models nor in Julie Gainsburg's model.

While working engineers are often confronted with situations where data is not available or where precise data would be highly expensive to collect, naïve students ascribed little value to imprecise calculations. This set of practices could make McNeill *et al.*'s observation that students rarely encounter situations during their studies where a quick "back of the napkin" calculation is useful (2016) more visible to instructors during their course planning.

5.2.5 Contextualising Key Ideas about Epistemic Sophistication in Engineering

In addition to the novel epistemic practices reviewed in the preceding sections, some epistemic practices I observed relate to aspects of knowledge manipulation identified in general models: *Existence and number of correct answers*, and *Self-assessment of understanding*. The engineering-specific characteristics of the epistemic practices in these sets manifest in Level 3 coherence and Level 4 sceptical reverence. It is interesting to consider how the inclusion of additional contextual information when designing problem sets and assignments can permit students to perform more sophisticated self-assessments. It also illustrates how even paper-based exercises can be used to develop advanced epistemic skills.

From an epistemic beliefs approach, the Level 1 and 2 practices related to *Existence and number of correct answers* are most closely related to certainty of knowledge, that is the ability to conceive of knowledge beyond a binary correct/incorrect, whereas Levels 3 and 4 are more closely associated with the justification of knowledge and aspects of how reliable answers are determined. The cross cutting of these epistemic practices across the hypothesised semi-independent dimensions may explain the issue with co-loading observed for some certainty, simplicity and justification items (e.g. Qian and Alvermann 1995, Hofer

2000, Stathopoulou and Vosniadou 2007, Rizk *et al.* 2012).

While my think-aloud tasks, and perhaps the current abilities of my participants, were not conducive to observations of *sceptical reverence*, I drew on Gainsburg and King and Kitchener to formulate epistemic practices to complete the 4-level sets. Characterising the intermediate epistemic practices addresses gaps between the extremes of the naïve epistemic beliefs of general models and the high level practices from Gainsburg's work (2007). It is precisely these intermediate practices that it is important to nurture and challenge in order to encourage students to interact with engineering knowledge in more sophisticated ways.

5.3 Cognitive Processes Approach to Measuring Epistemic Sophistication

5.3.1 Measuring Epistemic Sophistication in Engineering

The weaker epistemic sophistication of engineering students compared to other disciplines observed by Pavelich and Moore (1996) and Wise *et al.* (2004) illustrate how useful it would be to have robust, scalable instruments to follow students' epistemic development during their studies and beyond. Given that engineering programmes typically have 10^3-10^4 students, quantitative instruments that allow relatively economical large-scale data collection and analysis are highly desirable. While the continued efforts to develop such instruments are therefore understandable, a robust construct is an essential underpinning for quantitative instruments. This section briefly addresses how this thesis's cognitive processes approach contributes to the development of methodologies to characterise epistemic sophistication in engineering.

5.3.2 Epistemically-stimulating Think-aloud Tasks

While think-aloud protocols have previously been used in studies of epistemic sophistication, there appears to be little work that uses more disciplinary tasks. The success of the tasks I developed for this study provide a useful model for future work. The tasks I developed are sufficiently difficult and novel to create opportunities for engineering students to employ a wide range of relevant epistemic practices. A key aspect that makes these tasks effective is that each one is presented in a contextualised format that allows for the possibility to use more sophisticated practices, such as verifying the plausibility of an answer or to reason with physical reality. For example, the task about heat capacity in the first set of tasks involved an *in situ* dental filling. The most open-ended task, about rubber wear on tyres, is particularly useful to stimulate higher level epistemic practices. This task most resembles King and Kitchener's ill-structured problems (2004), however, my task focuses on engineering science knowledge and contextualised problem-solving, rather than broader societal issues.

5.3.3 Measuring Fine-grained Epistemic Sophistication

In keeping with the fine-grained approach of Elby, Hammer and colleagues (Hammer and Elby 2002, Louca *et al.* 2004, Elby and Hammer 2010), the current work charted the range and distribution of epistemic practices exhibited by each student rather than assigning students to stages or phases. In my observations, all students who used Level 4 practices also used Level 1 practices. This apparent "inconsistency" has been repeatedly identified in previous work (Leach *et al.* 2000, Elby and Hammer 2001, 2010, Tsai 2004, 2008, Greene *et al.* 2008, Chinn *et al.* 2011, Gottlieb and Wineburg 2012, Gainsburg 2015, Zhu and Cox 2015). My observation that students do not approach every task with the highest level of epistemic sophistication available to them is consistent with Elby and Hammer's focus on effectiveness (2010).

Reporting which practices and levels occur most frequently for each student is simplistic but nevertheless provides a crude measure of how students are interacting with the engineering science knowledge. An important caveat is that each instance of an epistemic practice is recorded irrespective of the practice being peripheral or central to students' problem-solving. Level 2 practices occurred most frequently in my observations, whereas Julie Gainsburg observed Level 1 practices most often. While Gainsburg used a different set of code descriptors to me, it is unlikely that my think-aloud tasks were significantly harder than the homework exercises in her study. For me, the fundamental difference is that her students could thus rely much more on routine and memory than mine. This leads me to conclude that there is strong agreement between the two studies. The difference between the most frequent level observed by Gainsburg and in the current project is an excellent illustration of the influence of the task and a specific student's background on the epistemic practices they mobilise.

In both this study and Julie Gainsburg's, very few Level 4 practices were recorded. One possible explanation for this is that few engineering students have reached this level of sophistication. This explanation is supported by Litzinger *et al.*'s observation that "few of the students could reason physically" and therefore did not make connections between physical reality and calculations or models (2010, p. 337). Another explanation is simply that the tasks that students were solving did not require them to leverage such skills. Perhaps open-ended, interdisciplinary projects could provide a more likely context in which to observe students employing highly sophisticated practices.

The strong correlation between the level of epistemic practices professed by students and the practices that they were directly observed to employ suggests that self-report instruments could be developed. Such an instrument could enable non-interview, and thus more economical and scalable, data collection. This is an interesting methodological possibility to explore in future work.

5.3.4 Concluding Remarks about Measuring Epistemic Sophistication

The focus on epistemic practices, not beliefs, employed in this thesis offers some interesting methodological paths for measuring engineering students' epistemic sophistication. The think-aloud protocols generated rich, contextualised observations of epistemic practices and students' self-reporting also appears to be quite accurate. However, the development of a quantitative assessment tool still requires a more robust theoretical underpinning and would benefit from further research.

This research focused on certain aspects of engineering practice, omitting ethics, management, communication, and environmental science that Johnston *et al.* (1996) report are consistently neglected in engineering education research. This is important as these broader skill sets, which are built on the underlying disciplinary technical skills, have been repeatedly identified as lacking in engineering graduates (Martin *et al.* 2005).

5.4 COMPARING THE EPISTEMIC PRACTICES APPROACH TO PRIOR MODELS

5.4.1 The Cognitive Processes Approach Has Been Underexploited

This section highlights differences between this work and previous work on epistemic beliefs in engineering. It is thus central to my argument for why the approach employed in this thesis advances the field.

The first major contribution is the focus on epistemic practices, that is the specific actions that students perform when manipulating engineering knowledge, rather than epistemic beliefs. In addition, this thesis has organised the epistemic practices into sets related to the function of the practice, i.e. answer-checking. These sets are composed of four related practices, an organisation that will be useful to instructors who seek to implement Finster (1991) and Lynch *et al.*'s recommendation (1994) to stimulate students' epistemic development with practices just beyond their current level.

My final contribution to models of epistemic sophistication addressed in this section is my observation that appropriateness or effectiveness of the knowledge strategies a student uses is greatly influenced by their prior knowledge related to the specific task. This thesis makes the novel contribution that the range or diversity of strategies employed by a student is a more coherent indicator of epistemic sophistication.

5.4.2 Characterising Engineering Students' Epistemic Practices, not their Beliefs

Examples of how epistemic practices and epistemic beliefs are conflated abound. For example, Gainsburg's 2015 study presents the following 2 codes together without distinction *Perceives coursework as authentic career preparation* and *Uses units on intermediate values to … guide the solving process* (2015, p. 156). The first code conveys a broad, overarching belief about a variety of coursework activities encountered during engineering studies, while the second pertains to a specific problem solving action undertaken in context.

The difference between epistemic beliefs and epistemic practices informs both my methodology and my theory generation. I have defined epistemic practices as: behaviours or actions of students related to knowledge manipulation and justification that convey a student's epistemic approach to that specific bit of knowledge in the current context. The epistemic practices that are relevant to each discipline will be distinct to the discipline, arising from the practices and knowledge central to the discipline. This is a significant contrast to prior models of epistemic beliefs that seek to identify the student's overarching or underpinning belief system in general or for the discipline. Rather, this pragmatic, fine-grained approach focuses directly on how a student interacts with knowledge.

The behaviour-focused approach to epistemic practices taken in this thesis most resembles King and Kitchener's reflective judgement model (2004). Indeed, some aspects of the think-aloud problem solving is reminiscent of the (less structured tasks) of the reflective judgement model interviews. The approach of this thesis is different from reflective judgement model interviews because it encompasses a wider range of practices, characterises the fine-grained practices rather than the students, and focuses on engineering-specific situations. Despite these differences, I found the reflective judgement model to be very useful for reviewing the formulations and categorisations of the epistemic practices.

The set of epistemic practices *Strategies for verifying answers* are an excellent illustration of how the focus on epistemic practices avoids entanglements of prior epistemic beliefs models. The Level 1 and 2 practices reflect elements of certainty of knowledge, whereby absolute answers can be obtained from experts or from calculations. The epistemic practices of Levels 3 and 4 are more closely associated with the justification of knowledge, and aspects of answers are assessed and evaluated. While one might have expected that *Strategies for verifying answers* would all be related to justification of knowledge, this is not the case when we examine the epistemic practices in detail. Indeed, my framework may explain some of the co-loading observed for items employing semi-independent dimensions models (e.g. Qian and Alvermann 1995, Hofer 2000, Stathopoulou and Vosniadou 2007, Rizk *et al.* 2012).

