Process, Precedent, and Community: New Learning Environments for Engineering Design

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Declaration

I declare that this thesis has not been submitted as an exercise for a degree at this or any other university and it is entirely my own work.

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Abstract

Project-based design courses are an increasingly common component of engineering education. Most engineering schools have traditionally emphasized the analytical and scientific aspects of the discipline, and an increase in practical and experiential learning represents a transformation of established approaches to teaching in these institutions. However, there are significant challenges to developing and delivering these courses. Minimal guidance is available to educators who face these challenges. In particular, there is a paucity of research aligning learning objectives with pedagogical theories and practical guidelines.

This thesis makes a contribution to both research and practice in engineering design education. A pedagogical framework for a particular type of project-based engineering design course is developed. The framework is intended to guide the development and evaluation of learning environments for these courses. It consists of learning objectives in the form of essential design knowledge, learning theories that align with each of these objectives, and practical guidelines for course design.

The pedagogical framework is initially developed through a review of previous research on design cognition and of learning theories from the fields of educational psychology and social anthropology. The framework is subsequently used in three phases of participant observer research in project-based design courses at two universities. During each phase of research, the framework is used to guide the interpretation of results, and the results are in turn used to expand the framework to include guidelines for the development and improvement of learning environments. The expanded framework provides guidance in improving subsequent course iterations. Thus, the learning environments and the pedagogical framework evolve in parallel throughout the research.

The thesis highlights fundamental obstacles to learning in the project-based engineering design courses studied, including challenges in providing structure for students while supporting flexible exploration of potential designs, and a lack of both social and documentary sources of detail design knowledge for mechanical engineering. Approaches to overcoming these obstacles are identified and demonstrated through implementation in the observed courses. The development and testing of new resources to support teaching and learning are described.

The results presented in this thesis contribute to an improved understanding of engineering design education. The pedagogical framework addresses the unmet needs of educators while providing a foundation for future research in these novel but increasingly common educational contexts, which until now have remained largely unexplored.

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Chapter 1

Introduction

The objective of this thesis is to contribute to the theory and practice of engineering design education. Design is generally considered a central activity of engineering. However, for much of the 20th Century it was an underemphasized aspect of engineering education. The dominant view in most engineering schools was that the analytical, scientific aspects of the discipline were inherently superior to the creative, social activities involved in design (Blandford, 1990; Dutson et al., 1997). The business of engineering education was seen as teaching fundamental theory rather than applied, practical knowledge (Heywood, 2005). Furthermore, design was assumed to lack a rigorous, theoretical basis; even among design researchers and theorists there was a feeling that its unscientific nature was a problem that needed to be addressed (Cross, 1999). Although the role of design in engineering practice was recognized, this practice was assumed to rely primarily upon scientific and analytical knowledge which students generally lack. In this view, it was necessary to establish a theoretical foundation before engaging in practical work (Hoole, 1991). As a result, practical design experiences for students were rare.

However, there were many objections to this dominant view and the place of design in the engineering curriculum remained a topic of debate. The assumption that theory necessarily preceded practice was challenged (Warner, 1989), and a focus on solving well-defined problems with unique correct answers was highlighted as a particular shortcoming of engineering programs (Cawley, 1988). During the 1990s, arguments in favour of design experiences for students became more common. These arguments contended that design should be explicitly taught, "rather than simply teaching engineering science and hoping that the students will acquire design skills incidentally" (Blandford, 1990, p. 213). Such arguments were bolstered by industry opinions that viewed engineering graduates as ill-equipped for professional practice (e.g., King, 2007; Nicolai, 1998). In response to demands from industry, professional accreditation bodies began requiring more emphasis on design activity in undergraduate programs (Dutson et al., 1997).

As a result, new design experiences for students have been developed in recent decades. Engineering schools began introducing integrated courses that sought to connect engineering theory and practice by giving students the opportunity to work on "real-world" problems (e.g., Amon et al., 1996; Sutton, 1995). Much of the initial work in this area focused on developing introductory and final year ("capstone") design experiences. Introductory design courses were seen as a means of exposing students to engineering practice and thereby increasing motivation, while capstone projects were intended to integrate the knowledge learned throughout the program (Dym et al., 2005). More recently, there have been efforts to provide design experiences throughout the curriculum either by adding design activities to existing courses or by developing new design-focused courses at both undergraduate and graduate level (e.g., Bucciarelli, 2003; Hanumara et al., 2013; Lande and Leifer, 2010).

Thus, engineering education is in the midst of a gradual transformation from an almost exclusive emphasis on technical and factual knowledge to a pluralist approach combining scientific and theoretical knowledge with practical and applied understanding. This is the context in which this thesis is situated. The research consists of an exploration of new design courses, with the aim of understanding and improving learning environments for engineering design.

1.1 Learning Environments for Engineering Design

Attempts to integrate design into engineering programs have adopted a variety of formats. The majority of new courses are based on experiential and project-based models of learning, in which students work either individually or in teams to complete a design project (Dym et al., 2005). The projects may be relatively well-defined or more open-ended. For example, Thompson (2002) describes a studio-based program in which all students focus on the detail design and implementation of a full-scale manned aircraft, while Hanumara et al. (2013) describe a course in which each student team collaborates with a different group of stakeholders to develop new medical device technologies. In the former, the subject matter and the related technology remains relatively stable between one year and another, while in the latter these may vary widely both within and between years. Project topics may be "made up" by faculty or may be authentic attempts to meet the needs of real stakeholders. An example of the latter is Purdue University's Engineering Projects in Community Service (EPICS) program, in which student teams engage in long-term collaborations with not-for-profit community organizations to identify and solve technology-based problems (Coyle et al., 2006).

The research presented in this thesis focuses on project-based learning environments with the following characteristics:

- **Course settings:** Design experiences may be delivered in a variety of settings, including industrial placement schemes, research internships, formal courses, or the independent projects more typical in studio-based design education. The cases studied in this thesis take place in formal classroom settings. This presents a particular set of constraints for the learning environments, such as the need to develop course structures, learning activities, and lecture content that can support a wide variety of teams.

- **Team-based:** Engineering education typically emphasizes individual learning, and one of the common requests from accreditation bodies has been an increase in team-based activities. The courses studied in the thesis involve teams of 3–8 students collaborating on design problems.

- **Open-ended:** All design problems are to some extent open-ended, in that they have no unique correct solution. However, design briefs vary in their level of specificity and there are degrees of open-endedness. In the courses studied, student teams are provided with minimal problem specifications and are expected to define their own design brief. As a result, the types of projects undertaken vary widely within and between student cohorts.

- **Authentic:** Learning activities in general are often seen as inauthentic and disconnected from "real-world" activities (e.g. Brown and Campione, 1994). In the courses considered here, efforts are made to expose the students to real problems involving real stakeholders with whom the students must interact. In most of the courses there is an implied assumption that successful projects may eventually be implemented beyond the classroom.

Thus, the research is conducted in open-ended, authentic, team- and project-based engineering design courses. For brevity, these will hereafter be referred to as OATPB courses. While this may seem overspecified, it is important to differentiate between the varieties of approaches to design education. OATPB courses are increasingly common in engineering education, and in both institutions studied were among the most recent additions to the curriculum. The observed courses took place in mechanical engineering departments and primarily involved mechanical design projects but, due to their open-ended nature, also involved projects with an electronic or software focus.

1.2 Motivation

There are a number of significant challenges that must be overcome as part of the ongoing transformation of engineering education. The development and delivery of project-based design courses is a demanding task for educators. Many engineering faculty members have neither experience in teaching such courses, nor experience in taking them as students. Furthermore, most engineering academics' practice consists primarily of scientific, analytical research conducted with the primary aim of publishing technical articles. Structures for evaluating and promoting faculty tend to emphasize these types of research activities over more design-oriented ones (Todd and Magleby, 2004). As a result, most faculty members are not practicing design engineers.

However, even academics who have significant design experience are not necessarily well-suited to teaching the subject. Design ability relies to a large extent upon procedural knowledge, or the knowledge of how to accomplish a task. Experts have typically gained a tacit and intuitive understanding of procedural knowledge, and can face difficulty making this knowledge explicit or understanding the misconceptions of novices (Bransford et al., 2000; Nathan and Petrosino, 2003). In addition to knowledge of the domain, effective teaching requires "pedagogical content knowledge." This includes an understanding of the typical difficulties that learners face and potential strategies for helping students to overcome these difficulties. This knowledge is not a combination of general teaching strategies with a particular subject matter; the strategies are domain-specific (Shulman, 1987). Pedagogical content knowledge is developed through experience teaching a particular subject. It follows that for new courses identifying and developing this knowledge is a challenge.

A potential source of pedagogical content knowledge is the literature on design education. A substantial number of publications and conferences dedicated to engineering education exist, and articles related to design teaching and learning are common. The majority of these articles describe particular courses or learning activities, and may serve as useful sources of information on teaching methods for design educators. However, these articles often contain no evaluation of the methods presented and rarely make reference to results from design or education research (Martin et al., 2002; Turns et al., 2006). They are primarily accounts of teaching practice written by and for practitioners, rather than the results of research.

This is not to deny the value of practice-focused knowledge sharing. In fact, this thesis draws primarily on an interpretivist research paradigm, which holds that the reflective accounts of experienced practitioners are a valid and valuable form of research (Willis, 2007). However, it is problematic when this work is disconnected from theoretical underpinnings. Among educational researchers, "fidelity of implementation" is recognized as a major issue

(Palincsar, 2005). Transporting an educational method from one context to another often results in essential features being lost due to a focus on surface features rather than underlying principles (Brown and Campione, 1994). Furthermore, descriptions of a wide variety of teaching methods and activities with little, if any, evaluation are not particularly informative for educators. In some ways not much has changed since Cross (1980) reviewed design literature for schoolteachers and observed that "the collective impression given by these publications is one of confusion."

Attempts have been made to provide a general framework to guide the development and evaluation of engineering design education. These efforts are best represented by the Conceive-Design-Implement-Operate (CDIO) initiative. The CDIO syllabus is intended to support curriculum development at the program level and consists of a comprehensive list of curricular goals, framed as tasks that graduating engineers should be able to complete (Crawley et al., 2011). It was developed through focus group interviews with faculty, students, and industry leaders (Crawley, 2002). The syllabus provides guidance for distributing learning activities throughout engineering programs. However, it is by necessity a high-level overview; there is no guidance on what each particular goal (such as "the [design] process for single, platform and derivative products") consists of or how it might be taught. To address this gap, CDIO organizes regular conferences and meetings at which engineering educators share details of their teaching methods (e.g. Hussman, 2011). However, these events suffer from the shortcomings discussed above, in particular a lack of theoretical foundations and links to design research.

A fundamental disconnect between design research and design education has been identified as the source of issues and challenges in teaching design (Bucciarelli, 2003; Devon et al., 2004). Thus, attempts to support design educators have often focused on addressing this disconnect. Typically, these efforts involve synthesizing results from research on design studies with the aim of providing guidance on how designers think and work (e.g. Adams et al., 2003; Cross, 2001a; Eastman et al., 2001; Turns et al., 2006). However, guidelines on interpreting or applying these results for design education are typically minimal or unrealistic. For example, Turns et al. (2006, p. 382) propose that "an instructor could have students complete a variation of a task used in a research experiment, analyse the students' data in class, compare the results to the published research results, and discuss implications." However, the experiments to which Turns et al. refer consist of in-depth analyses of audio recordings

Table 1.1: An excerpt from the Informed Design Teaching and Learning Matrix (reproduced from Crismond and Adams, 2012)

Design Strategies	Beginning vs. Informed Designer Patterns		Learning Goals Where Students...	Teaching Strategies Where Students...
	What Beginning Designers Do	What Informed Designers Do		
Understand the Challenge	Pattern A. Problem Solving vs. Problem Framing		Define criteria and constraints of challenge. Delay decisions until critical elements of challenge are grasped.	State criteria and constraints from design brief in one's own words; Describe how preferred design solution should function and behave; Reframe understanding of problem based on investigating solutions
	Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve.	Delay making design decisions in order to explore, comprehend and frame the problem better.		

that can take many hours to interpret for a single subject. It is difficult to imagine how an instructor could produce data that could be meaningfully compared to such results in real time and for multiple students.

Crismond and Adams (2012) propose a more detailed set of guidelines for educators based on the results of design research. The Informed Design Teaching and Learning Matrix consists of nine elements of the design process, including "Generate Ideas" and "Conduct Experiments." The matrix compares the characteristic behaviours of novices engaged in each task with those of experts, and outlines learning goals and teaching strategies intended to help learners develop expert-like behaviours. Table 1.1 contains the entries for an example task.

Of the supporting tools for educators discussed in this section, Crismond and Adams's matrix is the most detailed, and the only one that provides explicit links between research results and practice. However, there are a number of shortcomings in its design. First, there are no explicit links drawn between the matrix and any pedagogical principles or learning theories. As discussed previously, this presents a risk of misapplication. Second, the focus of the matrix is solely on behaviour, and in particular on improving the behaviour of novice designers. Ironically, this results in the matrix apparently contradicting findings from the research literature. For example, Crismond and Adams suggest that students should learn that design requires "lots of ideas, and the wider the range of ideas, the better" (p. 755). This suggestion is indeed supported by psychological studies of creativity which have correlated idea quality with quantity (e.g., Paulus et al., 2011). However, such studies take a very narrow focus of creativity, and typically involve undergraduate psychology students engaged in essentially meaningless tasks. Their implications for design are questionable. Fricke (1996) compared design strategies and found that either generating a very large number of ideas or a very small number of ideas had a negative impact on the quality of the resulting design. He suggests that designers must instead follow a "balanced search." In contrast, studies of experienced mechanical engineers and architects have found that often designers do not generate any alternatives, focusing on one solution and modifying it in response to emerging problems (Rowe, 1987; Ullman et al., 1988). Clearly, the results on this topic are somewhat inconsistent.

In fact, designers' behaviour is in many ways characterized by inconsistency. This is due to the contingent, context-dependent nature of design. Rather than following a consistent approach to solving problems, designers select between a variety of strategies based on the particular details of the problem at hand. The development of a "repertoire" of strategies is therefore one of the most important parts of becoming a successful designer (Lawson, 2004). This highlights a fundamental issue with focusing on behaviour. Crismond and Adams's (2012) matrix provides a single "correct" strategy that design students should be taught to follow in all situations, thereby undermining the goal of supporting students in developing a repertoire of context-dependent strategies.

This brief review of the field of design education has demonstrated that there is a paucity of research aligning design education, design practice, and learning theories. Such an alignment would support educators in designing, evaluating, and improving learning environments. Thus, the objective of this thesis is to develop a pedagogical framework which combines results from research on design cognition and practice, learning theories from the fields of educational psychology and social anthropology, and pertinent features of learning environments identified through empirical exploration of project-based engineering design courses. The objective is not to define a rigid template or a collection of particular learning materials and activities, but rather to define a set of broad principles. By linking broad learning objectives, pedagogical principles, and practical details, the aim is to address the issues identified above, for example by supporting the acquisition of design pedagogical content knowledge. In addition to its role in supporting educators, the framework is intended to function as a theoretical foundation for design education researchers.

The CDIO syllabus focuses on high-level planning of curricular topics, but provides no details of how these topics should be taught or how course efficacy should be evaluated. The Informed Design Teaching and Learning Matrix prescribes specific activities and provides suggestions for evaluating the performance of students, however it does not provide any guidance on the context in which these activities should take place. The framework developed in this thesis targets an intermediate level between these two, by focusing on parameters that define the learning environments of project-based design courses. As discussed above, the thesis focuses on OATPB courses and the framework is therefore intended primarily for use in those contexts. However, it may provide a foundation for similar research in other educational settings.

The framework is developed initially through a review of design research and educational theories. This results in a set of learning objectives and guiding principles for OATPB courses. The framework is then used to explore the experiences of students and educators in OATPB courses at two institutions. The results of the research are in turn added to the framework to record problematic aspects of OATPB learning environments. This process is repeated in two subsequent phases of research. In each phase, modifications are made to the learning environments in an attempt to address, and to gain a deeper understanding of, the issues identified. The framework and the learning environments therefore evolve in parallel.

1.3 Research Contributions

The work presented in this thesis makes several contributions. The first contribution is the pairing of fundamental aspects of design knowledge with apposite learning theories. Four categories of essential design knowledge are identified: strategies and processes, models, knowledge reuse, and the social nature of design. For each category, learning objectives are identified and aspects of social constructivist and situated learning theories are selected as potential sources of guidance in achieving those objectives. Linking objectives to theory is intended as a means of addressing the issue of "fidelity of implementation" (Palincsar, 2005). Reference to the framework may thus act as a tool to enable more effective sharing of teaching methods between educators.

The second contribution is the identification of features of the learning environments that support the learning objectives. These features are identified through the three phases of research in OATPB courses. They constitute the third element of the framework, with each feature representing a guideline associated with a learning objective and learning theory pair. For example, the review of the design research literature identifies an objective of exposing students to a "flexible-methodical" design process, which involves following a generally methodical problem solving process but remaining flexible in deviating from this process when necessary (Fricke, 1996). The framework relates this to cognitive apprenticeship theory, which provides guidance on making processes and strategies explicit. Research in the courses identifies a teaching model which supports a flexible-methodical process: the use of regular milestones to provide a methodical, top-down, breadth-first problem solving process, and regular design review meetings to provide opportunities to guide students in deviating from this methodical process where appropriate.

The third contribution is the identification of fundamental obstacles and recurring issues in OATPB courses, in particular: the prevalence of task optimization strategies undermining both learning and design goals; the need for, and difficulty of, achieving the appropriate balance between the flexible and methodical aspects of the design process; a lack of access to detail design precedents for mechanical design; and a lack of access to engineering communities of practice. Each of these issues is explored in depth and its root causes are identified.

Task optimization strategies, which students use to focus efforts on immediate deliverables to the detriment of long-term goals, are found to be closely related to difficulties balancing the flexible and methodical aspects of the design process. Both are caused by a variety of environmental cues including: a lack of clarity about the overall course process, frequent quantitative grading of student deliverables, and a lack of explicit permission to deviate from the methodical process when appropriate. The thesis identifies two categories of design precedent, or previous examples of design work, that are required by students in OATPB courses: concept precedents, which are high-level descriptions of existing devices, and detail precedents, which provide in-depth information on particular means of implementing concepts. Insufficient access to detail design precedents is found to be closely related to a lack of access to engineering communities of practice.

The fourth contribution is a demonstration of an approach to providing a database of detail design precedent knowledge for mechanical design. Similar resources for electronic and software design are accessible to students, but the nature of mechanical design presents challenges in capturing and sharing the type of information required by novices. The process followed in this thesis involves using observations of expert-novice interactions to identify the types of knowledge being shared, collaborating with experts to document that knowledge, and conducting user tests to ensure the clarity of the documentation. The thesis also proposes a model for populating and sustaining the database, by framing it as a tool to support technology researchers in sharing knowledge and disseminating research.

Further contributions include an initial demonstration of an instrument for measuring aspects of design knowledge. The instrument is developed as a data collection tool. However, initial results indicate that the approach taken could be used to measure changes in student understanding over time, thereby providing feedback to educators so that they can adjust teaching methods or address common misconceptions.

1.4 Thesis Structure

The remainder of this thesis is structured as follows:

Chapter 2 considers paradigmatic and methodological issues in order to define the procedure followed in the thesis. A pragmatist paradigm and a design-based research methodology are selected as appropriate for use in this research. The data gathering methods, data analysis approach, and ethical issues related to research in educational settings are discussed.

Chapter 3 reviews the literature on design cognition and practice, followed by a discussion of the learning theories identified as appropriate for inclusion in the framework. An initial embodiment of the framework is presented, consisting of learning objectives for OATPB courses and related learning theories.

Chapter 4 describes an exploratory research study conducted in three OATPB courses. The experiences of students and educators are described and interpreted in terms of the knowledge types and theories that comprise the theoretical framework. The results are then used to expand the framework to record the pertinent aspects of learning environments studied.

Chapter 5 describes the second phase of research, which was carried out in two OATPB courses. The learning environments of each are modified based on the framework, and the effects of these modifications are investigated. Again, the framework is used to interpret the results, and is further expanded to account for these results.

Chapter 6 describes the development of a database of detail design precedent knowledge in order to address the problems of access identified during previous phases. The development of a collection of open-ended conceptual questions for use as a data gathering tool is also described. Both resources are pilot tested and the results are used to guide further development.

Chapter 7 describes the third and final phase of research in one OATPB course. The resources developed in the previous chapter are deployed in the course and the effects on students' activities and experiences are observed. As in previous phases, the framework is used to guide the research, and the results are used to expand the framework

Chapter 8 concludes the thesis by summarizing the research and presenting the complete version of the framework developed throughout the previous chapters. Limitations of the research and opportunities for future work are discussed.

Chapter 2

Methodology

The objective of this thesis is to develop a pedagogical framework for open-ended, authentic, team- and project-based (OATPB) engineering design courses. The previous chapter described the context in which this research takes place, in particular the increase in project-based engineering design courses and the paucity of research linking teaching practice with research in this area. This chapter discusses the methodological foundations of the research. The choice of a guiding research paradigm has implications for the type of data collected and how the results are interpreted. The chapter begins by reviewing the dominant research paradigms. Pragmatism is selected as an appropriate paradigm for the research in this thesis. Research methodologies are then discussed, and design-based research is identified as a methodological approach that aligns with the goals of this thesis. The methods used to collect and analyse data, as well as the measures taken to ensure trustworthy results, are described. The chapter concludes with a discussion of the ethical issues related to the research.

2.1 Research Paradigms

A paradigm is a set of beliefs that defines the nature of reality (ontology), knowledge (epistemology), and value (axiology). Paradigms deal with first principles: metaphysical assumptions that cannot be proven or disproven but must be accepted on faith. Research paradigms define the scope of legitimate research questions, the types of methods that may be used to answer those questions, and how data should be interpreted (Guba and Lincoln, 1994). In the natural sciences the guiding paradigm is typically implicitly clear (postpositivism). However, when studying the thoughts and behaviours of human subjects, researchers must explicitly define their paradigmatic assumptions. Doing so is essential in order to avoid contradictions in data analysis, and to assist readers in interpreting and evaluating the research (Giddings and Grant, 2006). Furthermore, the choice of paradigm is particularly important in educational research as it influences both the practice of research and the practice of teaching.

The paradigm adopted in this thesis is based on pragmatism, a school of philosophy originally developed in the United States in the late 19th Century. As a research paradigm, pragmatism draws on other philosophical traditions, and is in some respects a compromise between the major competing paradigms in social science research. This section begins by describing and comparing two such paradigms, postpositivism and interpretivism, to provide background for the subsequent discussion of pragmatism. Multiple alternative paradigms exist, including critical theory, postmodernism, feminism, and participatory inquiry, but these are often considered particular instances of interpretivism, and as such will not be discussed here.

2.1.1 Postpositivism

Postpositivism is closely related to the positivist view of science that dominated from the Enlightenment until the 20th Century. Positivism (or empiricism) emerged in response to the acceptance of religion and superstition as credible sources of truth, and positivists maintained that scientific experiments and observation were the only means of understanding the universe. Positivism was based on a correspondence theory of truth, which held that the knowledge obtained through scientific experimentation corresponded exactly with objective reality. Data was to be collected and analysed objectively, without any preconceived beliefs, and then used to develop theory (Willis, 2007). The business of science was seen as the accumulation of universal facts, with each experiment as part of a gradual progression towards a complete understanding of the world.

When the social sciences emerged as disciplines in the 19th Century, the successes of the natural sciences, in particular physics, contributed to a view that a similar scientific method should be used to explain social systems. The field of psychology, which would eventually exert a major influence on research in both design and education, placed a particular emphasis on the scientific method (Christopher et al., 2003). Objectivity and controlled experiments were seen as inherently superior to subjectivity and everyday practice. Positivist social sciences were concerned with developing rigorous approaches to data collection and analysis, separating facts from value, and discovering fundamental social laws. Inherent in this view was an acceptance of Descartes's duality of mind and body, which implied that the subjective feelings and opinions of individuals could be separated from the real, physical world (Willis, 2007, p. 43). While there were objections to positivism from within the social sciences, the most devastating critiques stemmed, ironically, from results in the natural sciences.

In the 20th Century, philosophers of science such as Karl Popper began to question the positivist paradigm, in particular the correspondence theory of truth. These critiques were in part a response to discoveries in relativity and quantum mechanics which undermined fundamental "facts" of physics that had been accepted as universal for centuries. Popper's (1937) postpositivism reframed science in terms of "falsification." Now, the business of science was to develop theory by making conjectures that they could be falsified experimentally. A theory could be disproven, but never proven definitively. Doubt could never be eliminated completely as a future experiment could disprove current theories. Kuhn (1962) further undermined positivism by demonstrating that the history of science was not in fact the gradual accumulation of facts, but was characterized by cycles of revolution (in which new worldviews displace old ones) and "normal science" (in which scientists refine the dominant worldview to explain a range of phenomena). Postpositivism acknowledges that data collection can never be free of preconceived theory, and the aim of experimentation is in fact to test and refine existing theories and worldviews.

Postpositivism has largely replaced positivism in the social sciences (Willis, 2007, p. 73). Beyond the changed view of the relationships between theory and data and between theory and reality, postpositivism retains most of the assumptions of its predecessor. All meaningful problems can and should be framed in a clear-cut, unambiguous way (Newell and Simon, 1972). Objective inquiry, based on time- and context-independent observations, and leading to the identification of universal cause and effect relationships, is both possible and desirable (Johnson and Onwuegbuzie, 2004). Quantitative data is inherently superior; while qualitative data is permissible it must be analysed in a reductive and systematic manner with an emphasis on cause and effect (Creswell, 2007). In keeping with Popper's theory-first model, specific hypotheses must be developed in advance and ideally the entire study should be planned in detail before data is collected. Elements of social activity should be isolated from their context and studied in controlled environments and subjectivity is to be avoided at all costs (Willis, 2007, p. 77). In other words, postpositivist social science continues the tradition of seeking to emulate the methods and values of the natural sciences.

2.1.2 Interpretivism

While positivism and postpositivism dominated the social sciences for most of the 20th Century, the idea that the methods and values of the natural sciences could or should be emulated has not gone unchallenged. Alternative paradigms, many of which have been grouped under the term "interpretivism" have always been a feature of the social sciences, and have become more prominent in recent decades.

A view of reality as socially constructed is core to the interpretivist paradigm. While interpretivists do not deny the existence of an objective, physical reality, they do deny the possibility of direct access to that reality. All research data has been filtered through socially constructed beliefs, theories, and languages, and can therefore not be treated as objective. Interpretivists argue that natural scientists and social scientists work in different realms, and reject the suggestion that the methods of the former are sufficient to address the research problems of the latter. Natural scientists impose meaning on an external world of matter, whereas the social world contains meaning that social scientists must interpret (Silverman, 1970). While physicists may be able to identify the cause-and-effect relationships defining the behaviour of billiard balls, social systems are "composed of a multitude of unique, idiosyncratic agents endowed with intentionality" who are self-aware and can therefore transcend supposedly deterministic laws governing their behaviour (Fendt et al., 2008).

The aim of interpretivist research is to draw on the subjective meanings already present in the social world, to accurately represent them, and to use them as building blocks in developing theory (Goldkuhl, 2012). In contrast to the positivist/postpositivist view that phenomena should be isolated from their context and that systems should be studied in terms of their constituent parts, interpretivists argue that an understanding of social systems requires a holistic view that can only be obtained in real contexts. Universal knowledge is deemphasized in favour of understanding a particular situation from the subjective viewpoints of its participants (Schutz, 1970; Weber, 1978). For interpretivists, the postpositivist belief that results from a sample may be generalised to the wider population does not account for the variety of human responses to environmental situations and assumes a deterministic view of human nature.

Where postpositivists advocate a rigorous, uniform scientific method (e.g. Carnap, 1934), interpretivists believe there is no particular correct path to knowledge. Both quantitative and qualitative data are acceptable, as are reflective analyses in which the researcher is also the subject (Willis, 2007, p. 100). Understanding the context in which research is conducted is critical to interpreting the data and evaluating the quality of research, and as such researchers should provide explicit and detailed contextual information when reporting their results. Given the interpretivist rejection of the objective methods, "trustworthiness" should be attained through explicit acknowledgement of potential biases, and through practices such as triangulation and peer review.

2.1.3 Mixed Methods Research

While debates between the two paradigms described above have tended to focus on their differences, a pluralist perspective has emerged which views the two paradigms as complementary. Mixed methods research, as the term suggests, combines quantitative, "objective" methods with qualitative, "subjective" approaches in an attempt to obtain a well-rounded understanding of the phenomena being studied. Mixed methods researchers have argued that "either-or" conceptions of research paradigms impoverish scientific inquiry, as an understanding of complex social systems requires a range of perspectives and approaches. Since there is no legitimate way of asserting with absolute confidence that one paradigm is better than another (Willis, 2007), the pluralist approach attempts to accommodate both traditions and draw on the strengths of each as appropriate to particular research settings. In seeking a middle ground, pluralist researchers seek to avoid "the arrogance of modernist empiricism [positivism] and the angst of postmodern deconstructions [interpretivism]" (Dillon et al., 2000, p. 25).

Mixed method research tends to focus on practical issues of how to combine aspects of quantitative and qualitative approaches rather than philosophical claims. Critics have objected that this results in a lack of ontological and epistemological foundations (Lincoln, 2010) and have warned that an uncritical adoption of mixed methods often amounts to paying lip service to interpretivist concerns while maintaining a postpositivist stance (Giddings and Grant, 2006). To address this perceived lack of paradigmatic foundations, many mixed methods researchers have turned to pragmatism, a school of philosophy based on the writings of Charles Stewart Peirce, William James, and John Dewey. Pragmatism's influence on mixed methods research has typically been implicit but recent efforts have sought to make its role as a research paradigm explicit (e.g. Goldkuhl, 2012; Hall, 2013; Morgan, in press). The following section provides an overview of pragmatist philosophy and its implications for research.

2.1.4 Pragmatism

Pragmatism is a philosophy that emphasizes the link between action and truth, arguing that the ultimate meaning of a concept or theory is its practical consequences (Dewey, 1920; Dillon et al., 2000; Fendt et al., 2008; Peirce, 1878). If, in a given situation, adopting either of two opposing metaphysical views would lead to the same practical outcomes, then to a pragmatist both views "mean practically the same thing, and all dispute is idle" (James, 1907). In situations where adopting one paradigm or the other would result in different outcomes, the choice should be made based on suitability to the problem at hand. Pragmatism thus offers a philosophical and methodological middle position between the dominant paradigms, rejecting the view that the two are incompatible (Fendt et al., 2008; Johnson and Onwuegbuzie, 2004).

This does not mean a lack of epistemology. However, rather than focusing on undecidable metaphysical debates, pragmatists propose to "change the subject" to focus on practical implications (Rorty, 1983). Meaning is seen as inseparable from human experience and therefore actions and outcomes are the primary source of understanding (Dillon et al., 2000; Fendt et al., 2008). In this view, researchers "should be content to act without the privilege of basing their decisions on secure and universally valid knowledge" (Friedrichs and Kratochwil, 2009, p. 711).

Pragmatists see action and truth as at the service of each other through constant cycles of inquiry, which involve iteration back and forth between beliefs (concepts and theories) and action (implementation and observation) (Morgan, in press). However, this stance could lead to a view that "whatever works is true" if taken to an extreme (Dillon et al., 2000). Consensus within and between research communities must be used as a check on such "crude instrumentalism" (Friedrichs and Kratochwil, 2009). Results from previous research and theories developed by others should be used to guide inquiry. This is in contrast to some interpretivist approaches such as grounded theory, in which theory is derived solely from the situation being studied and predefined theoretical stances are to be avoided (Strauss and Corbin, 1994).

Pragmatist inquiry emphasizes change. Pragmatists deny neither the existence of an external world, nor the socially constructed nature of our understanding of that world, but for them both the world and our understanding of it is constantly changing as a result of human actions (Goldkuhl, 2004). The consequences of action are to be used to determine the merit of theories and, importantly, to help in deciding which action to take next in attempting to better understand real-world phenomena (Johnson and Onwuegbuzie, 2004). The knowledge resulting from this process consists of "warranted assertions" (Dewey, 1941), understandings that can be used to guide future action but are recognized as fallible due to the constantly changing nature of reality (Morgan, in press).

There is nothing revolutionary in this point of view, and in fact James (1907) viewed pragmatism as "a new name for some old ways of thinking." For pragmatists, the philosophy reflects the reality of research as it is practiced. Many exemplary studies from the dominant paradigmatic traditions actually transcend the supposed divisions. Educational research conducted by Waxman and Huang (1996) is firmly rooted in the postpositivist paradigm but they use their results to argue for more constructivist, subjective teaching and learning environments. Ironside (2003) uses both qualitative and quantitative data in her pedagogical research, treating inconsistencies between the findings from each as a means of highlighting tensions and issues. In the field of design education research, the protocol analysis studies conducted by Cynthia Atman and her colleagues are primarily based on a postpositivist and quantitative approach to coding (e.g. Atman et al., 2007), but they have also interpreted the same data from an open-ended, qualitative perspective (Krause et al., 2013). These examples illustrate the potential for pragmatic, mixed methods approaches to explore research questions in novel and illuminating ways (Giddings and Grant, 2006). Pragmatism allows a place for both positivist and interpretivist knowledge, and suggests that pluralism is better at producing truth in complex, ill-defined situations (Fendt et al., 2008).

For those coming from a postpositivist perspective, pragmatism has been seen as a way to acknowledge the differences between "Popperian fantasies" about idealized scientific procedures and the way research actually proceeds without embracing relativism, which is often seen as an attack on science itself (Friedrichs and Kratochwil, 2009). For interpretivists, pragmatism has been viewed as a way to move beyond interpretive description to produce "constructive knowledge" that can be used to guide change, without embracing the concept of universal and objective predictions (Goldkuhl, 2004, 2012).

This thesis takes a pragmatic approach to research, based primarily within the interpretivist tradition but occasionally drawing on postpositivist approaches (such as psychometric theory) in order to augment the qualitative data by probing particular aspects of the research context. In reviewing the literature to identify pedagogical principles for OATPB courses, results from all paradigmatic traditions are considered, including qualitative studies conducted in everyday contexts and quantitative experiments based in laboratory settings. The research presented in this thesis takes place in particular contexts with specific participants. However, by drawing on a wide range of results from design and education research, and by studying learning environments in two countries and involving multiple cohorts of students, it is hoped that lessons can be drawn which transcend those specific classrooms and provide guidance for the development of other OATPB courses. Pragmatism acknowledges the existence of general patterns of activity and experience, but recognizes that these are subject to change over time. Thus, models of social systems can apply "most of the time" unless the human participants undermine and change them (Feilzer, 2010). Any model of a process involving multiple actors, such as that of a design team or a classroom, is assumed to be at best incomplete and capable of being invalidated by future members of the social group (Fendt et al., 2008). The pedagogical framework developed in this thesis is thus intended as a set of principles that may require adaptation by educators and researchers in response to changing contexts.

2.2 Methodology

The methodology of a study is the general strategy that guides the research design, the selection of subjects, the procedures for data collection and analysis, and the interpretation of results (Willis, 2007). The selection of a methodology is influenced by the paradigm within which research is conducted; certain paradigms permit some methodologies while excluding others. Even pragmatism, which is intended as a broadly accommodating paradigm, aligns more closely with some methodological approaches than others.

The research presented in this thesis is an example of design-based research, an education research methodology originally proposed by Brown (1992) and Collins (1992). This methodological approach seeks to increase the impact of education research on teaching practice (Anderson and Shattuck, 2012). Design-based research treats learning environments as complex systems whose behaviour is defined by a large number of parameters. Rather than attempting to identify and control all variables, the researcher works with educators and students to conduct a series of interventions in the environment, with the consequences of each intervention used to guide future iterations. Interventions might include new learning activities, changes in technology, or alternative approaches to assessment. These interventions take place in real educational contexts rather than in laboratory settings (Brown, 1992). An essential aspect of the methodology is that these interventions are used not just to improve an educational setting, but also to develop theory (Brown, 1992; DBRC, 2003; Palincsar, 2005). This is the feature that differentiates design-based research from similar methodologies such as action research and formative evaluation studies (Anderson and Shattuck, 2012; Barab and Squire, 2004). The resulting theories are not intended as universal timeless laws, but domain-specific guiding principles on which course models or particular learning activities can be developed (Cobb et al., 2003).

Collins et al. (2004, pp. 19–21) compare design-based research to three common types of educational research approaches: laboratory studies, ethnographic research, and large-scale studies. Laboratory (postpositivist) studies observe learners undertaking tasks, for a brief period of time, in isolation from contaminating effects. Ethnographic (interpretivist) research takes place in real settings and observes learners over a longer period of time, but it does not attempt to modify the environment. Large-scale (typically postpositivist) studies attempt to evaluate the effect of a program or intervention, but rely on standardized measures that do not provide the detailed information usually required to refine a design. Collins et al. propose design-based research as a fourth alternative that draws on elements of the other approaches in combination with its own unique features, and by doing so "fills a niche in the array of experimental methods that is needed to improve educational practice."

While neither Brown nor Collins identified a paradigmatic foundation for design-based research, an affinity with pragmatist philosophies is clear (Barab and Squire, 2004, pp. 6–7; Cole, 2005, p. 3). In particular, the methodological approach is closely related to the pragmatist concept of "abductive reasoning" (Peirce, 1965). Whereas deduction involves applying an abstract theoretical template to particular situations, and induction involves inferring general theory from particular facts, abduction involves reasoning at an intermediate level (Johnson and Onwuegbuzie, 2004; Friedrichs and Kratochwil, 2009, p. 711). Theory is used to guide actions, and the resulting observations are converted into theory (Morgan, 2007, p. 71). Action and theory refine each other. Friedrichs and Kratochwil (2009) proposed that abductive reasoning is particularly suited to exploratory studies, in which researchers are interested in a set of phenomena for which they lack applicable theories. In these situations, following an abductive approach involves collecting pertinent observations while applying concepts from other fields of knowledge, rejecting and refining concepts as necessary while also redefining the boundaries of the class of phenomena under study.

Design-based research does not specify a particular set of methods to be used in collecting and analysing data, but a mixed-methods approach combining qualitative and quantitative data is common (Anderson and Shattuck, 2012). In keeping with the pragmatist paradigm, the data collection and analysis methods are continually adapted throughout the research, both during and between interventions (Collins et al., 2004, p. 34). These adaptations, and the reasons for them, should be documented as part of the data set. Data collection and analysis should attend to multiple aspects of the learning environment, including the cognitive understanding of individual students, the interpersonal interactions between students and educators, the classroom structure, the resources available to students, and the relationship of the classroom to external communities (Collins et al., 2004, p. 35).

2.3 Methods

This section describes the methods used in this thesis to collect and analyse data. The research progressed through three phases of intervention and observation. Each phase had three objectives:

1. Explore the learning environments using the pedagogical framework as a guide;
2. Improve the pedagogical framework based on the results of each exploration; and
3. Use the improved framework to redesign the learning environments in subsequent phases.