Models focusing on broad beliefs, while philosophically intriguing, have proved very difficult to support empirically (Briell *et al.* 2011, Sandoval *et al.* 2016). After my in-depth review of the literature, I have concluded that the inference of general, overarching beliefs from the specific actions or declarations of a student is a major issue with previous models. The approach of this thesis may be too pragmatic for some, but my fine-grained, specific epistemic practices answer Muis *et al.*'s (2006) call for models that are relevant and accessible to engineering teachers. Further, my analysis clearly demonstrates how a macro perspective obscures the rich, contextualised description of knowledge practices that can support theory generation.

5.4.3 Structuring the Description of Engineering-specific Epistemic Practices

Julie Gainsburg concludes her 2015 study by questioning whether or not it is possible, or relevant, to make a distinction between the intermediate levels of epistemic sophistication. She states that "distinguishing between Levels 2 and 3 was the most tentative aspect of analysis" (2015, p. 160) and questions whether these two levels should be collapsed into a single level. I have found this distinction to indeed be both possible and important, particularly when seeking to characterise students' development during their university studies. I named these levels Local Coherence and Coherence, and will use the epistemic practices related to the source of equations as an ideal illustration of why this is an important distinction.

The Level 2 Local Coherence approach to equations attributes their derivation and validation purely to their internal, mathematical logic, for example, when the mathematical operations result in logical, internally coherent equations or predictions. Level 3 Coherence practices take equations as descriptions of actual phenomena in the physical world. The distinction between my Level 2 approach, which seeks only an internal conceptual and mathematical coherence, and Level 3, which makes explicit reference to the physical world, is an important one. The Level 3 practice makes connections between the precise, abstract paper-based representations and real world contexts and is essential in engineering thinking. It is however not equivalent to Gainsburg's Level 4 Sceptical Reverence which involves the engineers exercising their own context-dependent judgement to determine which equations are most relevant and which should be ignored.

The tabular organisation into sets of epistemic practices characterised at four levels of sophistication makes the observations of this thesis more accessible, as both the overall arc and the intermediate points are apparent. As outlined above, I have developed clear criteria to distinguish my Level 2 Local Coherence from my Level 3 Coherence. Further, by grouping the epistemic practices into sets I have made the distinctions clearer and more salient. Since the ultimate goal of such a framework, for me, is an aide for engineering teachers, it is important to keep these two intermediate levels in order to better assess the development of students' epistemic sophistication during their studies. This will also enable teachers to see exactly what strategies or practices to target in their assignments for students, in order to implement Finster (1991) and Lynch *et al.*'s recommendation (1994) to stimulate students' epistemic development with requiring them to use practices just above their current level of sophistication.

My epistemic practices approach, while fine-grained and practice-focused, is not limited to a specific discipline. This is different from previous work by Entwistle *et al.* (2005) on analogue circuits in electrical engineering and by Christian (2011) on chemistry study groups that identified different ways students reasoned. Both of these studies were highly contextualised in their specific disciplines and did not seek to contribute to a general model of epistemic sophistication.

5.4.4 Diversity, not Correctness, Designates an Epistemically Sophisticated Approach

Elby, Hammer, and colleagues' (Hammer and Elby 2002, Louca *et al.* 2004, Elby and Hammer 2010) epistemological resources model is a significant departure from previous models. As presented in my Literature Review in more detail, their approach is based on fine-grained characterisation of the cognitive resources that people use in specific contexts and increased sophistication is characterised by an expanded set of resources and a growing ability to select a strategy effective in a given situation. Elby and Hammer, therefore, argue that employing an effective or appropriate practice in a given situation is an indication of epistemic sophistication (2010). This is very different from prior models that characterise increased epistemic sophistication as the use of increasingly sophisticated strategies, resulting in the implicit designation of less sophisticated approaches as less desirable or valuable.

It is therefore important to examine how the hierarchical relationships implied by my organisation of epistemic practices into sets should be interpreted.

The observations of this thesis support the epistemological resources model's claim that a sophisticated approach will make use of a range of epistemic practices depending on the specific context and therefore rejects the notion that more sophisticated is always better. Gainsburg has similarly offered support for the epistemological resources model, noting that "Veteran engineers capable of sceptical reverence will still engage in dualist behaviour in routine situations in which they are confident that formulas and prior examples can be followed lockstep" (p.160, 2015).

I take issue, however, with Elby and Hammer's postulation that practices should be classified as sophisticated when they are effective or appropriate in the given context and unsophisticated when ineffective. I think that this weakens the model, since adjudicating the appropriateness of an approach by comparing it to the most effective method is subject to many contextual constraints. The disciplinary background of the researcher, the task under observation, and the disciplinary background or prior knowledge of the participant will have a massive influence on how appropriate certain actions are judged to be. For example, students lacking disciplinary background may engage in elaborate detours during their problem solving. Berland and Crucet have also raised concerns about how *effective* or *appropriate* are defined and assessed. They propose that "A student's epistemological approach could be considered more sophisticated if the student was aware of the epistemological choices they made. However, awareness is difficult to assess" (2016, p. 22). While I agree with their position that "attending to students' rationales for their epistemological decisions" is an interesting approach, it is still subject to issues of students' prior knowledge and the specific context.

Arising from these observations, I have proposed that a more effective measure of epistemic sophistication in the epistemological resources model is the range, or diversity, of epistemic practices employed by a student. This refinement of Elby and Hammer's model has implications both for theory and empirical methods. First, characterising the diversity of practices, rather than their effectiveness, is more coherent with Elby and Hammer's key premise that an epistemically sophisticated person has a wide set of epistemological resources on which to draw. It is also coherent with Litzinger *et al.*'s finding that stronger engineering problem solvers used both more representations of problems and more self-explanations, and that these were distributed across the different approaches available. Secondly, my proposal to assess the diversity of epistemic practices is a more robust measure than effectiveness. While a designation of appropriateness depends on the researcher's own background, the specific task and the background of the participant, diversity requires only that participants attempt suitably challenging tasks.

The empirical observations of this thesis are not incompatible with characterising diversity as reflective of epistemic sophistication. The analysis presented in Figure 4.6 illustrates an apparent association between the diversity of epistemic practices that a student mobilised and their ability to solve the epistemically-challenging tyre question. The small study size is far from adequate to provide rigorous support for this model. It must also be noted that, in the current data, diversity is only a marginally better measure than simply taking the highest level practice. My refinement to Hammer and Elby's epistemological resource model increases its coherence with observations that increased expertise correlates with both more frequent and a wider range of problem-solving strategies (Randles and Overton 2015). This increased theoretical coherence is a strong argument in favour of using diversity, rather than effectiveness or appropriateness, as the measure of epistemic sophistication in the epistemological resources model.

5.4.5 Creating an Engineering-specific Dimensional Questionnaire Remains Elusive

My inability to establish an adequate factor structure, despite extensive attempts, is coherent both with Elby and Hammer's epistemic resources model and also with Faber *et al.*'s (2016) mixed quantitative and qualitative observations. This first-hand experience prompted me to deepen my review of the literature of quantitative measures of epistemic beliefs and strengthened my interest in pursuing cognitive processes approaches to epistemic sophistication.

Previous studies (Belenky *et al.* 1997, Palmer and Marra 2004, Wise *et al.* 2004) have found that epistemic beliefs do progress with studies (rather than age). So it is surprising that only two items in my questionnaire, both from Hofer's justification dimension (2000), showed any correlation with year of studies. Given that students encounter different curricula depending on their study concentration, such as the number and nature of design projects, experimental work and work placements, clear linear trends were not expected. However, the lack of measurable progress was surprising to me. I will return to this point in the following section.

5.4.6 Lack of Progress in Epistemic Sophistication

My epistemic practice data does not show senior students (i.e. Masters) to be more epistemically sophisticated than junior students (Bachelors). This observation is counter to multiple prior studies with American engineering students (Paulsen and Wells 1998, Marra *et al.* 2000, Wise *et al.* 2004). One possible explanation is that the apparently flat trend in epistemic sophistication in my study is that it is an artefact arising from the small number of participants. Another possible explanation is that junior students worked harder at the problem solving than Masters students, perhaps feeling more obligation to the researcher. This latter explanation is, however, undermined by the identical ratio of professed:enacted answer-checking practices for Bachelors students (n = 11, data in Tables 4.6 and 4.7) and for Masters students (n = 8). Another explanation could be that Masters students were able to solve the tasks without evoking more sophisticated practices; but the explanation is undermined by the fact that Masters students performed (in general) poorly on the open-ended task. However, the lack of increasing epistemic sophistication with year of study appears to be more than an artefact, as it is consistent across all my observations, both qualitative and quantitative. Unfortunately, the single contact point with each student does not provide additional avenues to pursue this unexpected result. I do not have a strong explanation for this observation.

5.4.7 Section Conclusion

Briell *et al.*'s paper is an excellent review of the persistent issues in the field of epistemic beliefs (2011) and, for me, provides motivation for the approach undertaken in this thesis. First, attending to epistemic practices removes the potentially problematic inference to underlying beliefs and entanglements between the dimensions of epistemic beliefs postulated by some models. Second, focusing on the rich, contextualised nature of the practices themselves advances the characterisation of epistemic sophistication in engineering and reflects the fine-grained approach of Elby and Hammer that avoids classifying people in stages or phases as postulated by other models. My proposed refinement to Elby and Hammer's epistemological resource model that diversity, not effectiveness, serve as the indicator of sophistication is both more coherent theoretically and supports robust measurement as it attenuates the influence of specific knowledge on assessing the behaviours mobilised by the student. Finally, both the novel and reformulated engineering-specific epistemic practices, organised into sets of practices, support the translation of this research into engineering teaching.