Figure 2.1 is a graphical representation of the process followed. The first two phases of research relied primarily upon qualitative data. During the third phase, both qualitative and quantitative data were used to explore previously identified issues in greater depth. The data collection methods used throughout the research evolved in parallel with the framework and the learning environments. This cyclical process, in which research methods, teaching practice, and guiding theory evolve in parallel, is the essence of design-based research and the pragmatist model of inquiry.

2.3.1 Data Collection

The primary method of data collection throughout the three research phases was participant observation. The researcher participated in all courses as a teaching assistant, a role which involved mentoring student teams, delivering lectures, and organizing learning activities. In participant observation research, the researcher is the instrument (Guba and Lincoln, 1981). The background and biases of the researcher are therefore relevant in interpreting and evaluating the results. In the case of this thesis, the researcher came from a mechanical engineering background and therefore understood most of the technical content of the courses. While this enabled interpretation of the language used by course participants, it may also have resulted in unwarranted assumptions about students' understanding of technical subject matter. Tacit knowledge of a domain can both support and impede interpretive research. Furthermore, the researcher participated in a variety of design courses, workshops, and summer programs in parallel to those described in the thesis. The researcher's role in these activities was primarily that of teaching assistant or student mentor.

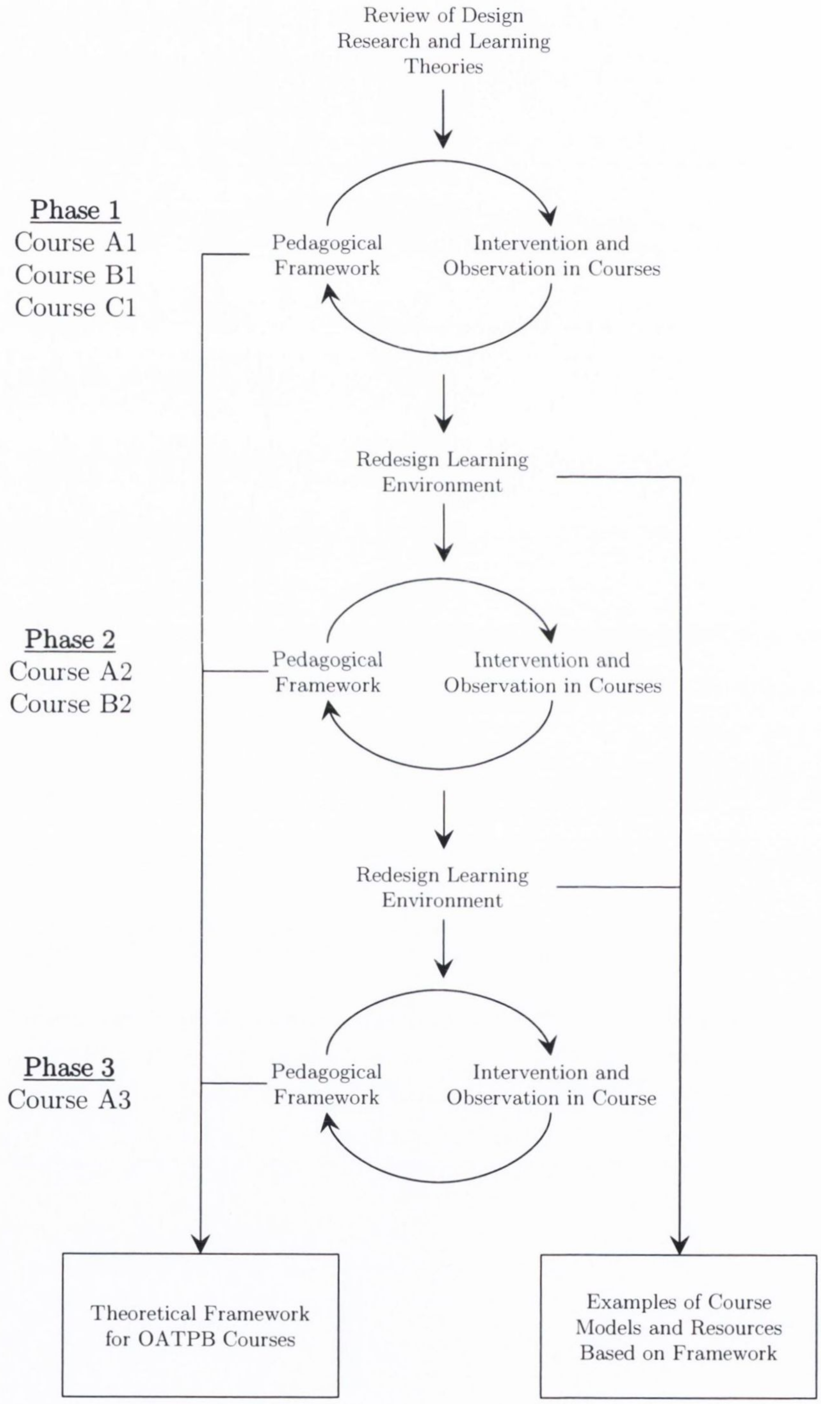


Figure 2.1: The research procedure followed in this thesis.

Participation in these additional activities may have exerted unexamined influence on the research conducted and the interpretation of events. The research in this thesis draws primarily upon the interpretivist tradition, which contends that eliminating such subjective factors in research is impossible. However, measures may be taken to decrease their influence, and thereby increase the trustworthiness of the results. Wallendorf and Belk (1989) recommend a range of procedures to increase trustworthiness in participant observations research, including:

- Prolonged engagement and persistent observation: Developing an understanding of the broad context of a study is necessary before focusing on particular aspects or themes. The duration of observation required to develop this understanding varies by context. Anthropologists studying an unfamiliar culture often spend at least a year immersed in the setting. Researchers conducting fieldwork in more familiar contexts may focus on particular aspects more quickly.

- Triangulation of sources, methods, and researchers: Trustworthiness is enhanced through interaction with multiple participants and preferably with multiple types of participant. Triangulation of methods involves including data gathered using multiple methods rather than relying solely upon personal observation. The involvement of multiple researchers studying the same context allows interpretations to be compared and refined.

- Negative case analysis: Seeking out examples and cases that contradict a general pattern enables the interpretation to be refined, by highlighting similarities and differences between participants and contexts.

- Debriefing by peers: Researchers should periodically meet with peers who are not researchers on the project but may offer an external perspective on the methods used and the resulting interpretation.

- Member checks: Sharing emerging interpretations with research participants allows the researcher to receive feedback from the members of the group being studied. This feedback may result in a revision of the interpretation or may provide further insight into the trends observed.

- Emergent research design: Adapting data collection methods in response to observed phenomena or evolving interpretations allows the research approach to be refined, and these adaptations may signal a need for modifications to the guiding theory.

- Explanation of change: Returning to sites over an extended period of time provides an opportunity to identify changes in the phenomena being studied and enables improvement of the interpretation to account for this change.

Some of these procedures, such as using an emergent research design and attempting to record and explain changes, are essential aspects of the pragmatist model of inquiry as discussed previously, and are therefore an inherent feature of the research procedure used in this thesis. The following sections describe the particular data collection methods used in the research and discuss the application of Wallendorf and Belk's recommendations in order to increase the trustworthiness of the results.

Fieldnotes

Participant observer fieldnotes were the primary form of data collected throughout the three phases. Fieldnotes were recorded during all course activities, including lectures, labs, student presentations, and design review meetings. Informal interactions with students outside of scheduled course activities were also recorded. Particular attention was paid to both formal and informal meetings of design teams as these provided opportunities to examine the participants' thought processes. As highlighted by Lloyd et al. (2007), "design meetings not only allow design activity to take place, but also force explanation of what is happening at a particular point, helping to externalise decision-making."

It was not always possible to produce detailed fieldnotes during course activities, and reflective fieldnotes were thus used to record events in greater detail. These were generated as soon as possible after a particular episode, typically but not always within the same day. In generating these fieldnotes the observations recorded during the episode were first reviewed and any details and events that had been omitted were noted. The observations were then elaborated in greater detail and descriptions of omitted events were added. A "roll-call" technique was used to examine the fieldnotes and ensure that each participant's name appeared and that the events or discussions involving that participant were recorded (Joseph, 2000, p. 124).

The researcher's role as a teaching assistant enabled prolonged engagement and persistent observation. In OATPB courses teaching assistants must interact regularly with students to provide mentoring and assistance with design tasks. Throughout the three phases of research, data was collected on all observed student activities rather than focusing exclusively on particular types of events, thereby ensuring that the data included contextual and environmental information. The degree of engagement with each team depended to a large extent upon the size of the student cohort and the logistics of the course, particularly the frequency and duration of scheduled contact time. In the courses with a smaller number of students (Courses A and C), substantial engagement was possible on an almost daily basis.

Triangulation of sources was achieved by observing multiple students teams in a variety of contexts. In total, 35 teams composed of 156 students were observed. Triangulation across researchers is only feasible in projects involving research teams, and was therefore inapplicable in this research. On occasion, other members of teaching staff were asked to record their own observations in design review meetings. While these observations tended to agree with those produced by the primary researcher, they were not sufficiently detailed to serve as a source of triangulation. Debriefing by peers was achieved through periodic consultation with design educators and with researchers from the fields of education and psychology. These interactions served to refine the interpretation of data and to provide guidance on the evolving research design. Finally, triangulation of methods was achieved using the data gathering approaches described in the following sections.

Artefacts

Artefacts produced by student teams served as a source of data triangulation. Students in all courses produced regular documentation describing their design activities and explaining their rationales for selecting particular concepts or procedures. Design projects afford a rich collection of documentation, and the student-produced artefacts collected during the research include meeting agendas, meeting minutes, presentation slides, written reports, video documentation of tests, CAD files, and software source code. Photographs of whiteboard sketches and prototypes were also recorded in the data set. During data analysis, many of these artefacts were used to understand events recorded in the fieldnotes. For example, discussions during design meetings often contained references to particular CAD models or sketches, and referring to these artefacts enabled an understanding of the topic of discussion.

Questionnaires

Questionnaires were used to provide insight into the perspectives and experiences of students and thereby triangulate the participant observation data. The design and use of questionnaires evolved throughout the research, partly in response to an evolving research focus and partly due to identified shortcoming in the questionnaires themselves. For example, during the first phase of research in Course A, an approach inspired by the Delphi Method was used (Hasson et al., 2000). This involved using a sequence of questionnaires, with the design of each informed by the results from the previous. Initially, open-ended questions were used to identify the frustrations and obstacles faced by the students. Their responses were used to identify categories of difficulties faced during the course, and the subsequent questionnaire asked students to rate the significance of each difficulty based on their experience. The final questionnaire presented the five difficulties that were rated most significant and asked students to explain how they had attempted to overcome each, and identify ways in which teaching staff could have supported these efforts. Appendix A contains the three questionnaires used.

While the results yielded some insights into students' experiences, the approach suffered from a number of flaws. Primarily, the sequence of questionnaires assumed that student experience was somewhat stable throughout the course, when in reality it changed from one week to the next. A difficulty faced by students during concept design activities may have been irrelevant during later stages of their projects. Furthermore, the open-ended nature of the course resulted in a wide variety of experiences, and a given team's difficulties were typically related to the particular details of their project. Thus, attempting to achieve consensus on the most significant issues via questionnaires was a flawed approach.

It was observed that the most informative results from these questionnaires were the responses to the open-ended questions about the difficulties each student faced. In subsequent courses it was therefore decided to focus on the use of this type of questionnaire. The instrument presented in Appendix B was used in three of the contexts studied. The design of the instrument was inspired by the concept of "muddiest point" cards, which ask students to identify aspects of a course that are unclear (Hall et al., 2002). Students were asked to indicate the primary difficulty or frustration they faced in their projects and any aspect of the course or process that they found unclear. By collecting students' responses periodically throughout the courses, it was possible to identify recurring issues as well as observe changes over time. The results obtained were used to guide subsequent participant observation data gathering by identifying issues to explore in greater depth.

One of the objectives of the third phase of research was to understand the role that particular aspects of the learning environment played in supporting students' design projects. Thus, students were asked to provide weekly ratings of how helpful they found each of 12 aspects of the learning environment during the preceding week (Appendix C). The results of these questionnaires were used to gain insight into both the activities of students throughout the course and the relationship between aspects of the learning environment and particular types of student projects. As before, the results were also used to inform subsequent data gathering. During this phase a quantitative pre- and post-test was used to examine aspects of students' design knowledge. Chapter 6 contains a detailed description of the development of the test instrument.

Interviews

Interviews with students were used as a further method of data triangulation and as a means of conducting member checks. Two types of interviews were conducted: contextual interviews and exit interviews. Contextual interviews involve observing subjects engaged in normal activities while asking questions about those activities (Beyer and Holtzblatt, 1997). The use of contextual interviews was found to be particularly appropriate and unobtrusive for the research presented here, as the procedure is essentially indistinguishable from the type of teaching activities required in OATPB courses. Teaching assistants in these courses often observe student work while asking questions to elicit thought processes. Recording detailed fieldnotes and including questions about emerging research themes thereby enabled teaching activities to also serve as data gathering and member checks. Contextual interviews were primarily informal and opportunistic, although a small number were scheduled in advance.

During the second and third research phases, exit interviews were conducted with students in Course A. These interviews took place upon completion of the course and after grades had been assigned, in order to prevent concerns about course grades from influencing the students' responses. The interviews focused on students' experiences in the course and were used to explore their opinions on particular episodes from the observation data and on aspects of the learning environment.

2.3.2 Data Analysis

Analysis of the qualitative data gathered using the methods described above was guided by the hermeneutic tradition. The term "hermeneutics" originally referred to the study and interpretation of religious texts, but its meaning has expanded to refer to the interpretation of any human activity in context, or rather, the definition of the term "text" has been expanded to include social structures, cultural artefacts, and any other human product (Prasad, 2002). There are many variations of hermeneutics, but the feature common to all is an emphasis on the importance of language and context as a frame for understanding (Willis, 2007, p. 104).

Hermeneutics, and in particular the concept of the hermeneutic circle, has been identified as particularly appropriate to a pragmatist, abductive approach to research (Friedrichs and Kratochwil, 2009; Polkinghorne, 2000). The concept of the hermeneutic circle suggests that an understanding of a text is based on the relationship between the parts and the whole. Gadamer (1976) illustrates the concept through the example of a sentence being translated from one language to another. Understanding of the meaning of each individual word is necessary but not sufficient for this task. Instead, preserving the meaning requires constant back-and-forth switching of attention between the individual words and the overall sentence, or between the parts and the whole.

Data analysis methods based on the concept of the hermeneutic circle are typically holistic rather than atomistic. Atomistic approaches involve decomposing the data into segments, applying codes or labels to each segment, and examining the relationship between codes (e.g. Miles and Huberman, 1994). In contrast, holistic approaches treat the data as a whole, and tend "to emphasize that meaning must be derived [from] a contextual reading of the data rather than the extraction of data segments for detailed analysis" (Willis, 2007, p. 297). The data analysis in this thesis followed a holistic approach, as the primary aim of the research was to understand the experiences of participants in the context of the learning environment. In particular, van Manen's (1997) selective approach was used to identify thematic elements of the data. The selective, or highlighting, approach involves searching the data for the episodes and statements that reveal the meaning of the events described. For van Manen, qualitative data cannot be understood through a rule-based, algorithmic approach to analysis, but requires to researcher to actively engage in identifying meaning.

The data collected through participant observation, interviews, and open-ended questionnaires was analysed using the following procedure. Qualitative data analysis software

(ATLAS.ti) was used to examine the data and record notes. Analysis began during data collection in order to identify emergent themes and guide further exploration. The data collected during each course was revisited and analysed in more depth after the course had completed. In each case, the data associated with the entire student cohort, such as observations from lectures or anonymous questionnaire responses, was first read through several times to gain an understanding of the overall context. The data set for each team was then considered in isolation. All fieldnotes, artefacts, and interviews associated with a given team were combined and examined in chronological order several times while notes were taken. When an understanding had been established of the team's experiences during the course, the data set was again explored to identify key episodes or quotes that were essential in explaining these experiences. These elements of the data represented emergent themes. The procedure was repeated for each team and the emergent themes were compared. Patterns of similarity and difference between the teams were noted, and the overall class data was again examined to identify related episodes and quotes. This process resulted in a set of themes for each student cohort represented by illustrative events and student quotes. The themes for each course were then compared to each other, again to identify patterns of similarity and difference.

Negative case analysis was an important aspect of this procedure. Student teams whose experiences were unusual (compared to their classmates) were treated as negative cases, and the key episodes describing their experiences were examined in order to identify features that explained these anomalies. Particular attention was paid to teams who encountered greater difficulties than other students, under the assumption that the experiences of such teams may highlight subtle problems in the learning environment.

During the third phase of research, quantitative measures were used to probe particular aspects of the learning environment. Friedrichs and Kratochwil (2009) advise that simple descriptive statistics should be used when combining quantitative measures with a hermeneutic analysis of qualitative data, particularly if the aim of the research is to inform practice. The quantitative data consisted of student ratings of the helpfulness of aspects of the learning environment, their scores on the pre-test and the post-test, and website analytics data recording student use of a learning resource. The analysis of this data was straightforward. The analytics data, consisting of weekly counts of website visits and average visit duration, was plotted to identify patterns in student use of the resource throughout the course. Similarly, the mean helpfulness rating for each aspect of the learning environment was plotted to identify trends. Finally, the pre-test and post-test scores were compared using a Welch's t-test and a P-value < 0.05 was considered significant (Welch, 1947).

2.3.3 Ethics

Informed consent was obtained from all students whose experiences are described in this thesis (Appendix D). At the beginning of each course, the nature and purpose of the research was explained to students. The data gathering methods were described and the likely impact of these methods on their experiences in the course were discussed. The research did not involve exposing the participants to any risks, nor did it require deceiving or manipulating the participants in any way. However, in any research involving human subjects it is essential to consider ethical issues and this is particularly true in educational settings, where there often exists a power imbalance between the educator and the learner. In cases where the researcher is also a member of teaching staff, as in this thesis, any real or perceived power imbalance can negatively affect both the data and the learners' experiences. The primary ethical concern is that students may have felt coerced into participation in the research, under the assumption that refusing to participate would negatively affect their grades or their experience in the course.

In order to prevent any perceived coercion, the researcher and other members of teaching staff were unaware of students' participation or non-participation during the course. Consent forms were distributed and collected by graduate students and faculty members unconnected with the research, and the signed forms were stored in a sealed envelope until the course was completed. Participation in the questionnaires, most of which were anonymous, was voluntary. The only questionnaire which recorded any identifying information was that used during the third phase of research, which asked students to indicate the project team of which they were a member. These questionnaires were collected by a research intern who retained the identifying information until completion of the course. The results of questionnaires with the team identifiers removed were shared with the primary researcher in order to guide subsequent data collection. As discussed above, the participant observation research was conducted as a part of normal course activities. Therefore, this aspect of data collection did not rely upon knowledge of whether a particular student was participating in the research. Upon completion of the course, the consent forms were reviewed so that observation data related to any student who did not wish to participate could be removed from the data set. However, almost every student provided informed consent and the amount of data removed was minimal. This procedure was approved by the Harvard University Committee on the Use of Human Subjects.

A further ethical concern relates to the privacy of the participants. The thesis discusses difficulties faced by the student teams and this could result in discomfort for those involved were their identities to be revealed. Concerns about privacy could also have prevented students from participating in the research. Thus, the privacy of all participants was assured. Prior to analysis, all personal information was removed from the data set. Team identifiers were maintained to allow data to be associated with particular projects. However, many of the student teams have subsequently published articles or submitted patent applications related to the work conducted during the courses. Therefore, were project details to be provided in the thesis it would be possible for a reader to link results with particular individuals. In order to protect participants' privacy, the student designs are not described in any detail. In particular, where the experiences of a particular team are discussed, no details of their design project are provided.

2.4 Summary

This chapter has discussed the paradigmatic and methodological foundations of the work presented in this thesis. When conducting research in complex social environments it is essential to make fundamental assumptions explicit in order to avoid contradictions in the collection or analysis of data. The objective of this thesis is to contribute to teaching practice by linking theoretical foundations to empirical results. A pragmatist paradigm was selected as appropriate to this objective. Pragmatism emphasises the connection between research and practice, and evaluates knowledge in terms of its practical implications. Design-based research is an educational research methodology that embodies many of the principles of pragmatism. The thesis structure reflects a design-based approach, in which teaching practice and learning theory evolve in parallel through successive phases of research.

The research methods used in the thesis are primarily qualitative and consist of participant observation, student questionnaires, and interviews. The analysis of the qualitative data is guided by hermeneutic philosophy, and in particular the concept of the hermeneutic circle. A holistic, rather than atomistic, approach is used to identify themes in the data. The chapter concluded with a description of ethical issues related to the research as well as measures taken to address these issues.

The following chapter describes the initial development of a pedagogical framework for OATPB courses. The framework is developed through a review of the literature on design cognition as well as a review of learning theories. In subsequent chapters, this framework is used to guide the research and to inform modifications to learning environments. The results from each phase of research are used to further develop the framework, which in turn informs subsequent phases of teaching and data collection.

Chapter 3

Literature Review

The objective of this thesis is to develop a pedagogical framework for open-ended, authentic, team- and project-based (OATPB) engineering design courses. The previous chapter described the paradigmatic and methodological basis of the research. An approach informed by design-based research, grounded in pragmatist philosophy, was selected as appropriate for the research objective. As outlined in Chapter 2, the procedure followed in the thesis consists of successive phases of research conducted in educational settings, with the interpretation of the research both guided by and contributing to an evolving pedagogical framework. The aim of this chapter is to define the initial version of this framework through a review of the literature from the fields of design studies and educational research.

The chapter begins with a brief overview of historical trends in both design and education research. Parallels between the two fields, influenced in large part by developments in psychological theory, are described in order to provide context for the subsequent discussion of themes. Studies of expertise have informed research in both fields and are therefore briefly discussed. The subsequent section reviews research on four aspects of design cognition: processes and strategies, models, knowledge reuse, and the social nature of design. The types of knowledge identified are proposed as learning objectives for OATPB courses. The work of educational psychologists and social anthropologists is then used to identify a set of learning theories that address many of the topics raised in relation to design knowledge. These theories may therefore provide guidance in achieving the proposed learning objectives. The chapter concludes by defining the initial framework, in which each essential aspect of design knowledge is paired with a theoretical perspective on knowledge and learning. Subsequent chapters will draw on this framework to interpret the results of research and to guide improvements to learning environments.

3.1 Background

3.1.1 Trends in Psychological Research

This chapter is concerned with the literature in two broad research fields: design studies and educational research. Both fields are concerned with the activities and thought processes of human subjects, and as a result have been heavily influenced by changing theories and research paradigms in psychology. This section presents a brief history of the three fields since the 1960s, highlighting parallel trends that have defined current theory and practice.

The aim of this section is to provide background information to contextualize the subsequent discussions, which explore many of the topics mentioned here in greater depth.

Behaviourism was the dominant theory of human psychology for most of the 20th century. It was grounded in positivism, and held that the only legitimate object of investigation was the study of observable behaviours. Internal mental structures and processes could not be observed objectively, and therefore could not be studied. From a behaviourist perspective, learning was seen as changes in behaviour and the aim of education was to condition the correct behaviour rather than to enhance knowledge (Murphy et al., 2012; Palincsar, 1998). In design research, the "design methods movement" of the 1960s had the aim of identifying a "correct," rigorous design method to match the scientific method (Cross, 1999, 2001b, 2007a; Cross et al., 1981; Simon, 1969). The assumption was that typical design practice, with its reliance on intuition and individual creativity, was unscientific and therefore unsound. In both fields, behaviourism's influence was evident in the view that the aim of science should be to correct human behaviour based on objective measures of merit.

The "cognitive revolution," which began in the 1950s, was a reaction to behaviourism that manifested as a gradual change of focus from external behaviours to internal mental structures. Cognitive psychology and information processing theories rejected the behaviourist claim that mental states and processes could not be studied (Duit and Treagust, 1998; Murphy et al., 2012). From the cognitivist perspective, the objective of psychological research was the identification and analysis of the ways in which knowledge is stored and processed. All cognitivist theories were to some extent "constructivist," which is to say they viewed knowledge and knowledge structures as individually constructed through interpretation of experience (Palincsar, 1998). However, there was a broad spectrum of theories within constructivism, from those that focused on whether the resulting mental structures were "correct" to those that held that there was no objectively correct knowledge.

Design and education research was heavily influenced by cognitive psychology theories. In both fields the objective of research became understanding the cognitive strategies of subjects, and the use of protocol analysis, in which subjects "think aloud" while completing a task, became common (e.g., Bereiter and Bird, 1985; Cross et al., 1996; Davey, 1983). The focus of much educational research was on learning strategies and metacognition (Brown, 1992). Metacognition refers to the ability to reason about one's own knowledge, and researchers attempted to identify the metacognitive strategies of exceptional students and use these to train other learners. In design studies, much of the research attempted to model the mental structures and thought processes of designers, often with the aim of constructing computational models of design cognition (e.g., Gero, 1990; Guindon, 1990). During the 1980s, researchers in both fields came to accept as valid cognitive strategies that had once been considered inadequate. The strategies of "ordinary" students were recognized as efficient and effective responses to features of the learning environment (Scardamalia et al., 1994, pp. 203–204). Rather than being defined in relation to science, design came to be viewed in its own right, with its own knowledge and "its own ways of knowing" (Cross, 2007b, p. 3).

The focus of both behaviourism and cognitive psychology was on the individual, and research was conducted through laboratory-based experiments that attempted to remove social and contextual influences on cognition. During the 1980s and 1990s, theories emphasizing the importance of social interactions and everyday contexts became more influential. Social constructivism views learning as a social process; new knowledge arises through social interactions with others and is gradually internalized by the individual (Schuh and Barab, 2008). Situated cognition theory asserts that knowledge is inseparable from its context of application; the theory represented a challenge to the decontextualized settings in which most psychological experiments are conducted (e.g., Lave, 1988). In reaction to these theories, the focus of much educational research became observations of real classroom settings, and interventions aimed at increasing the amount of social interaction in these classrooms (e.g., Brown, 1992; CTGV, 1994). In parallel, observational studies of designers in real contexts began to exert more influence in the field of design research (Bucciarelli, 1994; Schön, 1983). During the 2000s, the dominance of protocol analysis studies in design research waned as a wider variety of methods emerged, many of which focused on social and situated activity (Lloyd et al., 2007).

This section has presented a brief overview of three broad research fields. Any such review is by necessity an oversimplification. In reality the trends presented here could be decomposed into multiple competing theories and schools of thought. Research in both design and education continues to draw on a mixture of cognitivist, social constructivist, and situated theories. In keeping with a pragmatist approach, this chapter will draw on results from all of these paradigms.

3.1.2 Expertise

The study of expertise has received significant attention from cognitive psychologists, under the assumption that understanding the cognitive processes of experts would shed light on the nature of cognition more generally (Bransford et al., 2000). This research has influenced the development of theory in both design and education; thus, this section briefly summarizes some of the major findings on expertise. Contrary to common assumptions, expert performance appears to be largely unrelated to innate talent, and is instead acquired through years of experience. A remarkably consistent result that emerges from studies of expertise in a variety of domains is that it takes ten years of practice to develop expertise (Ericsson and Charness, 1994). However, experience alone is not sufficient; it must involve regular, deliberate practice. That is, the learner must be engaged in monitoring and directing her learning process, by identifying shortcomings in her current ability and concentrating on making appropriate improvements (Ericsson and Towne, 2010).

Much of the research on expertise has sought to compare experts to novices. The earliest of such studies demonstrated that experts and novices perceive the same information differently. For example, chess masters do not conduct a more thorough search of possible moves than less experienced players, but recognize features of a situation that suggest the most promising set of solutions to consider (De Groot, 1965). Furthermore, chess masters demonstrate better recall of chess piece locations than novices when briefly shown examples of chess games. However, when shown random board configurations that could not arise in an actual game, both groups perform equally poorly (Chase and Simon, 1973). Similar results have been observed in architecture, where experts appear to see architecture drawings in terms of meaningful "chunks of information (Akin, 1979). The implication is that it is not better memory or more extensive search strategies that allow experts to identify better solutions. Rather, through their experience of hundreds of precedent examples they are better able to recognize salient features of a given situation.

Discussing expertise requires differentiating between types of knowledge. Declarative knowledge refers to factual information and is necessary but not sufficient for expert performance. More important seems to be procedural knowledge, which is the organization of factual information into domain-specific strategies for interpreting contexts and solving problems (Akin, 1990; Alexander and Judy, 1988). For example, the analysis of mathematical models relies on declarative knowledge of fundamental concepts and principles, but procedural knowledge is required to judge the level of detail appropriate for modelling a design based on the particular context or stage of the process (Bucciarelli, 2001). Although experts have mastered the content of their domain, they are not necessarily capable of teaching it; much of the expert's procedural knowledge is tacit, or difficult to express explicitly. Experts' understanding of subject matter is fundamentally different from novices, making them less likely to understand learners' misconceptions and needs (Bransford et al., 2000; Nathan and Petrosino, 2003).

A particular type of procedural knowledge that has received much attention is the approach to understanding and solving problems. Studies of physics (Dufresne et al., 1992), medical diagnosis (Johnson et al., 1981), software debugging (Rasmussen and Jensen, 1974), and electronic systems repair (Gitomer, 1984) have shown a consistent difference between experts and novices. Experts typically follow a top-down, breadth-first approach, in which the expert first attempts to fully understand the problem, before considering and evaluating a range of potential solution approaches, and only then pursuing the selected approach in depth. Novice problem-solving tends to be characterized by a depth-first or trial-and-error approach which involves less attention paid to understanding the problem and a tendency to focus on a single potential solution. Alternative solutions are considered only if the preferred approach fails.

The consistency with which this difference between experts and novices was observed in a range of domains led to assumptions that this approach to problem-solving was a general, domain-independent problem-solving strategy (Guindon, 1990). However, most of the studies that observed this result focused on the solution of relatively well-defined, closed-ended problems for which a single correct answer could be identified. The following section describes difficulties in applying this problem-solving approach to open-ended, ill-defined problems such as those encountered in design.

3.2 Design Studies

Attempts to define a systematic design method have often been inspired by results from general studies of expertise and by a "logical analysis of design tasks" (Ball et al., 1997). Such models typically prescribe idealized procedures that designers should follow to deterministically solve problems (e.g., Hubka, 1982; Pahl et al., 1984; Pugh, 1991). However, the rigid prescriptions of these methods do not seem to have been adopted in practice and many designers resent the portrayal of design as a deterministic, algorithmic process (Cross, 2001a; Darke, 1979; Goldschmidt, 2001; Stauffer and Ullman, 1988). Designers who claim to be following a structured process are often observed to deviate from that process in response to emerging ideas and difficulties (Cross and Clayburn Cross, 1995; Visser, 1990). As noted by Stempfle and Badke-Schaub (2002), even under ideal conditions in laboratory settings, designers who have been trained in methodical approaches do not rigidly adhere to them (e.g., Günther and Ehrlenspiel, 1999).

The current consensus among design researchers and theorists is that design is fundamentally different from other disciplines and involves "activities that are not readily characterized by formal procedures" (Candy and Edmonds, 1996; Cross, 2001a, 2007a; Cross and Clayburn Cross, 1998). Spiro et al. (1992, p. 61) note the differences between well-structured and ill-structured problem-solving:

> Engineering employs basic physical science principles that are orderly and regular in the abstract and for textbook applications... However, the application of these more well-structured concepts from physics to "messy" real-world cases is another matter. The nature of each engineering case (e.g., features of terrain, climate, available materials, cost, etc.) is so complex and differs so much from other cases that it is difficult to categorize it under any single principle, and any kind of case (e.g., building a bridge) is likely to involve different patterns of principles from instance to instance.

Rather than importing prescriptive problem-solving strategies from other domains, many design researchers have focused on studying design as it is really practiced. This section reviews the results of such studies carried out in a wide range of design disciplines and using a variety of research methods including protocol analysis studies, participant observation and ethnographic research, retrospective studies, interviews, surveys, historical studies of technology development, and diary studies.

3.2.1 Design Processes and Strategies

One feature of design that has emerged from this research and that differentiates design from well-structured problem-solving is the coevolution of problem and solution. Designers do not first try to understand the problem completely before considering potential solutions, and the problem is not treated as stable throughout the process. It is not just that potential solutions are used to gain a better understanding of the problem as given, although this is certainly a factor (Maher and Poon, 1996). Designers actually redefine the problem in light of potential solutions, for example by expanding or narrowing the scope, or changing, eliminating, or adding constraints (Maher and Tang, 2001; Wiltschnig et al., 2013). This updated problem is then used to reformulate potential solutions, and in this sense the problem and the solution are said to co-evolve. Designers do not just synthesize solutions to meet given requirements; they also create their own requirements and problems to be solved (Suwa et al., 2000). In other domains this would be considered extremely "ill-behaved" problem solving, but it appears to be a common element of all forms of design (Cross, 2001a).

Dorst and Cross (2001) propose the following model to explain problem-solution coevolution. An initial exploration of the problem is used to identify features of a partial solution. This partial solution is then developed and related constraints are transferred back to the problem space, where the implications of the partial solution are used to further structure the problem. This iterative process continues, with the eventual aim of creating "a matching solution-concept pair." In other words, the problem is "created" in parallel with the solution.

Problem-solution coevolution has been observed in the process, sketches, and decisions of individual designers (Schön and Wiggins, 1992), in the discussions between designers and clients (Smulders et al., 2009), and in the activities of collaborative teams (Wiltschnig et al., 2013). Engaging in coevolution appears to be a strategy to manage the uncertainty inherent in design. There is no way of determining "the correct answer" for a design problem, and any given problem could have a large number of valid interpretations and solutions. Initial ideas are therefore used as a "primary generator" (Darke, 1979), a starting point from which to restrict the range of alternative solution concepts and frame the problem from a particular perspective (Schön, 1984).

As noted, uncertainty is an inherent feature of design, and each of the topics discussed in this review relate to ways of reducing or managing it. Another common response to uncertainty that emerges from the research is the combination of breadth-first and depth-first problem-solving strategies. Design engineers generally follow a breadth-first approach, but engage in opportunistic deviations from this when deemed appropriate. For example, Visser (1990) carried out a longitudinal study of an experienced mechanical engineer engaged in a design task. While the engineer claimed to be following a structured plan, results of the study indicated that he often abandoned his plan to pursue interesting ideas as they emerged.

Guindon (1990) observed similar behaviour in a study of software designers and concluded that "these results cannot be accounted for by a model of the design process... where the design solution is elaborated at successively greater levels of detail in a top-down manner." The observed designers did not fully specify the problem before considering potential solutions, and often opportunistically jumped from considering potential solutions in breadth to pursuing particular partial solutions in depth.

Ball et al. (1997) studied experienced electronic engineers carrying out design tasks and proposed the following explanation for their observations. Through their experience of multiple design projects, expert designers develop a number of strategies, one of which is conducting a breadth-first exploration of the solution space with minimal commitment to developing any particular solution. This is possible due to their extensive, well-organised knowledge of analogous problems and solutions, which enables them to identify those concepts that are most feasible. However, when faced with a problem for which their knowledge of previous cases is insufficient, the engineers revert to a depth-first exploration of solution concepts in order to assess their viability. In other words, when necessary the expert will engage in "trial and error" to gain an understanding of potential solutions.

While some have claimed that the work of a designer resembles that of an artist, unguided by any particular methodology (e.g., Schön, 1983), these results do not imply that design should be approached as a chaotic, completely unstructured process. Ball and Ormerod (1995) did not regard deviations into depth-first explorations of potential solutions as an abandonment of a structured approach, and proposed that a top-down, breadth-first strategy was the default mode of problem solving, with depth-first explorations as a strategic response to unfamiliar contexts. Guindon (1990) saw such behaviour as "a natural consequence of the ill-structuredness of problems in the early stages of design." Furthermore, there is evidence to suggest that following a semi-structured process that leaves room for opportunism is particularly effective in solving design problems. Fricke (1996) compared the designs resulting from different strategies and found that a "flexible-methodical procedure" produced better results than either rigid adherence to a methodical approach or a completely unsystematic approach. The important point here is that an understanding of when and how to switch between the breadth-first and depth-first modes appears to be an essential aspect of expert designers' strategic knowledge.

The results discussed thus far have implications for design education. First, in contrast to analysis-focused engineering science courses, students in project-based design courses must not be required to treat the problem as "given" and stable, and should not be expected to fully define the problem, constraints, and requirements in advance of considering solutions. For the OATPB courses explored in this thesis, this does not imply that students should not focus initially on understanding user needs and creating the project brief, but that they should be free to revisit and redefine these as necessary throughout the process. It should also be noted that embracing problem-solution coevolution does not suggest that initial ideas should necessarily be retained. Smith and Tjandra (1998) observed student design teams and found that a willingness to discard initial ideas correlated positively with eventual design quality.

Second, students must be exposed to a flexible-methodical design process, and must reflect on the process and on their own thinking. Knowledge and understanding of a range of design strategies, what Reid and Reed (2005) call a "metaknowledge of design process," differentiates experts from novices (Ahmed et al., 2003; Ball et al., 1997; Guindon, 1990). Stempfle and Badke-Schaub (2002) assert that this metaknowledge and the related strategic flexibility "cannot be taught, but must be learned through experience and self-reflection."

3.2.2 Design Models

Uncertainty in design may be reduced or managed with the use of models. Designers make use of a variety of representations of the design product and process including sketches, prototypes, mental models, schematics, decision matrices, flow charts, and analytical and numerical models (Juhl and Lindegaard, 2013; Petre, 2004; Roy, 1993; Ullman et al., 1990). Knowledge of mathematical and scientific models is assumed to be the fundamental aim of engineering education, and most undergraduate problem-solving relates to the analysis of equations describing physical systems. This knowledge is indeed important, as mathematical analysis can be used to evaluate and refine design concepts (Roy, 1993). Design engineers often use an understanding of fundamental physical principles as the "primary generator" which guides the exploration of problem and solution spaces (e.g., Cross, 2011). However, the assumed primacy of mathematical modelling in engineering practice, which often results in graphical and three-dimensional models being neglected in engineering education, may be unfounded (Buur and Andreasen, 1989). In a study of experienced mechanical designers, Ullman et al. (1988) found that the subjects constructed very few mathematical models. Ferguson (1992) warns that:

> [A] system of engineering education that ignores nonverbal thinking will produce engineers who are dangerously ignorant of the many ways in which the real world differs from the mathematical models constructed in academic minds.

Project-based courses provide an opportunity to address this gap. This section reviews research related to the role of sketching, drafting, and prototyping in design.

Sketching may play a smaller role in engineering design than in other design disciplines such as architecture (Lloyd and Busby, 2001), but it is an essential one. A consistent result in studies of design is the view of drawing and sketching as part of the process, rather than simply documentation of that process (Ullman et al., 1990). Drawing is more than creating external representations of images held in the mind; rather it is an essential part of generating new ideas (Goldschmidt, 1991). A design concept is reinterpreted and modified while being externalized (Purcell and Gero, 1998). For Schön and Wiggins (1992), the act of sketching is a type of experimentation in which the internal and external representations evolve in parallel: the designer sketches, recognizes new meaning in the sketch, and uses that to guide further sketching. Schön (1983) refers to this process as "the designer having a conversation with the drawing." The advantage of sketches over other representations such as prototypes and technical drawings is that sketches are inherently ambiguous and therefore allow for creative reinterpretation (Suwa et al., 2001).