5.5 CHAPTER FIVE CONCLUSION

While a cognitive processes approach has rarely been used in prior studies (Briell *et al.* 2011), focusing on students' contextualised problem solving has provided rich insight into epistemic sophistication in engineering. It enabled me to answer my first research question (RQ1), identifying some practices which may be relevant only to engineering or science disciplines and other practices that are endemic to work in the field yet are enacted in particular, discipline-specific ways. The richness of my data underlines the need to attend to disciplinary and micro context highlighted by Sandoval *et al.* in their call to "Imagine possibilities for measuring or describing epistemic cognition in the many places where it occurs" (2016, p. 480).

I have proposed a four-level framework to characterise epistemic practices at different levels of sophistication. This structure makes the range and diversity of practices mobilised by all my participants clear, answering my second research question (RQ2).

The epistemic practices profiles of highly sophisticated students (my final research question, RQ3) span at least three levels and are very similar in range to moderately epistemically sophisticated students. Analysing the frequency identified that more sophisticated students used Level 3 practices more often but they did not necessarily use fewer Level 2 or even Level 1 practices.

Focusing on epistemic practices removed the need to infer underlying beliefs and enabled me to maintain the richness of Elby and Hammer's fine-grained approach that eschews classifying people in stages or phases. In addition to avoiding persistent issues with beliefs approaches, my cognitive processes approach also opens a robust methodological path for gathering empirical observations. While the think-aloud protocols are quite labour-intensive, they generate the contextualised observations that are the foundation of robust theory. My proposal to use diversity, rather than effectiveness, to characterise sophistication in Elby and Hammer's epistemological resource model is more coherent theoretically and supports robust measurement as it attenuates the influence of specific knowledge on assessing the behaviour mobilised by the student. The resulting analysis is relevant both for the characterisation of epistemic sophistication in engineering and models of epistemic cognition in general.

Finally, my epistemic practices approach is practical and accessible, which should support the translation of this research into engineering teaching. Cognitive structures approaches deserve to see their share of research attention in the field decrease, as their domination obscures alternative models that deserve to be explored. The next and final chapter of this thesis, Chapter 6, considers how these results should be used to inform future directions for research into epistemic practices in engineering.

6 Conclusion

6.1 OVERVIEW OF THE FINDINGS

The introduction to this thesis made the case for the importance of strong epistemic skills for engineers. Yet engineering students have been found to develop epistemic sophistication more slowly than other fields (Pavelich and Moore 1996, Wise *et al*. 2004). Taken together, this underlines the need to generate models and assessment instruments that are accessible to engineering teachers. This chapter takes a broader view of this specific research project and the field of epistemic cognition in order to consider these objectives.

This final chapter takes a three-part approach to situating the contributions of this thesis in the field of epistemic cognition. First, how does this thesis advance our understanding of epistemic cognition in engineering? Secondly, what does this thesis contribute to measuring epistemic cognition in engineering? Finally, what are the implications for developing engineering students' epistemic sophistication? The thesis concludes with proposals for future work, which includes some translational research ideas aimed at bringing these ideas and approaches into teaching. Returning to the teaching of engineering is a good place to end since these questions launched this thesis.

6.1.1 Methodological Approach

While this study set out with a primarily quantitative approach, intending to adapt existing questionnaires, I was profoundly dissatisfied with the robustness of the results. As I have detailed in the Literature Review, I think sufficient work has been invested in trying to create quantitative instruments for current models of epistemic beliefs and that epistemic cognition is a better approach. It appears that the gap is too large between overarching epistemic beliefs and individual, Likert-scored statements with little context. These observations prompted me to take a more practical approach, observing students' epistemically-relevant behaviours during think-aloud problem solving protocols. Given the persistent issues with quantitative, beliefs-focused instruments, it is surprising that qualitative methods have not been used more frequently in the area. Indeed, a grounded theory approach with rich, contextual observations is ideal for building theory.

The effectiveness of my methodology is born out in the framework of seven sets of epistemic practices for engineering. This framework is both practical, characterising the epistemically-relevant behaviours that students use while problem solving, and also has useful explanatory power regarding observations of students holding inconsistent epistemic beliefs in this thesis and in prior work. Inconsistencies in the levels of epistemic sophistication are not explicitly accounted for by most models and are dismissed as measurement issues or noise. The practical, fine-grained observations supported my grounded theory analysis that identified that diversity itself is an indicator of sophistication. Specific points related to my epistemic practices framework are addressed in section 6.2, and considerations of how the framework contributes to measuring epistemic sophistication in section 6.3.

6.2 Advancing Our Understanding of Epistemic Cognition in Engineering

6.2.1 Characterising Epistemic Cognition in Engineering

The first major contribution of this thesis is its novel focus on epistemic practices, that is on the specific actions that students perform when manipulating engineering knowledge, rather than epistemic beliefs. The recurrent and wide ranging issues with prior measures of epistemic beliefs are well documented in earlier chapters. Arising from my analysis of the literature, I identified a failure to make a distinction between observable, specific epistemic practices and overarching epistemic beliefs as a confounding issue for theory development. Making this distinction directed the methodology and theory generation of this thesis in important ways. I argue that we do not currently have adequate understanding of the nature of the constructs of epistemic beliefs in engineering to work at a broad, overarching level. Accordingly, I use the term epistemic practices to describe the epistemically revealing knowledge manipulation and evaluation behaviours of engineering students.

Building robust theory requires that we work with rich, contextualised empirical observations. This thesis proceeded in this sense, predominantly using a grounded theory approach to analyse students' problem solving activities. From these observations, I identified seven sets of epistemic practices to characterise engineering students' epistemic cognition. Of these, four sets are novel: *Source and validity of equations*, *Using models*, *Working with Peers,* and *Precision and estimation*. These practices are important in quantitative problem solving and reasoning with models, and therefore their identification is highly relevant to characterising epistemic cognition in professional engineering practice. The other three sets, *Existence and number of correct answers*, *Self-assessment of understanding*, and *Strategies for reasoning and verifying answers*, have previously been described but often with a mixture of beliefs and behaviours. My formulation in terms of *epistemic practices* and characterisation at each of the four levels of sophistication allows a rich portrait of a student's epistemically relevant behaviours to emerge.

Describing epistemic cognition in terms of four levels is reminiscent of many prior models, starting with Perry's. In keeping with the pragmatic approach employed through this work, my choice of four levels sought to provide an adequate yet parsimonious heuristic that would be relatively accessible to engineering teachers. I have used King and Kitchener's term *Absolute* for the least sophisticated level, which is composed of a series of epistemic practices that assumes that engineering thinking will produce a single, precise correct answer. I adapted Julie Gainsburg's term *Sceptical reverence* for the most sophisticated level, adding an explicit reference to uncertainty for a series of epistemic practices that recognises that engineering thinking requires making judgements based on the specific context and perspective. In between these two extremes are the levels of *Local Coherence* and *Coherence*; many of the practices at these levels appear not to have been previously described. *Local Coherence* practices are based on producing internally coherent, precise, and mathematically sound thinking. The shift to *Coherence*, which makes connections between physical reality and models to find all the solutions that meet or exceed the requirements, is an important step towards authentic engineering practice. The description of these four levels faciliates the applications of this framework to other contexts and situations.

While the seven sets of *epistemic practices* were developed from a limited number of quantitative problem solving tasks, they are nevertheless quite general. The attention to how engineering knowledge is manipulated and evaluated in a fine-grained way, rather than as overarching or underpinning beliefs, enables these epistemic practices to describe both the overall arc and intermediate points along the path to a well-developed sophisticated engineering thinking. This set of seven practices, characterised across four levels of sophistication, is the second major contribution of this thesis.

6.2.2 A Model to Characterise Epistemic Sophistication in Engineering

This thesis makes the novel argument that diversity, and not the appropriateness, effectiveness, or highest level strategy enacted by a student is the best characterisation of their epistemic sophistication. Many studies appear to evaluate students' level of epistemic sophistication by the dominant or most frequently observed level (i.e. Baxter-Magola 1992, Belenky *et al.* 1997, Perry 1970, King and Kitchener 2010, Zhu *et al.* 2019). Elby and Hammer proposed an important advance by recognising that the effectiveness of a given approach should be considered, as low level epistemic practices will always be most effective in some situations (2001, 2010). Julie Gainsburg refined their proposal by dividing development into two parts: capacity and selection (2015), where capacity is the total range of epistemic practices they are able to employ and selection is the ability to effectively identify when to use specific practices.

As I have argued earlier, selection of the most appropriate epistemological resource (to use Elby and Hammer's term) is not a good indicator for epistemic sophistication because it is too heavily influenced by the specific task, the background of the researcher, and the student's past experiences. An important corollary of this is that it limits our abilities to make comparisons across contexts, which in turn poses obstacles to translational research. In response to these issues and arising from my analysis, I propose that the diversity of epistemic practices is the most relevant measure to assess students' epistemic sophistication. Using diversity is coherent with Elby and Hammer's observations that a less sophisticated strategy is sometimes more effective and also explains the observations of students exhibiting behaviours and beliefs scattered across multiple levels of sophistication (Zhu *et al*. 2019). Diversity also explains Chandler *et al*.'s observation that "More or less identical claims about the supposed course of epistemic development are all made about research participants of wildly different ages" (2002, p. 146).

Gainsburg's capacity is similar to the measure of diversity that I have proposed, however, it omits the inherent value of using a broad range of epistemic practices. Further, capacity is a less effective tool for assessing epistemic sophistication because of notions of transfer, a key idea from learning science. In conclusion, my proposal of diversity as a measure of epistemic sophistication is a significant advancement to how we measure epistemic sophistication.

6.3 MEASURING EPISTEMIC COGNITION IN ENGINEERING

6.3.1 A Practical Approach to Epistemic Cognition via Epistemic Practices

Setting aside what students believe may seem like a step backwards from the development of a robust model of epistemic beliefs about engineering. However, the focus on beliefs over several decades has not produced a fully satisfactory model. The findings of this thesis support my decision to focus on epistemic practices and illustrate the value of this approach to advance the field.