Of course, more formal drafting, and in particular computer-aided drafting (CAD), is a core activity in engineering design. Robinson (2012) found that over 12% of design engineers' time was spent using CAD software, and Yang (2008) observed a correlation between the number of detailed, dimensioned drawings produced in the first half of the design process and the resulting design quality. However, Kavakli et al. (1998) claim that CAD models should not replace freehand sketching during the early stages of design. Similarly, Eisentraut and Gunther (1997) and Ullman et al. (1990) warn that CAD training should not replace freehand drawing and sketching in design education. Instead, the two should be learned in parallel.

Mock-ups and prototypes allow designers to explore and evaluate potential solutions and thereby reduce uncertainty. Physical prototypes can yield greater insight into three-dimensional systems than sketches or drawings, while providing a wider range of sensory feedback (Christensen and Schunn, 2009). Buur and Andreasen (1989) suggest that prototyping can have valuable side benefits such as learning about new technologies, about practical materials considerations, and about aspects of manufacturing. Accomplished design engineer Alexander Moulton (quoted in Roy, 1993) succinctly outlines the importance of prototyping in engineering design:

> Ideas and calculations must be translated into drawings and sketches... drawings must be made into hardware as soon as possible, so that reality can be tested and analysed. This is the most important part of the development cycle.

Peter et al. (2013) conducted experiments in which pairs of students were asked to solve a design task using either sketching or one of three physical prototyping media. Their results indicate that prototyping encourages a more collaborative process than sketching. Youmans (2011) found that access to prototyping materials resulted in better designs compared to sketching alone. Often in engineering design courses the emphasis is on creating high-fidelity "final" prototypes rather than building rough exploratory models. However, creating rapid, low-fidelity prototypes during the initial stages of the process can support early evaluation of design concepts. Rapid prototypes provide a low-risk and low-commitment means of reducing uncertainty. Gerber and Carroll (2012) found that these early prototypes allow designers to accept the failure of an idea, and to view failure as a learning opportunity. They also found that creating low-fidelity prototypes can increase designers' confidence in their own creative abilities.

Clearly, representations play an essential role in design, and project-based design courses should therefore encourage students to engage in sketching, drafting, and prototyping throughout the process. Given the emphasis on mathematical models and the production of formal documentation (such as lab reports) in engineering education, effort should be made to highlight the role of informal, nonverbal and non-scientific modes of thought during project-based courses. These activities should be framed as more than mere documentation of ideas; students should learn to value them as a necessary part of the creative process.

3.2.3 Design Knowledge Reuse

In addition to the strategic knowledge discussed above, designers rely upon an extensive knowledge of previous problems and solutions to guide concept generation and evaluation

(Lawson, 2004). Reference to precedents supports a breadth-first approach by allowing designers to evaluate solutions through analogy to previous examples and decide whether a given solution is worth pursuing in more depth (Ahmed et al., 2003; Ball et al., 1997). Bardasz and Zeid (1992) claim that the majority of mechanical design activities relate to modifying precedents to fit new problems. Among the characteristics of design expertise identified by Lawson (2004) is the ability to make analogies between past experiences and current problems and to use that knowledge to generate new solutions. Comparisons of expert and novice designers have confirmed this; experts are more likely to refer to previous designs than novices (Ahmed et al., 2003).

Design knowledge reuse is not a matter of simply copying a design from one situation to another. Precedents can be used to generate novel solutions, for example by combining aspects of existing designs into new configurations, or by modifying existing designs to incorporate new features (Gero, 1994). Successfully reusing design knowledge requires an understanding of the similarities and differences between the current and previous contexts, and an ability to use that understanding to identify potential issues that must be addressed (Ahmed and Christensen, 2009; Deken et al., 2012; Demian and Fruchter, 2006). Bucciarelli (2001) argues that this type of context-dependent judgement is underserved by current engineering education, with its focus on abstraction and generality.

Engaging in this type of analogical thinking is another strategy for reducing uncertainty (Ball and Christensen, 2009). Precedents can provide guidance with which to avoid "reinventing the wheel" (Akin et al., 1997). Knowledge of particular production processes, materials, and technologies can serve as the "primary generator" discussed in Section 3.2.1, framing the problem in terms of past designs that have proven successful (Roy, 1993). Lloyd and Scott (1994) found that design engineers with experience in the specific problem domain were more likely to adopt this solution-focused approach to design.

A potential concern with the use of precedents is the risk of "fixation," that is, attachment to a particular concept which prevents alternatives being considered. Jansson and Smith (1991) found that engineers who were shown an example solution to a design problem were more likely to produce solutions containing features of example than a control group who were not shown an example. They proposed that this type of fixation may have negative effects if it prevents designers from considering novel solutions. However, subsequent experiments have found that domain knowledge, that is, experience with the type of problem being solved, can in fact reduce or even eliminate fixation (Purcell and Gero, 1998; Viswanathan and Linsey, 2013), and improve the quality or practicality of designs (Rietzschel et al., 2007; Ward, 2008). Furthermore, as Cross (2001a) notes "it is not clear that fixation is necessarily a bad thing in design."

A more troubling view of issues related to design knowledge reuse emerges from a study of reuse failure, that is, cases of designers not using existing designs in situations where doing so may have reduced cost and risk. Busby and Lloyd (1999) examined 170 such cases, and found that each case had complex explanations. For example, in many cases reuse failure was a result of idiosyncratic opinions based on misinterpretations of prior experience. This may be related to some common psychological tendencies, such as the "availability heuristic" (Tversky and Kahneman, 1973), which is the tendency to judge the likelihood of an event based on how easy it is to recall a previous instance. People are more likely to remember unusual events, such as a single failure of a previous design, and therefore overestimate the likelihood of that event reoccurring in future. Confirmation bias, the tendency to favour information that confirms beliefs, may compound this effect. Busby and Lloyd conclude that the interpretation of experience can be problematic, and that designers should be encouraged to reflect critically on their experiences and evaluate their opinions.

Design reuse is a complex issue, but it is an essential element of engineering design (Court et al., 1997; Roy, 1993; Zack, 1999). Thus, students in project-based courses should be provided with examples on which to draw, and encouraged to engage in reasoning with and about precedents. The use of precedents is not intended to simply increase students' domain knowledge or to improve the quality of their designs, although it has been shown to have that effect (Casakin, 2010). Rather, it is an opportunity for learners to rehearse the type of analogical reasoning required for creative problem solving. Furthermore, engaging students in critical self-reflection on their interpretation and use of precedents may produce engineers less likely to exhibit the problematic behaviours identified by Busby and Lloyd (1999).

However, access to documentation of previous designs may not be sufficient. Studies of design knowledge transfer in industry have shown the importance of social networks; engineers, in particular novices, require social interactions to support design reuse (Deken et al., 2012; Demian and Fruchter, 2006). Interactions with more experienced peers are necessary to understand the context and rationale related to previous designs, and important knowledge about the current design context is actually created through discourse between design engineers with varying levels of experience. The significance of social relationships and interactions for design is discussed in the following section.

3.2.4 The Social Nature of Design

Among the shortcomings of idealized models of the design process is the portrayal of design as a purely technical process. In reality, design is a complex, inherently social activity, and this is perhaps more true of engineering design than of other domains such as architecture or graphic design (Lloyd, 2000). Engineering design projects typically involve multiple teams, departments, and stakeholders. That design requires effective teamwork and communication is a trivial observation. A growing body of work has demonstrated more fundamental and profound aspects of the social nature of engineering design.

Bucciarelli's (1988, 1994) ethnographic studies were seminal in highlighting the central importance of social processes in engineering design. According to Bucciarelli, while marketplace needs and scientific law are ingredients of the design process, the more fundamental components are the social norms and practices through which a consensus is reached between the multiple participants and perspectives involved in designing. In addition to a team of engineers, a typical design project may involve marketing staff, lab technicians, purchasing agents, inventory controllers, and many other roles, each of which brings a valid perspective to the project. The design cannot be split into separate tasks that address each of these perspectives independently, "it requires instead the continuous engagement of, and exchange among, individuals schooled and trained in a range of disciplines" (Bucciarelli, 1994, p. 186). Design does not simply rely upon social agreements in order to proceed; design is the act of creating social agreements (Lloyd, 2000). The designed product is an embodiment of the various agreements created during the process.

Language therefore plays a central role in engineering design. Design decisions are based as much on rhetorical factors as on objective or technical reasoning (Lloyd and Busby, 2001). As mentioned in Section 3.2.2, graphical representations may play a larger role in non-engineering design disciplines such as architecture. It seems that design engineers rely more heavily on discourse to model and explore potential solutions and their consequences, which is interesting given the common view of engineers as more technical and perhaps less socially adept compared to other types of designers. This is not to deny the importance of the models discussed previously. The point to note is that "verbal sketching" skills are central to successful engineering practice (Lloyd and Busby, 2001). Design teams tend to construct a language specific to particular projects; the creation and use of shorthand terms for design concepts, shared assumptions, and previous experiences enables team members to engage in more efficient and effective collaborative discussions (Bucciarelli, 1994; Lloyd, 2000). Again, for Bucciarelli this language creation is not an incidental activity. Labels carry meaning for designers; they contain analogies and metaphorical implications that will influence the design. Thus, "naming is designing" (Bucciarelli, 1994, p. 174).

Design requires skill in the use and manipulation of language. During team interactions, expert design engineers have strategies for using language in such a way as to signal openness to alternative ideas and to defer disagreement so as not to impede overall progress (Cross and Clayburn Cross, 1995; McDonnell, 2012). For example, teams may defer judgment on contentious issues through noncommittal agreements, or by agreeing to disagree until a more convincing argument or evidence can decide the matter. This allows the overall project to progress by focusing on other issues. Expert and standard practices or fundamental theories and principles are often used to depersonalize debate and resolve disagreements (Brereton et al., 1996).

In a professional environment, we may expect that most roles and relationships will be formally established. However, within design teams certain roles can emerge and dissolve more informally, often based on different styles of working. Brereton et al. (1996) describe the different working styles observed by two team members from a well-known protocol analysis study. One member repeatedly tried to "pin down" part of the solution from an early stage by focusing on previous designs, while another participant seeks to "preserve ambiguity" for as long as possible. Cross (2011, p. 117) suggests that having these two perspectives within a team could be complementary, as long as the disagreements can be managed to achieve a constructive outcome. Successful teams spend a significant amount of time reflecting upon their progress and organizing their design process (Lahti et al., 2004; Olson et al., 1992).

The importance of social interactions in design extends beyond individual teams. In any complex engineering project, no single individual or team possesses all of the knowledge related to the design. Rather, it is distributed within and between organizations, a phenomenon known as "distributed cognition" (Saloman, 1993). Difficulties in sharing knowledge can lead to errors in design. Busby (2001) studied errors in the design of complex process plants which were due to failures of distributed cognition. Difficulties included understanding when, how, and with whom knowledge should be shared, and adhering to both formal and informal norms. Busby suggests collective reflection on failure as a potential remedy, and proposes that designers could benefit from framing design tasks in terms of distributed cognition.

Recognition of the social aspects of design has implications for engineering design education. Project-based courses tend to involve students working in teams, and accreditation criteria typically require team-based experiences as part of engineering programs. However, simply requiring students to collaborate may not be sufficient. There is often no guidance on teamwork available to students, and assistance with group dynamics is a common student request (Brereton et al., 1996). Furthermore, requirements for educators to provide team-based experiences typically provide little guidance on what form these experiences should take, and what support should be provided to students. The research reviewed here indicates some potential guidelines. Learners should be required to communicate and defend their decisions and rationales as often as possible, in order to practice rhetorical skills. Attention should be drawn to the importance of language and discourse in design. Doing so may help students to become more aware of the factors that influence their decisions (Lloyd and Busby, 2001). It would also encourage the type of reflection that has been highlighted in previous sections.

3.3 Learning Theories

The previous section identified aspects of design knowledge that are essential for successful practice, and that should therefore serve as learning objectives for OATPD courses. However, an awareness of these types of knowledge alone does not provide much by way of guidance for educators and researchers seeking to understand or improve learning environments. Thus, this section reviews a range of learning theories that may provide a theoretical perspective on methods of supporting students in developing "designerly ways of knowing" (Cross, 1982). The importance of recognizing the strategic, contingent, and social nature of design knowledge has been highlighted. Similarly, the theories selected for review in this section represent perspectives on the strategic, context-dependent, and social nature of learning. The section begins with three theories that are more descriptive than prescriptive, in that they seek to understand the nature of learning rather than prescribing specific teaching methods. However, they have inspired particular approaches to teaching nevertheless, and the remainder of the section describes some of these prescriptive teaching models.

3.3.1 The Strategic Nature of Learning

During the 1970s and 1980s, much educational psychology research focused on the role of cognitive strategies, in particular the strategies that learners use when completing educational tasks. The objective of this type of research was to address the problem of "passive learning" (Brown, 1992, 1997). Students who performed poorly in school were viewed as not engaging in intentional, self-directed action to improve their knowledge. Researchers attempted to identify the strategies that differentiated exceptional students from "ordinary" students. These strategies involve metacognitive reasoning, and include:

- Noticing and formulating comprehension difficulties as problems;
- Summarizing what has been understood so far;
- Reconsidering previous conclusions;
- Drawing nonobvious inferences; and
- Explicitly connecting new information with prior knowledge. (Bereiter and Bird, 1985; Scardamalia et al., 1994)

The performance of average and below-average students was characterized by an absence of these strategies. These results informed training studies, which attempted to teach such students about the use of effective learning strategies (Brown, 1978, 1992). The objective of the research was to explore whether such students were simply unaware of these strategies, or if they were aware but incapable of using them. There was evidence that such training worked, in that participants in experiments were able to apply the strategies to solve tasks. However, there was no evidence of retention beyond the experiment (Brown, 1992).

Eventually, the assumption that ordinary students were lacking in effective strategies changed. It was recognized that in fact students possess sophisticated strategies that tackle the task at hand (Wellman et al., 1975). For example, in a study of how students summarize texts, schoolchildren were observed to use a "copy-delete" strategy, which involves evaluating sentences one by one, copying those they judge important and ignoring those judged unimportant (Scardamalia et al., 1994). College students completing the same task first attempted to comprehend the entire text before producing a summary. The latter approach is clearly a more effective strategy if comprehension is the goal of the activity. However, the schoolchildren's strategy was extremely effective at creating a summary that largely agrees with that of adults while requiring minimal effort of the student. In other words, the strategy resulted in the desired product, but undermined the educational goal. The implication was that students, rather than lacking strategies, have adopted effective strategies in response to the school environment's focus on deliverable products. This realization led to a growing interest in adapting the learning environment rather than attempting to directly intervene in the cognitive processes of the students. One such attempt is discussed in Section 3.3.6.

3.3.2 Constructivism and Social Constructivism

Constructivism is closely related to interpretivism, and in fact the two terms are often used interchangeably. Constructivist learning theories view education not as the transmission of knowledge from experts to learners, but as the active construction, on the part of the learner, of a conceptual framework based on experiences (Hruby and Roegiers, 2013). When faced with new experiences, the learner either integrates the resulting knowledge within her existing conceptual framework, or modifies her framework to make sense of the knowledge (Piaget et al., 1977). A common feature of the various constructivist learning theories is the influence of John Dewey, whose work was discussed in Chapter 2.

The aspect of constructivism that has had the most influence on teaching practice is the concept of "discovery learning" (Bruner, 1961), which involves self-directed, active learning in which students discover knowledge for themselves (Anthony, 1973). However, discovery learning has often been implemented in a "minimally guided" approach, in which students are presented with problems and expected to direct their own problem-solving activities. This approach has been shown to be ineffective (Kirschner et al., 2006). Brown and Campione (1994) note that students are adept at "discovering" misconceptions and propose as more effective an environment of "guided discovery," in which the educator acts as facilitator and adopts a more traditional teaching role when necessary.

Social constructivism (or sociocultural theory) extends constructivism to take account of the role of social and cultural interactions upon learning. There is a broad spectrum of social constructivist theories, all of which are based in some way upon the work of Lev Vygotsky. Vygotsky was a Soviet contemporary of Dewey, but his work only came to prominence outside of Russia four decades after his death. Vygotsky rejected the idea that learning and knowledge could be isolated from social or cultural influences. For Vygotsky, learning was a process in which an external operation was transformed into an internal one (Kaptelinin and Nardi, 2006, p. 42). This internalization is not a transfer of the external processes into a pre-existing internal structure; the mental structure is created through internalization (Leontiev, 1978). Vygotsky also held that the individual could not be considered separately from their social environment (Kaptelinin and Nardi, 2006, pp. 46–47).

One of the most influential aspects of Vygotsky's work has been the concept of the "zone of proximal development" (ZPD), which was an alternative solution to the problem of matching instruction to the current ability of the learner. The typical approach is to evaluate the ability of the individual learner, for example using an exam. For Vygotsky, this approach resulted in learning lagging behind the development of the child. Instead it is necessary to consider the difference between two measures: the ability of the child acting alone, and the ability of the child acting with assistance from another. This difference is the zone of proximal development (Vygotsky, 1978). For example, consider two students that demonstrate the same arithmetic ability when acting alone. If the same external assistance is subsequently provided to both students and they perform differently on more advanced problems, then each student has a different ZPD (Kaptelinin and Nardi, 2006, p. 49). The ZPD thus reflects the student's immediate learning potential, and instruction would best be aimed at meeting this potential (Palincsar, 1998). External assistance can include educators, peers with varying experience, or even artefacts such as books or computer systems.

The concept of the ZPD led researchers and educators to consider the need for learning environments to have multiple zones of proximal development, thereby accommodating a wide range of learning potentials. Attempts to create such an environment have often involved the restructuring of classrooms to encourage more social interaction between peers of different abilities (e.g., Brown and Campione, 1994) or developing computer environments to act as adaptive assisting agents (e.g., Salomon and Perkins, 1998).

3.3.3 Situated Learning

Situated learning theory highlights the importance of the context in which learning takes place, and is primarily based on the work of Jean Lave and Etienne Wenger. Lave (1988) compared the arithmetic abilities of adults in exam-style situations and in everyday contexts such as shopping for groceries, or budgeting calories when dieting. She found that the performance of the same subjects in either context bore little relation to each other. In particular, participants who struggled to complete arithmetic problems in an exam setting were extremely proficient at performing mental calculations using personal methods during everyday activities. Lave's work was an attack on many aspects of cognitive psychology, including the belief that psychological experiments which isolate participants from the context in which cognitive activities take place are more valid than research carried out in the field (Pea, 1991). Her work also undermined a foundational assumption of formal education, that "knowledge acquired in context-free circumstances is supposed to be available for general application in all contexts, widely transportable but relatively impervious to change in the course, and by the process, of travel and use" (Lave, 1988, p. 9). In other words, a guiding principle of formal education is that by removing learners from everyday contexts and presenting them with abstract, generalized knowledge, they will be better able to transfer that knowledge to a wide range of situations. For Lave, this assumption is flawed; the contexts of application are an essential part of any cognitive activity, and attempts to eliminate that context are flawed.

In subsequent work, Lave and Wenger (1991) explored cases of informal learning, in particular apprenticeship programs, and used the results to develop a general model of how learning takes place. In this model, learning was viewed as participation in a "community of practice" (CoP), a group who share a domain of interest and engage in and identify with a common practice (Dennen and Burner, 2007; Wenger, 1998). Communities of practice may be either formally or informally bounded, and any individual is usually a member of multiple such communities. An example might be a group of engineers working on similar problems. Learning occurs through interactions with the CoP, in particular through participating in tasks and observing the actions of others. Knowledge is thus co-constructed by the group, rather than transmitted from one person to another (Billett, 1996). Education is the means by which the community reproduces itself, by creating a new generation of practitioners. However, learners' roles in this process are not passive; the community and its practice are changed as a result of newcomers' involvement (Lave and Wenger, 1991, pp. 113–117).

A common misinterpretation of this work is that informal, situated learning is "better" than traditional schooling. However, for Lave and Wenger, all learning is situated. The classroom is as much a real setting as the factory floor (Lave and Wenger, 1991, pp. 39–41). Their theory was intended as a description of all types of learning rather than a prescription for a specific type of education. The implication of the theory is that in order to understand learning, attention must be paid to the type of setting in which learning takes place, and the type of community in which learners are participating. In this view, it was no longer appropriate to think of classrooms as somehow neutral and the learning that takes place in classrooms as abstract and available for universal application.

Situated learning theory may be particularly relevant to engineering design education due to the decline of workplace-based apprenticeship programs for novice engineers. Difficulties accessing engineering communities of practice have had a negative impact on learning opportunities for new designers (Carkett, 2004). As stated, situated learning is not a prescriptive theory. However, any learning theory represents a particular perspective on education, and inevitably influences models of teaching. The following three sections will review teaching models that have been influenced by situated learning and social constructivist theories.

3.3.4 Cognitive Apprenticeship

One interpretation of situated learning theory is that all education involves some form of apprenticeship between a master and a novice. From this perspective, teachers are the experts in a particular domain, such as calculus or manufacturing science, from whom students learn procedural knowledge. This is in fact the basis of most university teaching. However, as discussed in Section 3.1.2, experts do not necessarily make good teachers. A condition of expertise is that knowledge has become internalized to the extent that it is tacit and intuitive; as a result experts may not understand the misconceptions of learners and may have difficulty making their knowledge explicit.

Cognitive apprenticeship theory is a pedagogical model, inspired by situated learning theory, which attempts to address the challenge of making expert knowledge explicit (Hennessy, 1993). The aim of cognitive apprenticeship is to go beyond teaching facts and concepts and also teach the strategic knowledge required for expert performance, including the types of metacognitive strategies that have been identified as important for design and for learning in general (Wedelin and Adawi, 2014). The theory draws on constructivism and social constructivism, and advocates that learning should consist of guided participation in activities appropriate to the learner's ZPD (Dennen and Burner, 2007). The model has been applied at both school (e.g. Scardamalia and Bereiter, 1985) and university (e.g. Liu, 2005) levels.

Cognitive apprenticeship theory does not prescribe specific learning activities, but outlines methods which may be incorporated into the learning environment. These include:

- *Modelling* involves the student observing the expert or peers demonstrating aspects of a task (Collins et al., 1991).

- *Coaching* involves providing feedback, guidance, and hints while the student completes tasks or tackles problems (Wedelin and Adawi, 2014).
- *Articulation* requires students to explain their thought processes and make their knowledge explicit (McLellan, 1994).
- *Reflection* involves encouraging students to analyse their previous activities. The role of the educator is to assist the learner in comparing their process to that of the expert or of other students (Ghefaili, 2003).

As an explicit theory, cognitive apprenticeship is a relatively recent development. However the activities it prescribes are core features of traditional studio-based design education. Student architects primarily work on projects with coaching from tutors, who may intervene and model aspects of the design process when required (e.g. Schön, 1983). The "group crit," a critical review of work by peers, provides regular opportunities for articulation and reflection (Horton, 2007). However, this approach is rare in engineering education, partly due to large student-teacher ratios and heavy course loads which restrict the amount of time that students and faculty can dedicate to design projects. Thus, cognitive apprenticeship theory, with its focus on applying these methods in classrooms settings, may provide some guidance.

3.3.5 Cognitive Flexibility Theory

Cognitive flexibility theory is an instructional model that focuses on the nature of learning in complex and ill-structured domains, such as design. Solving problems in ill-structured domains requires using the same knowledge in different ways depending on the particular details of a problem, and methods of applying knowledge often cannot be known in advance (Spiro et al., 1992). Thus, cognitive flexibility theory emphasizes the importance of enabling learners to adapt their knowledge to new situations. Rather than focusing on the retention and retrieval of pre-existing knowledge structures, cognitive flexibility "stresses the flexible reassembly of pre-existing knowledge to adaptively fit the needs of a new situation" (Spiro et al., 1992, p. 59). The aim is to enable students to manipulate their problem-solving knowledge in response to contextual clues.

In the approach to learning objected to by Lave (1988), problems and solutions are typically stripped of their context with the aim of making the lessons more generally applicable. An example from mechanical engineering education is the predominant focus on the analysis of disembodied, idealized machine elements. From the cognitive flexibility perspective, this approach is misguided. Instead, specific and rich contextual information should be provided. The objective is to expose students to the ways in which a given principle or procedure is enacted in real situations. Furthermore, content should be viewed from multiple perspectives and in multiple contexts, thereby enabling transfer of knowledge from one situation to another (Bromme and Stahl, 2002). Thus, the theory is primarily concerned with the transfer of knowledge beyond its initial learning situation.

Cognitive flexibility theory proposes the following instructional principles (Jacobson and Spiro, 1993):

- *Multiple knowledge representations:* involves presenting multiple themes, multiple perspectives, and multiple analogies
- *Concepts linked to different case examples:* illustrating general principles through particular cases
- *Early introduction of domain complexity:* rather than learning small conceptual units in isolation before combining them, maintaining complexity throughout
- *Emphasis on the interrelated nature of knowledge:* demonstrating the relationships between different concepts and cases
- *Encouragement of knowledge assembly:* supporting learners in synthesizing aspects of previous case-specific knowledge for the problem at hand

With reference to design education, cognitive flexibility theory relates to the importance of design precedents, and indicates the importance of presenting contextual information relating to precedents. This need has also been highlighted in results from research on knowledge transfer within design organizations (e.g. Deken et al., 2012). The theory also suggests that multiple precedents should be used to demonstrate a particular principle, or that a given precedent be analysed from multiple perspectives, such as those of different stakeholders.

3.3.6 Learning Communities

Over the past two decades one of the most common topics of education research has been the study of communities of learning. This is partly due to the influence of social constructivist and situated learning theories, and partly as a result of the emergence and growth of the

Internet; studies of "virtual communities" have been especially prevalent. However, there have been objections to the widespread use of the term "community" with little consideration for what exactly constitutes a community. As Grossman et al. (2000) observe, "groups of people become communities, or so it would seem, by the flourish of a researcher's pen." Hewitt (2004) warns against "unwarranted optimism" about learning communities in general, and proposes that research should focus on the design of particular community models that best support learning. This section describes one such model which has a significant influence on the work presented in this thesis.

Fostering a Community of Learners (FCL) is a model for teaching biology to schoolchildren, developed through a program of design-based research (Brown, 1997; Brown and Campione, 1994; Collins et al., 2004). The model integrates many of the concepts discussed in this chapter, including theories of strategic learning and the work of Vygotsky, Lave, and Wenger. FCL classrooms are framed as learning communities in which students engage in guided discovery on a general theme, such as food chains. The class is divided into groups, with each group assigned to a particular aspect of the overall theme, for example, photosynthesis, energy exchange, and so on. The groups conduct research on their assigned topic, with each student specializing in a particular subtopic. Sharing of knowledge within and between groups is encouraged and expected. At the end of the research cycle, the groups comes together to combine their knowledge in a "jigsaw" activity (Aronson, 1978). There are three such research cycles per year, with each cycle lasting for weeks or months.

For Brown and Campione (1994) the particular details of implementation were less important than the guiding theoretical principles developed during the research project. These principles include (Brown, 1997; Brown and Campione, 1994):

- *Metacognition:* FCL is designed as an environment that emphasizes the strategic nature of learning and requires students to regularly reflect on their own knowledge and ways of improving it. As in cognitive apprenticeship, students are required to make their thought processes explicit.

- *Contextualized and situated:* FCL emphasizes the creation of classroom communities of practice engaged in authentic tasks, and attempts to link school activities to outside activities. The classrooms are modelled on communities of scientists, and provide students with opportunities to practice being a researcher or a teacher at various points in the cycle.

- *Dialogic base:* The primary activity in FCL classrooms is dialogue on multiple levels, between team members, between teams, between students and educators, and between the class and external experts.

- *Distributed expertise:* Individual students specialize in particular topics, and the teacher is no longer the sole classroom expert. In order to complete their projects the students must consult peer "experts" and share knowledge. (The term expertise is used quite broadly in FCL, in contrast to the studies of expertise discussed above.) Furthermore, the boundaries of the learning community are extended by providing access to domain experts including biological researchers; these experts visit the classroom to take part in discussions, and the students are encouraged to continue the dialogue via email or telephone.

- *Multiple zones of proximal development:* The distribution of knowledge throughout the classroom, and the extension of the learning community beyond the school, supports varying levels of learning potential. As each individual is an "expert" in a particular topic, there are more opportunities for learners to receive peer assistance rather than relying solely upon the teacher.

The FCL model seems relevant for the study of OATPB courses. On the surface, the two share many features; both involve classrooms composed of student teams working on somewhat self-directed projects with guidance from educators. However, where OATPB courses generally lack a clear theoretical basis, the FCL model is the result of 30 years of rigorous educational research (Collins et al., 2004). The guiding principles of the FCL model address many of the issues raised in relation to design, including the central importance of language, the role of distributed knowledge, the need to engage with domain experts beyond the project team, and the requirement for effective cognitive strategies.

3.4 Towards a Pedagogical Framework

Based on the discussion of design research and learning theories contained in this chapter, it is now possible to outline a pedagogical framework to use in exploring and improving the learning environments of OATPB courses. This section summarizes the results of the literature review and pairs aspects of design knowledge with relevant learning theories. Table 3.1 records the essential features of the framework.

Design Processes and Strategies

The most fundamental aspect of design ability is strategic knowledge. Rather than following a single, universally optimal procedure, designers rely on a repertoire of strategies that allow them to respond to particular situations. These strategies may dictate the type of process to be followed, the selection of an appropriate design model for a given problem, or the interpretation of design precedents. In particular, designers require an understanding of whether and how to deviate from a methodical design process. Thus, a core objective of OATPB courses should be the development of strategic knowledge related to the design process. Students should be supported in rehearsing strategies for managing uncertainty and balancing flexible and methodical approaches to problem-solving. This activity should be supported through elements of cognitive apprenticeship theory, such as coaching and modelling.

Developing design strategies in turn requires effective learning strategies, which include reasoning about one's own understanding and taking measures to improve it. Learners should therefore be engaged in reflecting on their performance while rehearsing design strategies. Finally, the role that task optimization strategies can play in undermining educational objectives should be recognized. Careful attention must be paid to whether assignments and other tasks align with the overall learning objectives from the perspective of the students. Of particular concern for OATPB courses is the risk of emphasizing the design product rather than the process that was used to create it.

Design Models

The use of design models relies on a particular type of strategic knowledge: the ability to judge the most appropriate type of model for a given situation. In many cases, analytical or numerical models are not the appropriate for the task at hand, but engineering education emphasizes these over all others. Thus, OATPB courses should be used as a means of introducing students to the nonverbal and non-scientific aspects of engineering design knowledge. Learners should be encouraged to experiment with alternative approaches as a way of discovering the strengths and weaknesses of each. However, this should not be an unguided process; principles of guided discovery should be used to assist the students in considering alternative approaches and to identify and correct any misconceptions. For example, visual representations should not be treated as static documentation of fully formed concepts but rather an essential activity in generating those concepts.

Design Knowledge Reuse

A substantial amount of design activity involves identifying and synthesizing aspects of previous solutions, or improving existing solutions through redesign. Successful design reuse requires extensive declarative knowledge relating to precedents as well as strategic knowledge about how to make use of those precedents. Transferring elements of a solution from one situation to another requires an ability to identify the context-specific features of a precedent and reason about whether those features are appropriate for the problem at hand. Cross (2011, p. 146) succinctly explains the implications for design education:

> In order to develop expertise it seems that a novice needs lots and lots of practice, guided by skilful teachers. The novice designer also needs exposure to many good examples of expert work in the area, and needs to learn to perceive and retain these examples, or precedents, in terms of their underlying schemata or organising principles. Like learning a language it is a matter of immersion and internalising different levels of understanding and achievement.

Cognitive flexibility theory is ideally suited to guiding efforts to provide the required practice with and exposure to precedents in OATPB courses. The theory was developed as an approach to teaching problem-solving in ill-structured domains such as engineering design. It prescribes the use of multiple knowledge representations as a means of supporting analogical reasoning and transfer. Concepts, theories, and precedent cases should be examined in multiple contexts and from multiple perspectives to allow students to reason about the role of context in solving ill-structured problems.

The Social Nature of Design

Design is a process of achieving consensus among a range of requirements, domains, and participants. This is especially true in engineering compared to other design disciplines. The role of language and rhetoric is thus fundamental to engineering design. In sufficiently complex projects, no individual possesses a comprehensive understanding of the entire design or the ability to accomplish all required tasks. Thus, design relies on distributed cognition and designers must understand when and how to share knowledge. Situated learning theory and the principles underlying the "Fostering a Community of Learners" classroom model provide guidance on how these aspects of design knowledge could be incorporated into OATPB courses. In particular, learning activities should be framed as participation in communities of practice, and attention must be paid to the types of communities in which learners are participating.

Table 3.1: Pedagogical Framework for OATPB Courses

Design Knowledge	Guiding Theory
Strategies	*Strategic Nature of Learning*
• Learning strategies	• Metacognition
• Design strategies	• Reflection
• Task optimization strategies	• Alignment of tasks and learning goals
Process	*Cognitive Apprenticeship*
• Flexible-methodical process	• Coaching
• Problem-solution coevolution	• Modelling
• Tolerating uncertainty	• Articulation
	• Reflection
Models	*Social constructivism*
• Sketching	• Guided discovery
• Prototyping	
Design Knowledge Reuse	*Cognitive Flexibility Theory*
• Precedents	• Multiple representations
• Fixation	• Contextual information
	• Concepts linked to precedents
	• Emphasis on interrelations
	• Knowledge assembly
The Social Nature of Design	*Fostering a Community of Learners*
• Role of language	• Dialogic base
• Team roles	• Distributed expertise
• Inter-team communication	• Communities of practice
• Distributed cognition	• Multiple zones of proximal development
	• Instructor guidance

3.5 Conclusions

This chapter has identified essential aspects of engineering design knowledge and has paired these with relevant learning theories in order to create a pedagogical framework for use in designing and evaluating OATPB courses. The framework is intended to act both as a theoretical lens through which to explore learning environments and as a set of guidelines to inform the development of learning activities and resources. In the next chapter, three OATPB courses are explored using qualitative methods. The experiences of students and educators in these settings are described and interpreted in terms of the knowledge types around which the framework is organized. The framework provides a means of identifying and understanding problematic aspects of the learning environments. In subsequent chapters, the framework indicates potential approaches to solving these problems. However, the framework is not treated as stable or unchangeable. It is intended to evolve in parallel to the research and the learning contexts. Each of the chapters describing empirical research in OATPB courses conclude by revisiting the framework, making additions as appropriate and drawing attention to aspects of the framework that require further attention. This coevolution of theory and practice is the essence of the abductive, pragmatist philosophy underpinning this thesis.

Chapter 4

Research Phase 1

The objective of this thesis is to develop a pedagogical framework for open-ended, authentic, team- and project-based (OATPB) courses. The previous chapter reviewed the literature on design practice and theories of learning. Based on this review, an initial version of the framework was developed, consisting of essential aspects of design knowledge that may serve as objectives guiding the development of learning environments. For each aspect of design knowledge a corresponding learning theory was identified; these theories are intended to provide guidance on achieving the learning objectives.

The remainder of this thesis focuses on using the pedagogical framework to improve learning environments in OATPB courses, and to use observations of teaching and learning in these courses to further develop the framework. This reciprocal relationship between theory and practice is fundamental to the pragmatist philosophy and design-based research methodology adopted in the thesis. This chapter describes the first of three phases of empirical research in educational settings. Three very different instances of OATPB courses are explored through qualitative participant observer studies. The chapter begins with a description of each of these contexts, followed by an overview of the research methods used in each. The experiences of students and learning staff are then reported and interpreted in terms of the pedagogical framework. This discussion is structured around the fundamental aspects of design knowledge identified in the previous chapter. This chapter concludes by expanding the framework to reflect the results of the research and identify topics of focus for subsequent phases.

4.1 Context

This section describes each of the three courses investigated in this chapter, which took place in the School of Engineering at Trinity College Dublin (TCD) and the School of Engineering and Applied Sciences at Harvard University. A major difference between the two institutions is that in Harvard a class is not typically composed of a persistent student cohort. Course participants may include students from a variety of levels, including both undergraduate and graduate, and from a range of disciplines. In contrast, the majority of undergraduate engineering courses at TCD are delivered to students at the same level and with the same disciplinary background. Both schools traditionally emphasized the engineering sciences but have introduced project-based design experiences for students throughout their programs, in particular during the past decade. Each of the courses explored in this chapter was a recent addition to the school or had been significantly altered in recent years. All were nominally

Table 4.1: Overview of courses

Course code	A1	B1	C1
Academic Year	2011-2012	2012-2013	2012-2013
Level	Mixed	Undergraduate	Graduate
Types of projects	Electromechanical	Mechanical, electronic, and software	Software
Duration of project	15 weeks	15 weeks	31 weeks
Number of students	16	46	4 (+4)
Number of teams	4	10	1
Team codes	1.1-1.4	1.5-1.14	1.15

mechanical design courses but their open-ended nature resulted in some projects focusing on electronic or software design. Table 4.1 provides an overview of the courses studied, and the following sections describe each in more detail.

4.1.1 Course A1

Course A1 was an electromechanical design course at Harvard focused on medical device development. In advance of the course, clinicians were invited to submit project proposals outlining unmet clinical needs. A shortlist of eight such proposals was chosen and presented to students at the beginning of the course. Each student was required to select three preferred projects, and these selections were used to form teams around the four projects to be pursued in the course. Each team worked directly with the relevant clinician, as well as consulting other stakeholders and conducting background research, to better understand the medical problem. Prior art searches were used to identify gaps and opportunities in the market. Based on this initial work each team defined its own brief in the form of a mission statement and set of functional requirements. Regular class presentations and documentary deliverables were used as milestones to provide structure to the course, leading the students through a top-down, breadth-first process. Each student team was provided with a "wiki" webpage hosted on Harvard's virtual learning environment, and were expected to use this to document their project. The second half of the course was dedicated to detail design, prototyping, and testing.

Each team was provided with a budget of $2,500 and expected to work with external vendors to produce a high-quality functioning prototype. The course culminated in a showcase in which students presented their designs to an invited audience. In addition to the working prototype and final presentation, each team was required to submit a publication-quality article describing their project.

The weekly course activities included two 90-minute lectures and a three-hour lab period. The lecture time was dedicated to discussion of mechanical design topics such as machine element design and material selection, as well as student presentations and guest lectures from medical device industry professionals. In the initial weeks the labs were used to provide training on prototyping equipment including CNC mills and laser cutters. For the majority of the course the lab was dedicated to self-directed project work with assistance from members of the teaching staff. In addition to the lectures and labs, each team met with the teaching staff for a one-hour weekly design review meeting. These meetings were used to update the teaching staff on recent progress and to receive guidance and advice on the project. During the meetings, the students were required to engage in metacognitive reasoning by describing and defending the decisions they made during the preceding week. The labs and meetings took place in a dedicated course room located adjacent to the workshop containing the prototyping equipment. Only course students and teaching staff had access to this room and each team was assigned a desk and storage space.

The class was composed of eight undergraduate and eight graduate students from a range of science and engineering disciplines. Enrolment in the course required previous design and prototyping experience; all of the enrolled undergraduates were either "junior" (3rd year) or "senior" (4th year) students. The course was first offered in the 2011-2012 academic year; the observations reported in this chapter describe the second iteration of the course.