Further, focusing directly on how engineering students manipulate and interact with knowledge may also make these observations more accessible and relevant to engineering teachers. While some people navigate comfortably in the intellectual space around epistemology and philosophy, many of us in science and engineering are more comfortable with more practical models. Thus, Table 4.17 describes specific, concrete actions relevant to engineering problem-solving contexts, without allusion to an over-arching set of epistemic beliefs, and this may enable engineering teachers to better perceive the relevance. The approach with concrete, observable epistemic practices makes the connection between epistemic sophistication and engineering problem solving obvious.

6.3.2 Think-aloud Problem Solving Tasks to Observe Epistemic Practices

This project developed a methodology based on think-aloud problem solving tasks to elicit epistemically-relevant behaviours. Accordingly, the tasks I created sought to allow for students to reason with formulae and also personal experience (Appendix 3). This meant that each task was contextualised, pitched to offer a sufficient level of cognitive difficulty to require some concerted problem solving, yet did not exceed students' cognitive load and allowed for relatively brief sessions with students. These tasks can be used in other studies, or the concepts used to design new tasks. The next section picks up some of these opportunities.

6.4 Implications for Developing Engineering Students' Epistemic Sophistication

When teachers have a better understanding of the range of ways students may understand and experience the course material, they can design strategies to better accompany students in developing a more sophisticated understanding (Entwistle, 1997). Students' epistemic cognition is an important filter of how they see, experience, and interact with their courses. Therefore the framework can be a tool for engineering teachers to evaluate opportunities for epistemic development in their courses.

First, the six sets of epistemic practices of the framework can be used to evaluate course activities. For instance, a teacher could use the framework to review a homework assignment, asking what practices students must use to complete it. Is there sufficient scope or context to allow students to employ more sophisticated practices?

This is important because while Bachelors students arrive in engineering programmes with varying levels of epistemic sophistication, what we convey to them about the nature of engineering through the tasks and interactions with the teachers is not currently stimulating students to become significantly more sophisticated. The learning tasks and the nature of the interactions with their peers and teaching staff embed the epistemic approach we emit (Feucht 2010, Muis *et al*. 2016) and can influence students' approaches over time (Duffy *et al*. 2016). Baxter-Magolda also cites situations where the teacher is uncertain or not an absolute expert as useful for epistemic development (Chapter 9, 1992). The characteristics of the tasks found to support epistemic development are complexity, authenticity, multiple sources of information, and multiple possible approaches (Baviskar *et al.* 2009; Gordon 2009).

Worryingly, my participants reported that the tasks and assignments which constitute the bulk of their university experience do not encourage them to adopt more sophisticated epistemic practices. Their instructors' demonstrations of problem-solving and assigned exercises appear to nearly exclusively feature single, precise answer tasks that preclude the need to check the assumptions of the models used. The ability to calculate a highly precise answer was generally taken as equivalent to a highly accurate answer, completely omitting any simplifications or approximations employed in obtaining the equation to model the system. Further, it seems that assigned tasks rarely provide sufficient contextualisation for students to leverage their lived experiences for sense-making or answer-checking and do not require students to make estimates or work with a range of values.

These observations may both help explain why engineering students develop more slowly in their epistemic practices, but also point to small, easy-to-implement changes that can support students to acquire more epistemically sophisticated ways of interacting with engineering knowledge. Indeed, Table 4.17 can be used as a guide to providing scaffolded opportunities for students to work in less constrained, more imprecise situations even on paper-based calculation exercises in order to prepare them to work on big, open-ended projects at university and in their future professional lives. For example, ensuring that tasks are contextualised such that students are can leverage real-world sense-making and multiple *answer-checking* strategies.

The deliberate challenges of naive epistemic views by the instructional strategies and task characteristics listed above may elicit frustration and annoyance from students whose perspective prevents them from appreciating the value. This means that these students may shy away from this discomfort, seeking out what appears to be absolute truth or an absolute expert. This is problematic since these experiences do not occur often. Several researchers have noted that experiences which directly challenge students' dualistic views occur infrequently in engineering programs (Cheville and Bunting 2011; Danielak *et al*. 2014; Frye *et al*. 2012; Gainsburg 2015). Engineering education devotes little time to exploring different points of view on a given issue (Frye *et al*. 2012) and Gainsburg notes that "Undergraduate engineering courses may rarely confront students with the kinds of epistemic challenges which push liberal arts students towards relativism" (p.142, 2015).

This brings us to the second way to use the framework: to evaluate the effectiveness of teaching interventions on epistemic cognition, for example, as an observation guide to score students' problem solving practices. This would provide researchers and teachers with a measure of students' epistemic sophistication. While the considerable resources required for such a study are a barrier to implementation, the results would be rich and useful.

Several researchers have written that students need to be stimulated to reach and apply epistemic approaches just beyond their current level of sophistication (Finster 1991, Lynch *et al*. 1994). Lynch *et al*. caution that students may not be able to perceive strategies significantly above their current level (1994). Thus, implementing instructional strategies that are effective for epistemic development requires knowing the current level of your students.

King and Kitchener (2004) warn that developing epistemic sophistication is a slow process, even with deliberate interventions. Gainsburg further notes that engineering students in her study "complained that hectic academic schedules" prevented them from taking the time to process and make sense of new ways of thinking (2015, p. 163). My pragmatic, fine-grained approach focusing directly on how students interact with knowledge can make the relevant skills more visible to both teachers and students. It also matches Muis *et al*.'s calls for measures that are "easy to understand and readily applicable to the instructional context" (2006, p. 41).

6.5 Limitations of this Study

There are two main type of limitations to consider when assessing how well this thesis has answered its research questions: the trustworthiness of the findings and their generalisability to other contexts. Credibility and dependability are two major indicators of the trustworthiness of qualitative research findings (Denzin and Lincoln 1994). Reproducibility is a third standard measure of research quality. In qualitative research, this is often achieved by having several people review the coding. This was not done in this project. Credibility refers to the authenticity of the findings and is often supported by triangulating multiple data sources and methods (Bowen 2009). The current study predominantly used direct observations of students' epistemic practices and then interviews to collect students' accounts of their practices. All my data is highly coherent but this agreement may also arise from the similarity of the contexts where I collected the data. The credibility of the study could be reinforced by observations of students working on their course work or retrospective interviews with students about their homework assignments. The dependability of the findings is limited by single time point data collection with each student that does not provide information about the consistency of students' epistemic practices across time or contexts. However, the internal coherence identified by my analysis of students' epistemic practices across the six different think-aloud tasks support the dependability.

The generalisability of this study is limited due to the small number of participants and the fact that this study was conducted on a single university campus. This means that I cannot claim that the epistemically-relevant problem solving practices described are a good description for students in different contexts or faced with different tasks. Rather, transferability is a more appropriate measure for assessing the limitations of this predominantly qualitative study. Transferability of the findings refers to the relevance of the findings for other contexts. The rich, contextualised descriptions of the six sets of epistemic practices is a major strength for their transferability.

The overall framework is rich and built on many observations. However, because students came from several engineering programmes, it is not sufficient to see if the epistemic practices are adequate to describe the essential features of epistemically-relevant problem solving in these different disciplines. Additionally, while saturation was reached in each study, it is possible that inadequate sampling of the population resulted in a failure to capture some relevant practices.

My main concern is that the think-aloud tasks are more engineering science than engineering, and therefore may not have evoked all practices relevant for engineering problem solving. Further, the tasks drew only on first year knowledge and may not have prompted students to apply more sophisticated epistemic practices due to their framing or difficulty level. My decision to construct tasks that would not preclude the participation of students from any engineering study programme meant that students were not challenged with tasks from their own discipline that would be more likely to elicit their contextualised knowledge. This limitation could be addressed by conducting think-aloud protocols with more discipline-specific engineering tasks with third year and Masters students. Given the diversity of practices employed by all students, I would expect these upper level students to use practices from across the framework and consequently test the relevance and adequacy of the entire structure. Constructing tasks that appear tightly connected to the core disciplinary activities of students from different programmes (i.e. both electrical engineering and computer science, or both materials engineering and chemical engineering) would allow for a more robust testing of the relevance of the framework.

6.6 Directions for Future Research

Testing and extending the epistemic practices framework developed in this thesis in a broader range of contexts and with different types of tasks is the obvious next step. The set of six epistemically-relevant practices was developed with a narrow set of paper-based tasks focused on engineering science. The current study is far from the problem solving contexts encountered by professional engineers and does not fulfil Chinn *et al.*'s call for research across a variety of contexts to better understand how epistemic cognition develops and evolves (2011). Testing and extending the framework could investigate:

- Do these epistemic practices occur during a broader set of thinking and problem solving tasks in engineering, particularly for more specialised higher-level tasks?
- Are these epistemic practices sufficiently engineering-specific yet appropriate across a range of engineering disciplines?
- Are there other key epistemic practices that should be added, particularly when considering a broader set of engineering contexts?

A second strand for future work relates to the use of the framework as a measurement tool. The overall framework is built on many observations, but as these are spread across students from first year to Masters level and several disciplines, it is not nearly sufficient to see potential disciplinary or developmental trends. Some questions for future research addressing these areas include:

- While the *diversity* of epistemic practices is coherent with theory, under what conditions or context does it provide an effective measure of epistemic sophistication?
- By focusing on students in a single programme, can the framework capture epistemic development across their studies?
- Expert problem solving has been shown to be different in one's own area of expertise and another discipline (Voss *et al*. 1983). Can the framework capture a similar pattern with epistemic cognition?

Finally, how can this research be made relevant and useful to engineering teachers? Bråten (2016) adamantly stated that empirically based, testable models of epistemic sophistication that can guide teaching interventions are an important goal. This means collaborative research with teachers to address questions such as:

- Is the framework accessible and relevant to engineering teachers?
- Can it be implemented as a feedback tool for a course or programme?
- Can the think-aloud problem solving protocols be transformed into a less resource intensive, yet rich and relevant, measure?

To summarise, there are still many fascinating questions about epistemic practices and epistemic cognition in engineering that could be investigated.

6.7 Relevance of Epistemic Practices for Teaching Engineering

Problem solving is key to engineering. This is evident in the central place of projects and hands-on learning in engineering curricula. Indeed, problem solving is often how professional engineers describe their work. The thinking skills related to evaluating contradictory knowledge claims, navigating uncertainty, and operating with changing information are the foundation of good problem solving.

While epistemic cognition and epistemic sophistication sound like abstract and philosophical terms removed from the concerns of practicing engineers and engineering teachers, they are in fact at the heart of good engineering thinking, indeed, of good thinking in general. Information is more available than ever before but this has also meant that a lot of poor quality or even intentional misinformation is widely available. Our engineering graduates must be able to navigate through this vast amount of information, identifying what is more relevant and less relevant, what is relatively stable and what is evolving, what is quite reliable and what is corrupt. Coping with these multiple shades of grey requires a sophisticated level of epistemic cognition.

Being able to characterise, and ultimately track the development of, the epistemic sophistication of engineering students would be a highly useful tool for preparing graduates. This thesis has brought this ideal a little closer by contributing a practical, robust, and specific framework to characterise epistemic sophistication in engineering.

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APPENDIX A

ETHICS APPROVAL, EPFL

ETHICS APPROVAL, LANCASTER

PARTICIPANT INFORMATION SHEET, QUESTIONNAIRE

PARTICIPANT INFORMATION SHEET AND CONSENT FORM, PILOT INTERVIEW

PARTICIPANT INFORMATION SHEET AND CONSENT FORM, 2016-2018 INTERVIEWS

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EPFL HUMAN RESEARCH ETHICS COMMITTEE

Request for opinion on ethical acceptability of projects undertaken by researchers at EPFL

DECISION

HREC No: : 001_30.03.2015
Office use only

Applicants' Name: Siara Isaac

Title of the project: Epistemological Development and Classroom Learning Strategies in Engineering Student

For EPFL Research Ethics Committee use only:

Review date: 30.03.2015

Outcome: ☒ Approval (with comments)

☐ Approval Declined

Applicant informed (date): 16.04.2015

Prof. Andreas Mortensen

Chair Human Research Ethics Committee EPFL

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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Recommendations and comments from the reviewers

Reviewer 1 and 2

I am wondering why the applicant indicates at E1 (p11/16) "Yes" and "No" regarding "Written informed consent"? I think that it should be only a "Yes" answer, the argument supporting "No" seems to me irrelevant. I would be grateful if the applicant could clarify this question.

Reply of the applicant:
There are 2 types of participants in the study : interview participants (who will sign a consent form) and survey participants (who will not sign a consent form, per normal procedure for anonymous surveys). People will either be interview candidates or survey respondents.

Reviewer 3 (legal)
No legal comments: Approval.

Reviewer 4
No comments: Approval.

Reviewer 5
How will data containing information on the participants' identity be stored by the researcher, so as to make them inaccessible to others?

Reply of the applicant:
All data related to the study, including the participants' identity, will be stored on a password protected and encrypted computer.

From: Ethics (RSO) Enquiries
To: Isaac, Siara
Cc: Ashwin, Paul
Subject: Stage 1 self assessment approval UREC REFERENCE:
Date: 06 March 2015 14:10:00

Dear Siara

Thank you for submitting your completed stage 1 self assessment form and additional information for **Epistemological development and classroom learning strategies in Engineering students**. The Part B information has been reviewed by members of the University Research Ethics Committee and I can confirm that approval has been granted for this project.

As principal investigator your responsibilities include:

- ensuring that (where applicable) all the necessary legal and regulatory requirements in order to conduct the research are met, and the necessary licenses and approvals have been obtained;
- reporting any ethics-related issues that occur during the course of the research or arising from the research (e.g. unforeseen ethical issues, complaints about the conduct of the research, adverse reactions such as extreme distress) to the Research Ethics Officer;
- submitting details of proposed substantive amendments to the protocol to the Research Ethics Officer for approval.

Please contact the Research Ethics Officer, Debbie Knight (ethics@lancaster.ac.uk 01542 592605) if you have any queries or require further information.

Kind regards,

Debbie

Debbie Knight | Research Ethics Officer | Email: ethics@lancaster.ac.uk | Phone (01524) 592605 | Research Support Office, B58 Bowland Main, Lancaster University, LA1 4YT
Web: Ethical Research at Lancaster: http://www.lancaster.ac.uk/depts/research/ethics.html

Lancaster University

www.lancaster.ac.uk/50

Participant Information Sheet

Project: Epistemological Development and Classroom Learning Strategies in Engineering Students (questionnaire)

Researcher: Ms. Siara Isaac, Teaching Support Centre
Tel: +41 21 69 35289
BI B2 432, Ecole Polytechnique Fédérale de Lausanne, Switzerland CH-1015
Email: siara.isaac@epfl.ch

Supervisor: Professor Paul Ashwin, head of department, Educational Research
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Email: p.ashwin@lancaster.ac.uk
Room: County South, D32, Lancaster University, Lancaster, LA1 4YD, UK.

***Date:*____________,**

I would like to invite you to take part in my thesis research in the Department of Educational Research at the University of Lancaster.

Before you decide if you wish to take part you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully. Please ask if there is anything that is not clear or if you would like more information. Talk to others about the study if you wish. Take time to decide whether or not you wish to take part.

This document includes:

- Information about the purpose of the study.
- Information about what participation means and how to withdraw when and if you wish.
- Information about how this data will be secured and stored.
- How the information will be used in the thesis and for other purposes such as conference presentations or publication.

The purpose of the study

This research is for my thesis in the Department of Educational Research at Lancaster University, and may also be used for journal articles and conference presentations. My research aims to characterise the different objectives that EPFL students have for their time in class, and what strategies they employ in order to meet this objectives.

By participating in this study, I hope you will benefit from a greater understanding of the learning strategies you use in-class and that it will help you ensure that they are best adapted to the type of learning you seek.

What does it mean to participate in the study?

Why have you been invited?

Your whole class has been invited to participate in order to have broad representation from across the EPFL student population.

Do you have to take part?

No, it is up to you to decide whether or not to take part. If you do not wish to take part, then please do not complete the questionnaire.

What would taking part involve?

If you agree to participate, you would answer the adjoining questionnaire. The questions ask about what you learn in your classes, and about the strategies and approaches that you use to facilitate your learning.

How will your data and identity be kept private?

'Data' here means your answers to the questionnaires, which will be used and stored in accordance with the UK Data Protection Act. The data may be kept for one year after the successful completion of the PhD *Viva* as per Lancaster University requirements, and after any personal data will be destroyed. The completion of this study is estimated to be by January 2019.

Data may be used in the reporting of the research (in the thesis and then potentially in any papers or conference presentations). Please note that if your data is used, it will not identify you in any way or means.

Who to contact for further information or with ***any*** concerns?

If you would like further information on this project, the programme within which the research is being conducted or have any concerns about the project, participation or my conduct as a researcher please contact:

Professor Paul Ashwin – Head of Department
Tel: +44 (0)1524 594443
Email: p.ashwin@lancaster.ac.uk
Room: County South, D32, Lancaster University, Lancaster, LA1 4YD, UK.

Thank you for reading this information sheet.

Siara ISAAC
Teaching Support Centre, Ecole Polytechnique Fédérale de Lausanne
+41 21 69 35289
siara.isaac@epfl.ch

Participant Information Sheet

Project: Epistemological Development and Classroom Learning Strategies in Engineering Students (pilot interview)

Researcher: Ms. Siara Isaac, Teaching Support Centre
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Supervisor: Professor Paul Ashwin, head of department, Educational Research
Tel: +44 (0)1524 594443
Email: p.ashwin@lancaster.ac.uk
Room: County South, D32, Lancaster University, Lancaster, LA1 4YD, UK.

Dear ______________________________, ***Date:__________,***

I would like to invite you to take part in my thesis research in the Department of Educational Research at the University of Lancaster.

Before you decide if you wish to take part you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully. Please ask if there is anything that is not clear or if you would like more information. Talk to others about the study if you wish. Take time to decide whether or not you wish to take part.

This document includes:

- Information about the purpose of the study (what I hope to find out).
- Information about what participation means and how to withdraw when and if you wish (what you will be doing).
- Details of what notes, recordings and other sources of information may be used as 'data' in the study - for the group and with you as an individual.
- Information about how this data will be secured and stored.
- How the information will be used in the thesis and for other purposes such as conference presentations or publication.

The purpose of the study

This research is for my thesis in the Department of Educational Research at Lancaster University, and may also be used for journal articles and conference presentations. My research aims to characterise the different objectives that EPFL students have for their time in class, and what strategies they employ in order to meet this objectives.

By participating in this study, I hope you will benefit from a greater understanding of the learning strategies you use in-class and that it will help you ensure that they are best adapted to the type of learning you seek.

What does it mean to participate in the study?

Why have you been invited?

You responded to a notice posted on EPFL campus seeking participants for this study.

Do you have to take part?

No, it is up to you to decide whether to take part or not. Even if you decide to take part, you can withdraw, without giving a reason, up until August 20th 2018. In withdrawing, all information you provided will be removed from the study and destroyed.

What would taking part involve?

If you agree to participate, you would be interviewed (about 45 minutes) about your objectives for the different classes you are currently taking and what you do during class to best meet these objectives. All data collected will be anonymised under a pseudonym of your choosing, with only your section and year of study noted (i.e. SMA, Ba3). All information gathered will be encrypted and treated as confidential. Siara Isaac will conduct all the interviews, which will also be audio recorded to allow for her to review the conversation. The first interview would take place in the spring of 2015.

How will your data and identity be kept private?