4.1.2 Course B1

Course B1 was a mechanical design course delivered to 3rd year students at TCD. In contrast to Course A1, all participants were mechanical engineering students at the same academic level. Course B1 was a complex course spread over two semesters and composed of multiple elements including CAD training, practical activities focused on control system design, mechanical dissection activities (Sheppard, 1992), a module on finite element method (FEM) analysis, and a team-based design project. The weekly course activities consisted of two consecutive 50-minute lectures and two 2-hour lab periods. The labs were occasionally used for design review sessions, but were primarily dedicated to course activities unrelated to the design project.

The observations reported here focus solely on the project element of the course. The theme of this project-based component was universal design, or the design of devices and services that are accessible to people with as wide a range of physical and cognitive abilities as possible. Student teams were required to recruit their own user groups and conduct "needfinding" (Patnaik and Becker, 1999) research to identify a product to redesign with accessibility in mind. On two occasions during the course, a group of design advisors from the National Council for the Blind of Ireland (NCBI) acted as consultants representing the perspective of visually impaired technology users, answering student questions and providing feedback on proposed design solutions.

The structure of the course was similar to that of Course A1, with presentations and assignments used to guide students through a top-down, breadth-first process. The course also culminated in presentations and a showcase at which students demonstrated proof-of-concept prototypes. However, the students in Course B1 did not have a significant prototyping budget or access to dedicated course workspace. The process in Course B1 was also slightly less structured, with fewer project-related milestones overall. The overall course has existed in various formats for many years. However, the open-ended, user-focused design project was a recent addition.

4.1.3 Course C1

Course C1 was a graduate-level product design and innovation course delivered at TCD in partnership with Stanford University. The course was part of an international network involving universities from eight countries. Each team was composed of students from two institutions who collaborated remotely to design a solution to meet the needs of an industry sponsor. The problems set by sponsors were typically ill-defined and open-ended, and required the students to conduct needfinding research to define the project brief. Each half of the team was provided with a prototyping budget of approximately €5,000.

As in both other courses, regular presentations and assignments were used to structure the design process followed during the course. However, in contrast to the other courses described here, Course C1 followed a more depth-first approach to problem solving. Student teams were required to explore potential solutions sequentially and in depth, producing a prototype as part of each assignment. A guiding principle of the course was a commitment to "preserving ambiguity" in the design process (Carleton et al., 2008). In terms of the course structure, this principle was realised by withholding information from the students about forthcoming assignments and the overall process being followed. During the course the student teams produced three reports summarizing their design work, and the course culminated in a showcase in Stanford attended by student teams and teaching staff from all institutions involved. The showcase consisted of formal presentations followed by demonstrations of high-fidelity working prototypes.

The observations in this chapter focus on the experiences of the first team of TCD students to participate in the course. This team was composed of four graduate students with backgrounds in mechanical engineering, civil engineering, and computer science. They collaborated with remote teammates in another university and a multinational software firm acted as project sponsor. The weekly course activities included a two-hour lecture period, often used for discussion given the small "class" size, and a review meeting with teaching staff. As in Course A1, the weekly review meetings required the students to engage in metacognitive reasoning. Unlike the other courses described in this chapter, the students observed in Course C1 dedicated the majority of their working time to the project; three of the four students were not enrolled in any other courses. The team was provided with access to a design workspace which was also used by other courses and groups.

4.1.4 Methods

The data gathering in courses A1 and C1 consisted of participant observation, contextual interviews, artefact collection, and student questionnaires. The researcher's role in each course was that of teaching assistant, which primarily involved coaching students throughout their design projects. The degree to which the researcher influenced the design of each learning environment, in particular the course structure and logistics, was minimal during this phase. Fieldnotes describing the activities of each team were collected from weekly review meetings between the team and the teaching staff, internal team meetings outside of formal teaching hours, and lab sessions during which students worked on their projects with aid from teaching assistants. Informal contextual interviews were conducted on an opportunistic basis, and involved observing students carrying out tasks while asking questions. Both the observations and the contextual interviews took place in the context of teaching; there was essentially no difference between the questions asked in an effort to have students reflect on their activities as part of coaching and the questions asked for research purposes. Artefacts consisted of documentation produced by the students for the course, and photographs of whiteboards and prototypes. Open-ended questionnaires asked students to report on their experiences in the courses. The questionnaires used in Course A1 were based on the Delphi method, and are contained in Appendix A. In Courses B1 and C1 the questionnaires took the form of "muddiest point" cards (Angelo and Cross, 1993), and asked students to identify the primary difficulties they were facing in their projects that week and the main unanswered question they had about the course topics (Appendix B). Course B1 provided the fewest opportunities for direct interactions with students due to the lack of formal review meetings, and the lack of a dedicated course space where students worked on projects. The data primarily consisted of student answers to the muddiest point questionnaires combined with observations from student presentations and two design review meetings, as well as artefacts in the form of project documentation. Analysis of the data followed the approach outlined in Chapter 2.

4.2 Results and Discussion

4.2.1 Design Processes and Strategies

A common approach in all three courses was to use assignments and class presentations as a way of structuring students' design processes. The use of course-wide milestones required all student teams to progress through the same series of steps and at the same rate, a requirement that is not ideal given the nature of design. Opportunities for deviation from the prescribed script arose through guidance and feedback from the teaching staff to individual teams, largely in response to students' performance on deliverables. There is an inherent tension here between the imposition of a regimented structure and attempts to guide the teams through a process best suited to their particular situation. However, there was no indication that this tension in itself was necessarily problematic; it may be an inevitable result of the need for a flexible-methodical process as specified in the pedagogical framework developed in Chapter 3.

However, while all courses employed the same general tactic for structuring the students' design experiences, two very different types of process were observed. Courses A1 and B1 adhered to a generally top-down, breadth-first strategy, with students expected to focus initially on problem definition, before evaluating and selecting between a variety of potential solutions, and spending the remainder of the course on the detail design, prototyping, and testing of their preferred concept. In contrast, Course C1 required students to very quickly move to prototyping a particular solution, and subsequently proceed through a series of cycles of designing, prototyping, and testing alternative concepts. Unlike in the other courses, at no point in Course C1 were students required to explicitly compare the alternative solutions and present a rationale for their choice of final design.

A common complaint from students in Course B1 and C1 was a lack of clarity about the process being followed in the course and expectations regarding deliverables. This issue was never mentioned by students in Course A1. The reason for this seems to have been the provision of a detailed syllabus document in the latter course. This document listed the course activities, project milestones, and general expectations for each week of the course. A condensed version of the document is provided in Appendix E.

Comparing Courses A1 and B1, the process followed in the former was more structured, as that course required its students to produce a greater number of documentary deliverables and milestone presentations. However, Course A1 also provided more guidance for students in deviating from the structure, due to more regular and more in-depth design review meetings between the teaching staff and each team. As a result, the structure of Course B1 provided more opportunities for deviation from a methodical process, but less guidance on when and how such deviations might be pursued. In the early stages some students in both courses objected to the requirement to define their own brief, as they did not believe this type of activity constituted engineering, and to the expectation to consider and evaluate alternatives before pursuing them in depth. Difficulties in evaluating alternative designs seemed related to students' discomfort managing uncertainty, a topic discussed later in this section. However, after these initial objections most teams appeared to accept the overall structure of each course, although the Course B1 students continued to find the process somewhat unclear as discussed above.

The structure of Course C1 appeared to be designed to emphasize those aspects of design practice that make it different to the scientific, well-structured approach with which engineering students typically have extensive experience. For example, the process followed made it impossible for students to avoid engaging in problem-solution coevolution, and stressed the role that in-depth exploration of potential solutions could play in better understanding the problem to be solved. However, in the case of the observed team (team 1.15) the imposed process seemed to have some negative consequences. In particular, the emphasis on repeated divergence, with each 2-to-4-week design cycle in the early stages of the course being followed by a requirement to generate an alternative concept, seemed to result in the team becoming "stuck" in that mode of thinking. Towards the end of the course, when the team should have been focused on designing and implementing the details of their final prototype, one half of the team seemed discontent to settle on any decision. Even in week 30 of the project, days before the final showcase, some team members strongly advocated a complete change of direction for the project. At least part of the reason for some team members' inability to converge on a solution may be due to the course structure, which for most of the project emphasized the generation of concepts and building of low-fidelity prototypes. As a result, the importance, and difficulty, of detail design and high-fidelity prototyping seems not to have been made clear to some students.

A further issue with the Course C1 structure seemed related to the attempts to preserve ambiguity regarding the overall course process while also assigning specific short-term tasks. This combination of unclear goals and immediate product-focused tasks seems ideally suited to provoking the type of local task optimizing strategies discussed in in Chapter 3. The following description from Scardamalia et al. (1994, p. 205) provides some background.

> The typical school system... confronts [students] with an essentially endless series of tasks to be done. Typically, the time constraints for completing a task are severe, whereas the task requirements are quite liberal... Under these circumstances, any adaptive organism will develop strategies that minimize time to complete tasks, and the most likely way to do this is by trimming away activities that do not directly yield the deliverable product. In the case of research papers, this means minimizing research... In the case of a reflective essay, this means minimizing reflection.

In the case of coursework assignments in a design course, this may mean minimizing attention to the overall project goals in order to focus attention on the immediate deliverable. Thus, the relationship between a given task and the overall process should be made clear to students. If it is not, for example if process details are deliberately withheld in the interest of preserving ambiguity, it seems inevitable that some students will fail to make the connection. In fact, this was a recurring problem for the team 1.15; individual assignments were often completed with minimal attention paid to the overall project, and therefore often did not contribute to the development of either the project or the students' understanding.

It should be noted that these issues were observed among only some members of team 1.15; their teammates seemed more capable of adapting to the structure and imposing their overall project goals on the demands of immediate deliverables. Furthermore, the course coordinators indicated that the level of difficulty faced by some of the team members was unusual in comparison to other teams and previous student cohorts. However, viewed from the perspective of the pedagogical framework developed here, these experiences may be unusual to the extent that they cast into sharp relief systemic tensions in the learning environment that are usually more subtle.

Problem-Solution Coevolution

While problem-solution coevolution was a particularly obvious feature of Course C1, it was observed in all three courses. Requiring teams to define their own brief seemed an effective method of demonstrating the role of coevolution in design. The design brief both defines the problem to be solved and constrains potential solutions; creating the brief is therefore an exercise in problem-solution coevolution. The teaching staff in all courses coached the students to pay close attention to the language of the brief so that it did not frame the potential solution so exactly that subsequent exploration of a range of design concept would be difficult. That is, care was taken to preserve ambiguity in the wording of the brief. While Courses A1 and B1 placed emphasis on understanding the problem or need in advance of exploring solutions, the team briefs were not treated as stable and were regularly revisited, for example to modify mission statements or functional requirements.

Both design education and research on design practice often focus on the initial stages of the process, in particular on the concept design stage. As a result, most of the literature describing coevolution describes its prevalence during the early stages of concept development. However, it was clear from the data gathered in these courses that coevolution was a feature of the students' activities throughout the entire duration of the projects. Constraints were modified in response to lessons learned during detail design and the production of high-fidelity prototypes. This highlighted the importance of including these activities in project-based design courses. It seemed relatively straightforward for students to generate good ideas; the more interesting challenges and learning experiences typically arose as obstacles to making these ideas a reality. For example, the following quote from a student in Course A1 describes the experiences of many students.

> After spending many long days on looking for vendors, we basically changed many design ideas (and even discarded some of the functions) to adjust our models to the vendor capabilities... That's probably not the best way. We should deal with vendors much earlier...

Although the students had been advised many times to consider manufacturing capabilities when making design decisions, and the students believed they were doing so, many teams still found that their designs were unrealistic. These experiences provided valuable learning opportunities that would not exist in a course focused on concept design. However, the extent to which students benefited from these opportunities is unclear from the data.

4.2.2 Design Models

Models and Methods for Managing Uncertainty

Uncertainty is inherent in design but is often absent from the type of problem-solving addressed in engineering education. Engineering science courses typically focus on analysis problems with clear correct answers, and one of the aims of the new design courses studied here is to expose students to less well-defined problems. As would be expected, many students struggled when faced with this uncertainty and expressed frustration at the lack of objective methods for making decisions. Deciding between alternative concepts was one of the most commonly reported difficulties across the three courses. Table 4.2 contains a sample of survey responses from the concept design stage of the courses.

Design engineers use a range of approaches to reduce uncertainty, including drawing on precedents, prototyping, testing, and modelling and analysis. The teams were encouraged to experiment with these methods but found their application difficult. While the students were confident at solving analysis problems involving formulas and equations, the application of these equations to real physical systems proved problematic. This was due to difficulties making assumptions and estimates, another aspect of engineering that is typically ignored in analysis-focused courses (Dym et al., 2005; Linder and Flowers, 2001; Shakerin, 2006). In cases where students did engage in modelling and analysis, often this was done uncritically. For example one team used finite element method (FEM) analysis to evaluate the structural strength of their design. When the results were presented at a review meeting the teaching staff could immediately see that the graphical results looked "off," probably due to incorrect boundary conditions. Another team selected a motor based on analytically sound calculations

Table 4.2: Student perspectives on decision-making during the early stages of the courses

Course A1

S1: It is extremely difficult to take decision under uncertainty. It is really difficult to evaluate each possible design before going into extremely detailed designs. At the end of the day we choose strategies/concepts guided by hunches or by the positions of the stars that night.

S2: As you know, our biggest issue right now is to decide between two very different concepts. Since both have very different pros and cons and [our clinician] does not have a clear preference either, we are probably going to decide on the base of an intuitive feeling. I think the difficult aspect about this decision is to estimate the consequences that result from deciding on a concept.

Course B1

S1: [The main difficulty is] being decisive and directing all efforts towards a specific problem. [We're] trying to solve 50 problems instead of just focusing on one.

S2: [The main difficulty is] coming to an agreement with the rest of the group and getting a sense of direction as to what we are supposed to design.

Course C1

S1: Trying to decide on what direction to take, or how to converge on a final solution is proving difficult.

S2: Should we choose a new idea for the next prototype or should we be revisiting the previous concepts?

of power requirements, but ignored the unfeasibly large gear reduction that would be required to achieve the desired performance.

While these observations may seem troubling to engineering educators, in reality analysis of mathematical models often plays a small role in engineering design (e.g. Ullman et al., 1988). Testing may be of greater importance in guiding design decisions, and the observed teams performed tests whenever possible. However, engineering students' experience of conducting experiments usually involves following a procedure designed by the instructor or teaching assistant. As a result, students often struggled to design their own experiments. The teams in Courses A1 and C1 were expected to produce an experimental plan as a course assignment, but this plan was often subsequently abandoned by the students. Some teams expressed frustration at a perceived lack of access to testing equipment or difficulty recruiting people to take part in user testing and feedback.

The students were introduced to tools and methods to aid them in deciding between alternative solutions. An example is the Pugh Method, which prescribes the use of a matrix to evaluate possible solutions against criteria defined by the design team (Pugh, 1981). It is a group activity to be carried out during a meeting, and the matrix is intended as a visual aid to guide discussion rather than as an objective decision-making tool. Many of the student teams made use of the Pugh Method or a variation of it, with mixed results (Table 4.3). For some students the matrix seemed to work as intended, aiding team members in making preferences and concerns explicit. Other teams were more perfunctory in their use of the method, and seemed to consider it something they were obliged to do. In the case of the latter teams, Pugh matrices were often filled out by individuals for use in class presentations, rather than as part of a group discussion.

Systematic approaches to reducing uncertainty are an important part of engineering, but they do not replace the requirement for personal and intuitive judgment. This judgment is often based on reference to design precedents or to previous personal experiences, and the role of precedents in the observed courses will be discussed in detail in a subsequent section. Of interest here is the role of intuition in guiding student decisions. It is clear from the responses in Table 4.2 that during the early stages of the process the students were not comfortable basing their decisions on intuitive judgement. This observation is in line with commonly held views of engineers such as the following quote from an accomplished product designer (quoted in Cross, 2011, p. 9).

> A lot of engineering design is intuitive, based on subjective thinking. But an engineer is unhappy doing this. An engineer wants to test; test and measure. He's [sic] been brought up this way and he's unhappy if he can't prove something.

However, there are some indications that, through their experiences in these project-based courses, the students became more willing to trust their intuition. In the final weeks of Course A1 the students were asked to look back and describe how they dealt with uncertainty. Their responses often contained reference to intuition even though this was not a topic explicitly discussed in the course (Table 4.3).

Table 4.3: Student perspectives on decision-making during the later stages of Course A1

Decision-making methods

S1: Pugh charts and group discussion was very important. We operated usually on a consensus model since voting in such a small group was hard. Having regular meetings worked out a lot of the kinks in evaluating different ideas and figuring out which worked best

S2: After taking a number of design classes, the ideas are rather clear. My main issues still lie in the downselect process I guess. Pugh charts always seem a little uninspired – but it may be due to a dearth of many other good ideas rather than the process itself

Dealing with uncertainty

S3: Usually, we started by consulting all the resources we could find, including calling our doctor. Also, we gave ourselves time limits; if we didn't have a concrete rational[e] at the end of the time, then we just made a decision and moved forever.

S4: Choose what seems like the best option and going with it. If it ends up not being good, being flexible and going back.

S5: Follow our intuition and never look back!

Sketching and Prototyping

Sketching played a significant role in all of the courses, and this appeared to occur naturally; the role and benefits of sketching were never explicitly discussed by teaching staff. As would be expected, the use of sketches to develop and explain concepts was particularly prevalent in the early stages of the course, but was also a feature of student activity throughout detail design and prototyping. The use of whiteboards seemed particularly important to the students, with recurring complaints from teams who had difficulty accessing whiteboards during team meetings. This seems to indicate that sketching was conducted collaboratively and as a means of communication rather than simply to support an individual in working through design concepts. This reliance on sketching as a communication tool during the initial stages of projects may have been related to difficulties in expressing concepts verbally; as teams later developed their own project-specific terminology the reliance on explanatory sketching seemed to decrease, and collective drawings focused more on defining and recording details such as part dimensions (Figure 4.1). In addition to freehand drawing, students made extensive use

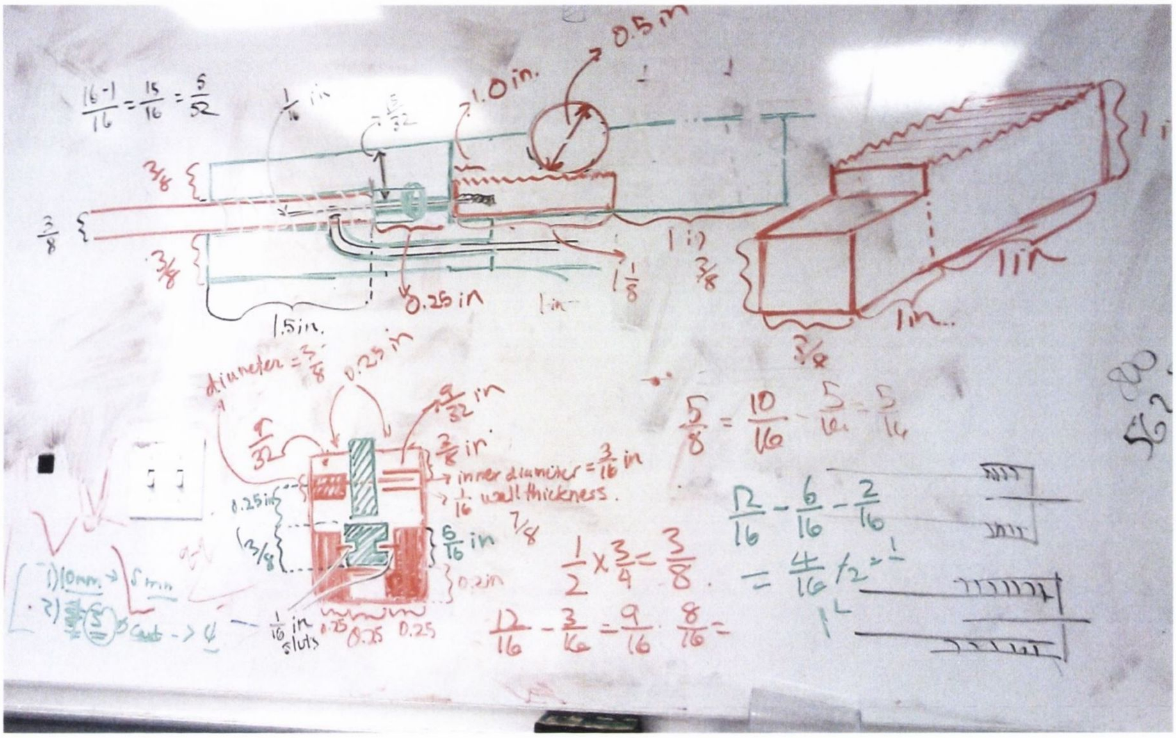


Figure 4.1: A student team's detail design whiteboard sketches.

of software environments to create visualizations. This ranged from basic graphics programs to create two-dimensional representations of concepts by combining simple geometric shapes to sophisticated three-dimensional CAD models and simulations. Of course, the use of these tools related to the nature of the design. Teams working on mechanical devices relied heavily upon CAD, while those developing software primarily used graphics programs to demonstrate user interfaces or create flow charts describing processes.