'Data' here means the researcher's notes, survey results, audio recordings and any email exchanges we may have had. The data may be kept for one year after the successful completion of the PhD *Viva* as per Lancaster University requirements, and after any personal data will be destroyed. Audio recordings will be transferred and stored on my personal laptop and deleted from portable media. Identifiable data (including recordings of your voice) on my personal laptop will be encrypted. With devices such as portable recorders where this is not possible identifiable data will be deleted as quickly as possible. In the mean time I will ensure the portable device will be kept safely until the data is deleted.

You can request to listen to the audio at the end of the interview and any parts you are unhappy with will be deleted, or disregarded from the data. Data may be used in the reporting of the research (in the thesis and then potentially in any papers or conference presentations). Please note that if your data is used, it will not identify you in any way or means.

The pseudonym you chose will protect your identity in the research report and any identifying information about you will be removed from the report.

You have the right to request this data is destroyed at any time during the study as well as having full protection via the UK Data Protection Act. The completion of this study is estimated to be by January 2019.

Who to contact for further information or with ***any*** concerns?

If you would like further information on this project, the programme within which the research is being conducted or have any concerns about the project, participation or my conduct as a researcher please contact:

Professor Paul Ashwin – Head of Department
Tel: +44 (0)1524 594443
Email: p.ashwin@lancaster.ac.uk
Room: County South, D32, Lancaster University, Lancaster, LA1 4YD, UK.

Thank you for reading this information sheet.

Siara ISAAC
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Lancaster University

Participant Consent Form

Project: Epistemological Development and Classroom Learning Strategies in Engineering Students (pilot interview)

Date:____________ **Please initial box**

1. I confirm that I have read and understand the information sheet dated XXXX for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw up until August 20th, 2018, without giving any reason. ☐
3. I understand that any information given by me may be used in future reports, articles or presentations by the researcher. ☐
4. I understand that my name will not appear in any reports, articles or presentations. ☐
5. I agree to take part in the above study. ☐

____________	____________	____________
Name of Participant	Date	Signature
____________	____________	____________
Researcher	Date	Signature

Researcher: Ms. Siara Isaac, Teaching Support Centre
Tel: +41 21 69 35289
BI B2 432, Ecole Polytechnique Fédérale de Lausanne, Switzerland CH-1015
Email: siara.isaac@epfl.ch

If you would like further information on this project, the programme within which the research is being conducted or have any concerns about the project, participation or my conduct as a researcher please contact:

Supervisor: Professor Paul Ashwin, head of department, Educational Research
Tel: +44 (0)1524 594443
Email: p.ashwin@lancaster.ac.uk

Participant Information Sheet

Project: Epistemological Development and Classroom Learning Strategies in Engineering Students (interviews)

Researcher: Ms. Siara Isaac, Teaching Support Centre
Tel: +41 21 69 35289
BI B2 432, Ecole Polytechnique Fédérale de Lausanne, Switzerland CH-1015
Email: siara.isaac@epfl.ch

Supervisor: Professor Paul Ashwin, head of department, Educational Research
Tel: +44 (0)1524 594443
Email: p.ashwin@lancaster.ac.uk
Room: County South, D32, Lancaster University, Lancaster, LA1 4YD, UK.

Dear ________________________________, ***Date:_____________,***

I would like to invite you to take part in my thesis research in the Department of Educational Research at Lancaster University. This study has been approved by the University's Research Ethics Committee.

Before you decide if you wish to take part you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully. Please ask if there is anything that is not clear or if you would like more information. Talk to others about the study if you wish. Take time to decide whether or not you wish to take part. This information page is yours to keep.

This document includes:

- Information about the purpose of the study.
- Information about what participation means and how to withdraw.
- Details of what sources of information will be used as 'data' in the study.
- Information about how this data will be secured and stored.
- How the information will be used in the thesis and for other purposes such as conference presentations or publication.

The purpose of the study

This research is for my thesis in the Department of Educational Research at Lancaster University, and may also be used for journal articles and conference presentations. My research aims to characterise the different objectives that EPFL students have for their time in class, and what strategies they employ in order to meet this objectives.

By participating in this study, I hope you will benefit from a greater understanding of the learning strategies you use in-class and that it will help you ensure that they are best adapted to the type of learning you seek.

What does it mean to participate in the study?

Why have you been invited? You have been invited because you indicated that you would be willing to be interviewed when responding to the questionnaire about in-class objectives.

Do you have to take part? No, it is up to you to decide whether to take part or not. Even if you decide to take part, you can withdraw, without giving a reason, up until August 20th 2015. In withdrawing, all information you provided will be removed from the study and destroyed.

What would taking part involve? If you agree to participate, you would be interviewed 3 times (about 45 minutes each) over the next 2 years about your objectives for the different classes you are currently taking and what you do during class to best meet these objectives. Siara Isaac will conduct all the interviews, which will also be audio recorded to allow for her to review the conversation. The first interview would take place in the spring-summer of 2015.

How will my data be used? Data' here means the researcher's notes, survey results, audio recordings and any email exchanges we may have had. Data may be used in the reporting of the research (in the thesis and then potentially in papers or conference presentations), including direct quotes from the interview. Please note that if your data is used, it will not identify you in any way or means. You can request to listen to the audio in the 3 weeks following the interview and any parts you are unhappy with will be deleted, or disregarded from the data.

How will your data and identity be kept private?

All data collected will be anonymised under a pseudonym of your choosing, with only your section and year of study noted (i.e. SMA, Ba3). All information gathered will be encrypted and treated as confidential. 'Per Lancaster University requirements, the data will be kept for 10 years before being completely destroyed. Audio recordings will be transferred and stored on my personal laptop and deleted from portable media. Identifiable data (including recordings of your voice) on my personal laptop will be encrypted. With devices such as portable recorders where this is not possible identifiable data will be deleted as quickly as possible. I will ensure the portable device will be kept in locked location until the data is deleted.

The pseudonym you chose will help protect your identity in the research report and any identifying information about you will be removed from the report.

You have the right to request this data is destroyed at any time during the study as well as having full protection via the UK Data Protection Act. The completion of this study is estimated to be by January 2019.

Who to contact for further information or with <u>*any*</u> concerns?

If you would like further information on this project, the programme within which the research is being conducted or have any concerns about the project, participation or my conduct as a researcher please contact:

Professor Paul Ashwin – Head of Department
Tel: +44 (0)1524 594443 Email: p.ashwin@lancaster.ac.uk
Room: County South, D32, Lancaster University, Lancaster, LA1 4YD, UK.

Thank you for reading this information sheet.

Siara ISAAC
Teaching Support Centre, Ecole Polytechnique Fédérale de Lausanne
+41 21 69 35289
siara.isaac@epfl.ch

Lancaster University

Participant Consent Form

Project: Epistemological Development and Classroom Learning Strategies in Engineering Students (interviews)

Date:____________ **Please initial box**

1. I confirm that I have read and understand the information sheet dated XXXX for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
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Name of Participant	Date	Signature
____________________	________________	____________________
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Researcher: Ms. Siara Isaac, Teaching Support Centre
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APPENDIX B

QUESTIONNAIRES, as distributed in 2015, 2016, and 2017

Epistémologie et activités pendant les cours

novembre 2015

Cette enquête explore comment les étudiants d'EPFL abordent leurs études et leurs actions pendant les cours, dans le cadre du projet doctoral de Ms. Siara Isaac avec Dr. Ashwin, Lancaster University, UK.
Pour plus d'information, veuillez consulter la page jaune ci-joint.

Il vous prendra 8 minutes pour répondre

UN GROS MERCI POUR VOTRE ASSISTANCE !

******dans le cadre de vos études***

PARTIE 1: D'accord ou pas du tout d'accord ?

		total accord	accord	ni accord ni désaccord	désaccord	total désaccord
1.	Je reconnais que quelque chose est vrai seulement quand je peux vérifier la preuve.	○	○	○	○	○
2.	Les principes en ingénierie ne peuvent pas être disputés ni modifiés.	○	○	○	○	○
3.	Les enseignants devraient se concentrer sur des faits plutôt que des théories.	○	○	○	○	○
4.	Ce qui est vrai aujourd'hui sera vrai demain.	○	○	○	○	○
5.	Interpréter les données est ma façon préférée de me décider.	○	○	○	○	○
6.	Tous les experts en ingénierie comprennent les problèmes d'ingénierie de la même façon.	○	○	○	○	○
7.	Il est ennuyeux d'écouter les enseignants qui donnent plusieurs approches sans indiquer laquelle est leur préférée.	○	○	○	○	○
8.	Même les conseils d'experts devront être mis en question.	○	○	○	○	○
9.	Mes propres observations et expériences sont les meilleures bases pour valider les connaissances.	○	○	○	○	○
10.	La plupart des problèmes d'ingénierie n'ont qu'une seule bonne réponse.	○	○	○	○	○
11.	Quand j'étudie, je cherche les faits exacts.	○	○	○	○	○
12.	Former vos propres idées est plus important que d'apprendre ce que les manuels disent.	○	○	○	○	○
13.	Le vérifier auprès d'un expert est le seul moyen de valider mon raisonnement.	○	○	○	○	○
14.	Le savoir d'ingénierie devrait être accepté comme une vérité incontestable.	○	○	○	○	○
15.	Il est difficile d'apprendre à partir d'un manuel à moins que vous commenciez au début et maîtrisez un chapitre à la fois	○	○	○	○	○
16.	J'aime réfléchir à des questions sur lesquelles les experts ne peuvent pas se mettre d'accord.	○	○	○	○	○
17.	Il y a de la place pour des opinions personnelles dans la définition des concepts fondamentaux d'ingénierie.	○	○	○	○	○
18.	Il y a une méthode universelle en ingénierie.	○	○	○	○	○
19.	Le savoir en ingénierie est une accumulation de faits.	○	○	○	○	○
20.	La partie la plus importante du travail scientifique est l'originalité de la pensée.	○	○	○	○	○
21.	Lors de l'attribution des subventions de l'état pour la science, il faut prendre en compte les croyances des gens.	○	○	○	○	○
22.	Si vous lisez quelque chose dans un livre d'ingénierie, vous pouvez être sûr que c'est vrai.	○	○	○	○	○
23.	Il existe une division nette entre les disciplines scientifique, comme la biologie et la physique.	○	○	○	○	○
24.	La seule chose qui est certaine est l'incertitude.	○	○	○	○	○
25.	Les opinions personnelles doivent être prises en compte lors de l'interprétation des données.	○	○	○	○	○
26.	C'est la responsabilité des enseignants de s'assurer que les étudiants ont la vérité objective.	○	○	○	○	○
27.	Devenir expert en ingénierie est un processus sans fin.	○	○	○	○	○
28.	Les bonnes solutions dans le domaine de l'ingénierie sont plus une question d'opinion que de faits.	○	○	○	○	○
29.	Il est de mon droit d'accepter ou de rejeter les théories d'ingénierie.	○	○	○	○	○
30.	Pour approfondir ma compréhension de nouveaux concepts, il faut que je revisite les concepts que j'ai déjà appris.	○	○	○	○	○
31.	Une théorie en ingénierie est acceptée comme correcte si des ingénieurs experts parviennent à un consensus.	○	○	○	○	○

	total accord	accord	ni accord ni désaccord	désaccord	total désaccord
32. Avec suffisamment de données, la bonne réponse émergera.	◯	◯	◯	◯	◯
33. Les relations entre les concepts/lois sont aussi importantes que les concepts eux-mêmes.	◯	◯	◯	◯	◯
34. Les connaissances d'ingénierie peuvent être construites à partir des observations d'un étudiant.	◯	◯	◯	◯	◯
35. L'expérience directe est la meilleure façon de savoir quelque chose.	◯	◯	◯	◯	◯
36. Seuls les experts peuvent contribuer à la connaissance de l'ingénierie.	◯	◯	◯	◯	◯
37. Je suis plus enclin à accepter les idées de quelqu'un avec de l'expérience directe que celles des chercheurs.	◯	◯	◯	◯	◯

****** dans le cadre du cours qui vous intéresse le plus ce semestre***

PARTIE 2: Toujours ou jamais?

	toujours	souvent	parfois	rarement	jamais
1. Je trouve qu'il est utile de faire des exercices, même si aucune solution est fournie.	◯	◯	◯	◯	◯
2. J'aime le défi des exercices qui ont plusieurs solutions possibles.	◯	◯	◯	◯	◯
3. Pendant le cours, je suis attentive/attentif à l'idée principale et ne m'inquiète pas trop pour les détails.	◯	◯	◯	◯	◯
4. Je dois faire des exercices pour tester ma compréhension d'un cours.	◯	◯	◯	◯	◯
5. Je peux apprendre beaucoup de mes collègues.	◯	◯	◯	◯	◯
6. Quand je peux décrire un concept avec mes propres mots, je sais que je l'ai compris.	◯	◯	◯	◯	◯
7. Etre présent en cours et identifier les idées principales est généralement suffisant.	◯	◯	◯	◯	◯
8. J'ai uniquement confiance aux paroles de mon enseignant.	◯	◯	◯	◯	◯
9. Être en mesure d'expliquer à un collègue est un bon moyen de vérifier ma compréhension.	◯	◯	◯	◯	◯
10. Je fais en sorte que je comprenne les étapes, la logique de la présentation, afin d'être en mesure de le faire moi-même.	◯	◯	◯	◯	◯
11. Quand je peux suivre tout le discours donné par l'enseignant, je pense que je l'ai compris.	◯	◯	◯	◯	◯

PARTIE 3: A quoi la priorité ?

A quoi un excellent enseignant doit-il donner la priorité ?

- ◯ fournir des informations complètes et claires
- ◯ montrer aux étudiants comment résoudre les exercices
- ◯ démontrer la pertinence et les connexions entre les différents aspects de la matière
- ◯ stimuler les étudiants à aborder les champs nouveaux et difficiles.
- ◯ stimuler les étudiants à explorer des problèmes complexes et sans réponses claires

A quoi un excellent étudiant doit-il donner la priorité ?

- ◯ être attentif et prendre des notes complètes
- ◯ résolution des exercices
- ◯ application des concepts dans de nouveaux contextes, tels que les projets
- ◯ développement de ses propres idées

PARTIE 4: Veuillez nous donner un peu plus d'information…

1. **Votre section :**

ENAC				SB		STI				IC		SV	CDM	Autre
AR	GC	SIE	CGC	MA	PH	EL	ME	MT	MX	IN	SC			
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

2. **Année :**

B1	B2	B3	M1	M2	Autre
◯	◯	◯	◯	◯	◯

3. **Age :**

<18	18-19	20-21	22-23	24-25	26-27	28+
◯	◯	◯	◯	◯	◯	◯

4. **Etudes avant EPFL :**

Swiss	France	Autre
◯	◯	◯

5. **Sexe :**

Female	Male	Autre
◯	◯	◯

PARTIE 5: Avez-vous des commentaires ou suggestions ?

Epistemology and in-class activities

May 2016

This survey explores how students approach their studies and their actions during classes. It is part of the doctoral project of Ms. Siara Isaac, supervised by Dr. Ashwin, Lancaster University, UK.

For more information, please consult the yellow (French) or pink (English) page.

It takes 8 minutes to respond

A HUGE THANK YOU YOR YOUR HELP!

******in the context of your studies***

PART 1: agree or disagree

		totally agree	agree	neutral	disagree	totally disagree
1.	There is space for personal opinion in how fundamental engineering concepts are defined.	○	○	○	○	○
2.	What is true today will be true tomorrow.	○	○	○	○	○
3.	There are clear boundaries between scientific disciplines, such as biology and physics.	○	○	○	○	○
4.	It's ok for an engineer not to know the answer if they have ideas about how to find one.	○	○	○	○	○
5.	Personal opinions must be taken into account when interpreting data.	○	○	○	○	○
6.	Principles in engineering cannot be argued or changed.	○	○	○	○	○
7.	First-hand experience is the best way to know something.	○	○	○	○	○
8.	Even advice from experts should be questioned.	○	○	○	○	○
9.	Engineering knowledge should be accepted as an unquestionable truth.	○	○	○	○	○
10.	Learning a new concept often changes how I understand what I already know.	○	○	○	○	○
11.	It is rare to learn something without a teacher.	○	○	○	○	○
12.	Correct solutions in the field of engineering are more a matter of opinion than fact.	○	○	○	○	○
13.	If you read something in a book for engineering, you can be sure it is true.	○	○	○	○	○
14.	I am more likely to accept the ideas of someone with first-hand experience than the ideas of researchers.	○	○	○	○	○
15.	Checking with an expert is the only way to validate my reasoning.	○	○	○	○	○
16.	New discoveries have caused major changes in our understanding of the physical world.	○	○	○	○	○
17.	It is the professors' responsibility to ensure students have the objective truth.	○	○	○	○	○
18.	I look forward to contributing to engineering knowledge myself.	○	○	○	○	○
19.	When awarding government funding for science, people's personal beliefs should be taken into account.	○	○	○	○	○
20.	Significant changes in fundamental engineering knowledge are still possible.	○	○	○	○	○
21.	Instructors should focus on facts instead of theories.	○	○	○	○	○
22.	I don't like to accept an expert's opinion unless I can work out the logic myself.	○	○	○	○	○
23.	The key to being an expert engineer is a comprehensive mental list of useful principles.	○	○	○	○	○
24.	I like to compare my ideas with the professor's ideas.	○	○	○	○	○
25.	I am more confident when I check my answer logically than when I ask a teacher.	○	○	○	○	○
26.	A significant part of learning engineering is building a list of important principles.	○	○	○	○	○
27.	The best engineers have assimilated the maximum amount of engineering knowledge.	○	○	○	○	○
28.	Decisions about awarding research funding should value expert interpretation over public opinion.	○	○	○	○	○

****** in the context of your favourite course this semester***

PART 2: always or never

		always	often	sometimes	rarely	never
1.	I learn most from exercises with a single clear answer.	○	○	○	○	○
2.	Comparing my answers with a peer is a good check of my understanding.	○	○	○	○	○
3.	Being present in class and picking up the main facts is usually enough.	○	○	○	○	○
4.	I enjoy the challenge of open-ended problems with several possible solutions.	○	○	○	○	○
5.	I find it useful to do exercises even if no solution is provided.	○	○	○	○	○
6.	I listen for how the professor thinks, how s/he approaches the material as an expert.	○	○	○	○	○

****** in the context of your favourite course this semester***

PART 2: always or never

	always	often	sometimes	rarely	never
7. I learn a lot from my peers.	○	○	○	○	○
8. I need to do exercises in order to test my understanding of a lecture.	○	○	○	○	○
9. I listen for why the professor has chosen this material and how it is relevant to my studies.	○	○	○	○	○
10. Following the solution is just a faster way to learn than having to solve the exercise myself.	○	○	○	○	○
11. When I can describe a concept in my own words, then I know that I have understood.	○	○	○	○	○
12. I feel class is less valuable when the professor lectures the whole time.	○	○	○	○	○
13. Getting the correct answer is more important than understanding each step of a solution.	○	○	○	○	○
14. I check my understanding by explaining to a peer.	○	○	○	○	○
15. I listen to build a picture of how the different aspects of the course relate to each other.	○	○	○	○	○
16. I appreciate when the professor ask me my opinion.	○	○	○	○	○
17. Memorising the exact formulation of the definition is the best way to be sure of understanding.	○	○	○	○	○
18. My favourite classes require me to develop my own ideas.	○	○	○	○	○

PART 3:

What is the **one** characteristic which marks out a really good professor?

- ○ providing complete, clear information
- ○ showing students how to solve problems
- ○ demonstrating the relevance and connections between different aspects of the material
- ○ challenging students to explore difficult, novel areas
- ○ challenging students to explore unclear, open-ended problems

What is the **one** characteristic which marks out a really good student?

- ○ being attentive and taking complete notes
- ○ being able to solve all the exercises
- ○ applying the concepts in novel contexts, such as projects
- ○ developing their own ideas

PART 4: Please tell us a little about yourself …

1. **Your section:**

ENAC				SB		STI				IC		SV	CDM	Other	UNIL
AR	GC	SIE	CGC	MA	PH	EL	ME	MT	MX	IN	SC				géology
○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

2. **Year:**

B1	B2	B3	M1	M2	Other
○	○	○	○	○	○

3. **Age:**

<18	18-19	20-21	22-23	24-25	26-27	28+
○	○	○	○	○	○	○

4. Studies before EPFL:

Swiss	France	Other
○	○	○

5. Sex:

Female	Male	Other
○	○	○

PART 5: Comments or suggestions ?

Engineering Epistemology

Sept 2017

This survey explores how EPFL students approach their studies. It is part of the doctoral project of Ms. Siara Isaac, supervised by Dr. Ashwin, Lancaster University, UK.

For more information, please consult the yellow (French) or pink (English) page.

Please answer thinking about your <u>favourite engineering/science course</u> this semester.

Course name/discipline : ______ ie. Chemical engineering design, hydrology…

		always	often	sometimes	rarely	never	does not apply
1.	Getting the correct answer is more important than understanding each step of a solution.	○	○	○	○	○	○
2.	I listen to build a picture of how the different aspects of the course relate to each other.	○	○	○	○	○	○
3.	I appreciate when the professor ask me my opinion.	○	○	○	○	○	○
4.	Memorising the exact formulation of a definition is the best way to be sure of understanding.	○	○	○	○	○	○
5.	It's ok not to know the answer if I have ideas about how to figure one out.	○	○	○	○	○	○
6.	Principles in this area of engineering cannot be argued or changed.	○	○	○	○	○	○
7.	Even advice from experts in this field should be questioned.	○	○	○	○	○	○
8.	Engineering knowledge in this field should be accepted as an unquestionable truth.	○	○	○	○	○	○
9.	Asking my teacher is the only way to check my reasoning.	○	○	○	○	○	○
10.	I listen for how the professor thinks, how s/he approaches the material as an expert.	○	○	○	○	○	○
11.	Expertise in this field is about making well-informed decisions.	○	○	○	○	○	○
12.	Problems with several possible solutions are useful for my learning.	○	○	○	○	○	○
13.	This class encourages me to develop my ideas.	○	○	○	○	○	○
14.	I learn most from exercises with a single clear answer.	○	○	○	○	○	○
15.	I find it useful to do exercises even if no solution is provided.	○	○	○	○	○	○
16.	I don't like to accept the teacher's answer unless I can understand the logic myself.	○	○	○	○	○	○
17.	I listen for why the professor has chosen this material and how it is relevant to my studies.	○	○	○	○	○	○
18.	Following the solution is just a faster way to learn than having to solve the exercise myself.	○	○	○	○	○	○

19. ***How frequently can you use each method to check your answers in this course/discipline?***

	always	often	sometimes	rarely	never		always	often	sometimes	rarely	never
Approximations or estimates	○	○	○	○	○	Reviewing the mathematical steps	○	○	○	○	○
Imagining extreme or limiting cases	○	○	○	○	○	Asking a teacher or expert	○	○	○	○	○
Thinking of a real world example or application	○	○	○	○	○	Verifying that order of magnitude is reasonable	○	○	○	○	○
Using the solutions provided by the instructor.	○	○	○	○	○	Using units during a calculation to see if you are on the right track.	○	○	○	○	○
Performing a physical experiment or observation	○	○	○	○	○	Asking a peer	○	○	○	○	○
Reviewing the concepts or logic of the thinking behind your answer	○	○	○	○	○	Checking the units of the final answer.	○	○	○	○	○

20. What is the <u>**one**</u> characteristic which marks out a really good **professor**?

- ○ Providing complete, clear information.
- ○ Showing students how to solve problems.
- ○ Demonstrating the relevance and connections between different aspects of the material.
- ○ Challenging students to explore difficult, novel areas.
- ○ Challenging students to explore problems that may not have a clear solution.
- ○ ______________________ *add your own option*

21. What is the <u>**one**</u> characteristic which marks out a really good **student**?

- ○ Being attentive and taking complete notes.
- ○ Being able to solve all the exercises.
- ○ Applying the concepts in novel contexts, such as projects.
- ○ Developing their own ideas.
- ○ ______________________ *add your own option*

Please turn over

22. What is the **one** characteristic that marks out a really good **engineer**?

- ◯ Knowing all the concepts and rules of the discipline by heart.
- ◯ Applying the concepts to the problem at hand.
- ◯ Deciding on the optimal solution by assigning priorities to multiple technical requirements
- ◯ Finding a compromise between disciplinary knowledge and real world constraints.
- ◯ Generating a novel approach or technique for the problem at hand.
- ◯ ____ *add your own option*

Please tell us a little about yourself …

23. **Your section:**	ENAC			SB			STI				IC		SV	CDM	Other
	AR	GC	SIE	CGC	MA	PH	EL	ME	MT	MX	IN	SC			
	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

24. **Year:**	B1	B2	B3	M1	M2	Other
	◯	◯	◯	◯	◯	◯

25. **Age:**	<18	18-19	20-21	22-23	24-25	26-27	28+
	◯	◯	◯	◯	◯	◯	◯

26. **Studies before EPFL:**	Swiss	France	Other
	◯	◯	◯

27. **Genre:**	Female	Male	Other
	◯	◯	◯

28. **Stage:** If you have done a stage(s) or worked in a science or engineering field, how long in total? ☐ months

29. **Projects:**

	0	1-2	3-6	7-11	12+
How many projects >2 weeks have you completed during your university studies?	◯	◯	◯	◯	◯
How many of these required you to propose a novel approach or design a product?	◯	◯	◯	◯	◯

30. Comments or suggestions ?

APPENDIX C

THINK-ALOUD TASKS, 2017 and 2018

Note: Exercises were provided in French or English, depending on the choice of the student.

Warm Up Task

If the reaction shown below produces B at a rate of $8 \cdot 10^{-2}$ mol/s, how long will it take to consume 10g of A?

$$2A \quad \rightarrow \quad B$$

Molecular mass	
A	46.08 g/mol
B	92.16 g/mol

Task 1 2016

The food preservative XO_3 is synthesised by the reaction 1, presented below. The speed of the reaction is expressed in terms of the change in concentration of XO_3.

Reaction 1: $XO_4 \; + \; \mathrm{Y} \longrightarrow XO_3 \; + \; YO \qquad \frac{\Delta[XO_3]}{\Delta t} = 8\,\frac{mol}{L \cdot s}$

A second undesirable product, Y_2XO, is formed by reaction 2, shown below. The speed of the reaction is expressed in terms of the change in concentration of Y_2XO.

Reaction 2: $XO_3 \; + \; 2\mathrm{Y} \longrightarrow Y_2XO \; + \frac{1}{2}O_2 \qquad \frac{\Delta[Y_2\mathrm{XO}]}{\Delta t} = 0.3\,\frac{mol}{L \cdot s}$

In order to determine the optimal reaction condition, an industrial synthesis of XO_3 is performed at 40 ° C with 10 kg of XO_4 and 3 kg of Y in 10 L of solvent. Calculate the concentration of XO_3 at t = 0,5 seconds.

Molecular mass	
XO_3	80.4 g/mol
XO_4	96.2 g/mol
Y	31.6 g/mol
YO	47.3 g/mol
O_2	32.0 g/mol
Y_2XO	110.8 g/mol

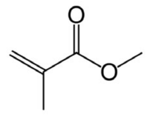
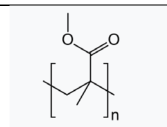
Task 2 2016

a. Is humid air more or less dense than dry air ? Show your reasoning.

b. In winter, water vapour in the air condenses into the solid state (ice) on car windsheilds, for example. Do you anticipate that this process consumes (endothermic) or releases (exothermic) energy? Justify your response in two ways.

Task 3 2016

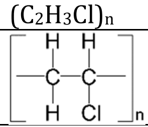
A dentist mixes 2,0 ml of methylmethacrylate with 4,0 g of polymethylmethacrylate beads and induces a polymerisation reaction with UV light. What is the expected change in temperature, assuming complete conversion of the methylmethacrylate?

	methylmethacrylate MMA	polymethylmethacrylate PMMA
Formula	$CH_2=C(CH_3)COOCH_3$	$[CH_2C(CH_3)(COOCH_3)]_n$ n = 5-6000
Structure		
Molecular mass	100.1 g/mol	510 – 550 x 10^3 g/mol
Density	0.945 g/cm^3	1.19 g/cm^3
Heat capacity	1.911 kJ/g•C	1.370 kJ/g•C
$\Delta H_{polymerisation}$	-54.3 x 10^3 J/mol	

$$MMA \xrightarrow[UV]{} PMMA$$

Task 1 2017-2018

The polymerisation process for the injection moulding of plastic components generates 1530 J of heat per g of PVC produced. The Hochelega injection moulding system weighs 17 kg and has a heat capacity of 2.17 kJ/(kg·K). If the temperature must be kept below 45°C, what is the maximum weight component (in g) that can be made if the starting temperature is 25°C?

Polyvinyl chloride PVC	
Formula	$(C_2H_3Cl)_n$
Structure	 n = 45-60000
Molecular mass	100 – 200 x 10^3 g/mol
Density	1.3 g/cm^3
$\Delta H_{polymerisation}$	1530 J/g

Task 2 2017-2018

A chemical explosion releases microscopic ash particles with an initial velocity of 17 m/s. What is the farthest distance this debris will travel from the explosion site, assuming the explosion occurred on a large flat surface?

Ash particles	
Composition	CaCO3; MgCO3; K2CO3; SiO_2 ; Al_2O_3 ; CaO ; Fe_2O_3
Average size	90 μm
Average density	0.561 g/cm^3

Task 3 2017-2018

How far does a car travel before a one-molecule layer of rubber is worn off the tires?