The production of low-fidelity prototypes during the initial stages of the courses seemed to have an impact on the process followed by teams. In Courses A1 and C1, prototyping exercises at the start of the courses were used to encourage students to build rapid low-fidelity prototypes using readily available materials such as cardboard, paper, and foam. In Course A1, these prototypes were referred to as sketch models, while prototypes referred to relatively high-fidelity physical models. This terminology will be used henceforth in this thesis to differentiate between the two types of prototypes produced in the observed courses. The introductory sketch modelling exercises observed ranged from a 90-minute class activity in which students were asked to build devices to transport a weight up an incline (Course A1) to a two-week mini-project in which students built a "bike," capable of transporting one of the team members, using cardboard and other paper-based materials (Course C1). These

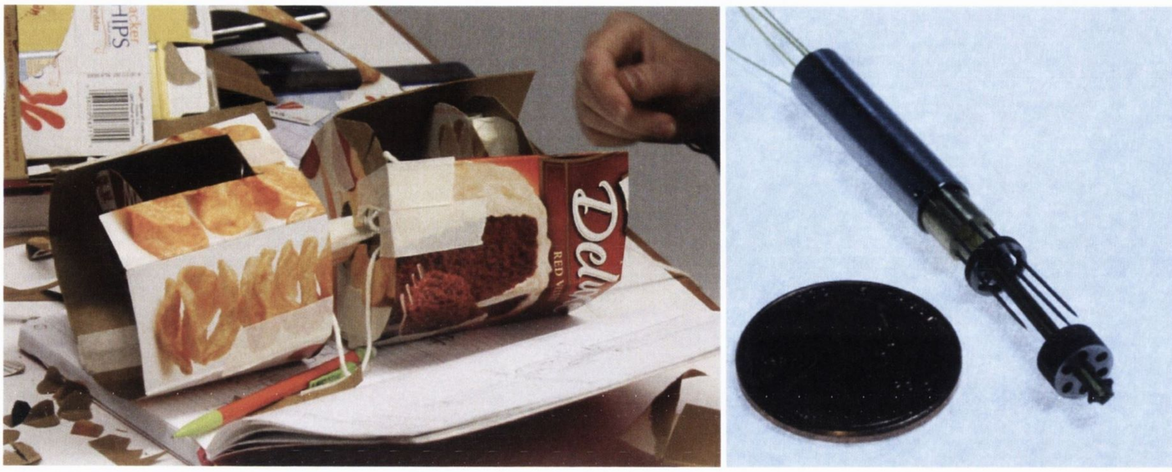


Figure 4.2: Student prototypes for a minimally invasive surgical tool. Left: early sketch model. Right: Final prototype.

activities seemed to have a positive impact on students' willingness to subsequently engage in sketch modelling and prototyping as part of their design projects. Course B1 did not involve an equivalent exercise and the students in that course seemed less likely to engage in prototyping activity of any kind. Similarly, the previous cohort of students in Course A had not completed a sketch modelling activity and the course lecturer observed that they were also reluctant to engage in physical modelling throughout their projects. In contrast, the teams in Course A1 built sketch models for each of their concepts throughout the course, and developed their final designs from initial cardboard models (Figure 4.2).

The learning opportunities provided by detail design activity and the production of high-quality prototypes were discussed in a previous section. Clearly, such activities rely upon access to facilities, a factor that varied between the three courses. Students in Course A1 appeared to spend more of their time solving problems related to detail design and prototyping, and these students also had more access to facilities, equipment, and materials. Hand tools were useful in all courses but typically did not provide insights into principles of design for manufacturability. Students' skill with such tools was minimal, resulting in low-fidelity models that did not highlight detail design problems such as tolerancing. More sophisticated equipment, such as CNC machine tools, or access to a prototyping budget to enable the use of external workshops, seemed crucial for mechanical design projects. A major difficulty in providing facilities to support student prototyping was identified: the open-ended nature of the courses made it impossible to predict in advance the types of machining operations, if any, that teams would need.

Finally, the importance of dedicated physical space was also highlighted. Typically, engineering students do not have access to personal work or storage space on campus, and this presents a significant obstacle to prototyping. The provision of a workspace dedicated solely to use by students in Course A1 was extremely beneficial in encouraging collective sketching and drawing, sketch modelling, prototyping, and testing.

4.2.3 Design Knowledge Reuse

The importance of design precedents for design and design education was discussed in Chapter 3. Students require access to design precedents for two reasons: becoming a successful designer requires developing a repertoire of previous design problems and solutions; and creative problem solving relies upon the ability to engage in analogical thinking, which in turn relies upon source material from which to transfer knowledge. Thus, the objective in providing access to precedents is to develop both declarative knowledge of previous cases, and procedural knowledge of how to make use of these cases.

Students were observed to use two types of precedents. First, in the initial stages of the projects existing devices were used to both frame the problem and to generate potential solutions. For example, problems were often framed so as to circumvent existing patents or commercially available devices. However, these same patents and devices were also used to inspire certain principles of operation, or synthesized with aspects of designs from other domains to produce novel combinations. These precedents, primarily used to guide decisions during the problem definition and concept design stages, are referred to hereafter as "concept precedents." The amount of information that teams required about concept precedents was minimal. Often, a patent drawing or description from a company website was sufficient for students to understand the design and reason about its applicability to their problem.

Concept precedents were typically identified as part of background research, prior art searches, or through interactions with stakeholders or teaching staff. Assignments were useful in encouraging students to identify these precedents. The first assignments in Courses A1 and C1 required teams to document the results of benchmarking research and prior art searches. Course B1 did not include an equivalent assignment, and those students seemed less aware of and less likely to draw on precedents for concept design. However, when students in all courses actively sought information on concept precedents, the level of access to this information seemed sufficient.

The second type of precedent used by student teams related primarily to the detail design and prototyping stages of the projects, and was used to identify methods of realizing a given concept. The information required about these precedents was much more detailed, and included specific mechanisms, machine elements, morphologies, materials, manufacturing processes, electronic circuit designs, software algorithms, and programming techniques. These precedents are hereafter referred to as "detail precedents." Detail precedents embody the type of domain-specific knowledge that novices must learn in order to become successful design engineers. A mechanical designer must understand the relationships between the dimensions of a part, the material of which it is composed, and the processes used in its manufacture. A software designer must understand the reasons to use different search algorithms in different situations.

In contrast to concept precedents, all teams encountered significant difficulties in retrieving and using detail precedents. In some cases this was due to poor strategy on the part of students. For example, some groups insisted on writing software code from scratch and through trial and error rather than referring to relevant and extensive documentation online. While the students' approach may have improved their low-level programming skills, it represents a lost opportunity to compare a range of approaches to achieving the same task, or to practice modifying and synthesizing code snippets from other programs. In many other cases, the difficulties were due to students' lack of technical knowledge or terminology. Searching for information on a particular type of mechanism was challenging if a student was unaware of the relevant term, or even whether such a mechanism exists. This type of difficulty was usually overcome through discussion with more experienced peers or teaching staff.

However, the most significant and widespread difficulty related to the use of detail precedents, in particular for mechanical design problems, was that the required information was simply not available. The details that students needed are typically omitted from patents in order to protect as wide a range of applications and instances of a design as possible. Information about manufacturing processes or material selection is often guarded as trade secrets. In other types of courses, experienced faculty may act as sources of knowhow, providing students with knowledge not attainable from textbooks or other documentary sources. However, in the open-ended courses considered here, in which each team worked on a different problem involving different technologies across multiple domains, it is unfeasible that teaching staff would be capable of providing all of the required detail precedent information regardless of their experience or expertise.

The effect of this issue is that much of students' time in these courses was dedicated to seeking basic information, rather than acquiring knowledge about how to interpret, modify, and use this information. This problem was so pervasive, and presented so significant an obstacle to the type of learning proposed as the objective of these courses, that it was identified as one of the primary issues to be investigated in subsequent research phases. The issue is closely related to some of the social aspects of design, which will be discussed in the following section.

4.2.4 The Social Nature of Design

In a team-based course it would be expected that issues related to teamwork, and in particular problems of "social loafing" (Latane et al., 1979), would be among the more common student complaints. Surprisingly, this was not the case: teamwork issues were rarely reported in questionnaire responses. This does not mean that teamwork was not an issue, and some students were observed to face substantial difficulties with teammates. However, many of these students indicated that they preferred to address the issue internally rather than seeking external assistance. In the majority of cases these difficulties did not appear to impact negatively upon other aspects of the course. Teamwork issues appeared to overshadow design work for only one team. When asked about their experience upon completion of the course, these students viewed the project as a learning experience, although what exactly was learned is unclear.

Whether the overall experience of sharing work was positive or negative, all students engaged in rehearsals of aspects of teamwork and collaboration skills. Multiple episodes of disagreement and resolution were observed during team meetings. In many cases students adopted strategies described in the literature, such as deferring disagreement and reference to standard practices or fundamental theories. Students employed rhetorical skill to convince teammates and teaching staff of the merits of one approach over another. These strategies appeared to emerge naturally, as none of the courses involved explicit coaching on them.

Invention of a Shared Language

As discussed in the previous chapter, the invention of a shared language is an essential part of engineering design discourse (Bucciarelli, 1988, 1994; Lloyd, 2000; Lloyd and Busby, 2001). In the early stages of the observed courses, the students struggled to make themselves understood when discussing their own ideas or existing devices, and relied heavily on non-verbal communication. As the projects progressed, all teams increasingly used their own terms for important assumptions and ideas. While this was evident in all courses, it seemed to be more prevalent in Courses A1 and C1. However, it is likely that this result relates to the amount of direct contact between the researcher and students in Course B1, rather than a difference in student behaviour; fewer meetings and discussions were observed in the latter course and opportunities to witness language creation were therefore minimal.

Table 4.4 contains extracts from team 1.1's meetings showing the changes in how they talked about their design over time. In the early stage of the course (Week 4) the students rely heavily on non-verbal communication, using visual aids and gesturing to explain both existing devices and solution concepts. When evaluating and selecting between alternative concepts three weeks later, the team has adopted a more precise technical language to describe types of mechanisms ("Sarrus linkage") and aspects of the clinical problem ("purse-string suture"). They are using common technical terms that would be understood by clinicians and engineers, and have started to name their own ideas, such as "collapsing device." During the detail design phase (Week 10), they have adopted their own project-specific vocabulary, with terms such as "slider" and "inner-shaft guides" referring to particular morphologies and principles of operation. These terms function as shorthand for shared ideas and experiences, containing references to prototypes and tests. While visual aids continue to play a part, team communication is now primarily verbal.

The type of language adopted by teams seemed related to the amount of domain experience possessed by team members. Each member of team 1.1 had extensive experience in either mechanical design or biomedical engineering, and as a result they tended to apply technically accurate terms to their concepts. In contrast, only one member of team 1.15 had experience in the relevant problem and solution domains. This team did invent a language to discuss their ideas and the terms used, such as "Lil' Jon" and "Tunnel Vision," tended to be less technical. While these terms are perhaps more imaginative, they seem to carry less meaning for the teams and refer more to surface features or wordplay than to principles or functions. For team 1.15, "Lil' Jon" is a reference to the lyrics of a popular song which do not carry any particular implications for the design. For team 1.1, the seemingly straightforward "slider module" term implies references to linear bearings and to design concepts such as St.

Table 4.4: Team discourse over time

Week 4

A team member (S4) is explaining the principle of operation of a device found during the prior art search. The explanation is largely non-verbal; S4 is standing beside a projector screen, pointing to parts of a patent application drawing, and using gestures to explain movement. Parts of the device are referred to as "this thing" and "this guy."

Week 7

S1: We could use a Sarrus linkage, but the joints would have to be super small. Would they be strong enough under force?
TS1: For a collapsing device you're going to have to insert a Foley catheter anyway. Can you go down in French size?
TS2: They do use smaller catheters if you have a constriction or something
[...]
S1: Will clinicians be upset if you create a constricture that might become permanent?
S2: And if you have to tie the purse-string sutures you could be in trouble as the tissue won't re-expand.

Week 10

S2: For the slider module we thought injection molding would be best but it's expensive.
[...]
S1: Well we 3D printed a slider and rigid tube and it works well–
S3: One thing we had talked about was the number of inner-shaft guides. We decided to have three so as to constrain the slider.

Venant's principle (Toupin, 1965), which guide their thinking on the appropriate constraints and aspect ratio for the part.

Distributed Expertise

The development of distributed expertise (in the FCL sense of the term) seemed an inevitable consequence of the learning environments. Each team tackled a different problem and therefore acquired and constructed different knowledge. Within teams it was not possible for all members to share equally in all aspects of the project, and individual students tended to assume responsibility for particular activities and subproblems. In Courses A1 and C1, this tendency was encouraged through coaching in the weekly review meetings. In each meeting, the students were asked to outline both their immediate and longer-term goals and to identify tasks required to achieve those goals. The students then assigned the completion of these tasks to particular team members with guidance from the teaching staff. Often these tasks were focused on immediate goals, and in the early stages of design the roles within a team typically changed from week to week. As the courses progressed, each team member tended to assume a managerial role for some aspect of the project, such as CAD modelling or testing of prototypes. In most cases it was not clear whether and to what extent students shared their specialized knowledge with their teammates, although in review meetings students seemed capable of explaining and discussing the work in each other's area of "expertise."

Given the importance of knowledge sharing between engineering design teams in industry, as discussed in Chapter 3, it would be valuable to encourage the student teams in a given course to interact and pool knowledge where appropriate. However this did not seem to be a feature of any of the courses. For team 1.15, this is understandable as they were the only group of TCD students participating in Course C1. In an approximation of the "group crit" used in studio-based design education, students in Courses A1 and B1 regularly presented their work to their classmates, who were encouraged to provide critical feedback and share any insights from their own projects. However, the level of audience participation was minimal; when pushed to respond to presentations the students typically asked for clarification on minor details without making any suggestions or criticisms.

It is possible that informal knowledge-sharing between teams was a feature of these courses, as it would be expected that such interactions would primarily occur outside of formal teaching settings. It is also reasonable to expect that the variety of projects observed in the courses was an impediment to inter-team communication; while the teams were not in direct competition, they also had little common ground on which to base such communication. However, in Course A1 it was observed that on several occasions students shared information with another team, by first sharing it with teaching staff members and suggesting that it could be of benefit to another team. The weekly review meetings were often used to highlight similarities between problems being faced by one team and a solution being considered by another, and students were regularly advised to make use of the specialized knowledge being developed by other teams. The reasons for students' reticence to engage in inter-team communication, and their reliance on the teaching staff to initiate such interactions, were unclear. Interestingly, it seemed that some students would have welcomed more interaction with other teams, but felt that this should have been organised as a formal activity. The following quote from a student in Course A1 illustrates the point.

> Perhaps having the opinions from people outside of our project [would be helpful]. It would be interesting to pair two groups for a day and do combined brainstorming to develop more ideas or variations. The presentations in class are nice, but they are not oriented to a think tank. A day or two of doing large group think tanking would be an awesome experience.

Communities of Practice

From the perspective of situated learning theory, learning is participation in a community of practice. In exploring a learning environment it is necessary to ask what community is being participated in, and reproduced, by the learners. In the case of engineering design courses, a reasonable aspiration would be for learners to participate in engineering communities of practice, that is, groups of engineers of varying levels of experience working on similar problems and sharing and co-constructing domain knowledge. If the aim of OATPB courses is to support students in rehearsing designerly ways of knowing, access to such communities would seem to be essential. However, all three courses were characterized by obstacles to participation in engineering communities of practice. In particular, students faced difficulties in accessing solution domain expertise.

Students did have direct access to experts: in Course A1, each team worked with an experienced clinician; Course B1 students consulted with design advisors from the NCBI; and the Course C1 design team worked closely with an industry sponsor. However, in each case these experts were sources of problem domain knowledge. Their role in the projects was that of the client, and not that of fellow practitioner. While these experts provided knowledge that was invaluable for the definition of problems and the framing of potential solutions, they did not provide the engineering knowledge required by students. These knowledge requirements typically arose in the later stages of the projects in response to difficulties in detail design, prototyping, and testing. Even in the case of Course C1, in which a software firm acted as sponsor for a software-focused project, this phenomenon was observed. The practical design knowledge of the sponsor seemed unavailable to the students while they were implementing their design in code.

Problems of access to communities of practice were not due to ignorance or neglect of this issue by teaching staff. As noted in Section 4.2.3, it is unfeasible for teaching staff to provide the domain knowledge required by all student teams. The observation data records multiple examples of teaching staff attempting to address this by connecting students with engineering researchers and professionals with experience relevant to a team's project. This was typically done in an ad hoc fashion, with teaching staff searching their social networks for candidate experts in response to emerging team needs. This reactive, improvisational approach was necessary as it was not possible to predict in advance the type of domain knowledge a given team would need. However, the time required to identify relevant experts and arrange meetings with the students, combined with the severe time constraints under which the students were working, often meant that the connections came too late. In some cases, the direction of a project had been altered by the time a meeting had been scheduled, rendering any potential interaction irrelevant.

There are clear parallels between this issue and that of design knowledge reuse: in both cases students have sufficient levels of access to support problem definition and concept design activity, but face significant impediments during the later stages of the projects. In fact, the two issues are interrelated. Studies of knowledge sharing in industry have found that when answering factual questions or clarifying tasks, designers refer to formal and documentary knowledge sources. However, during later design phases, and in particular when tackling diagnostic problems, the use of social sources is dominant (Ellis and Haugan, 1997; Milewski, 2007). That is, designers access problem definition information and concept precedents through documentary and other formal sources, but access detail precedents through informal social interactions with peers. Even when documentary sources of knowledge are available, novice designers require guidance from more experienced engineers to interpret and make use of design precedents (Demian and Fruchter, 2006). The observed problems related to students' lack of access to detail precedents may therefore be due to their lack of access to engineering communities of practice, and in particular to more experienced design engineers.

4.3 Conclusions

This chapter has described the first of three phases of research in OATPB courses. This phase of research was conducted in three courses at two institutions. The objective of the chapter was to explore the experiences of students and teaching staff in these courses from the perspective of the pedagogical framework developed in Chapter 3. Particular attention was paid to the type of process followed in each course, the use of design models, access to design precedent knowledge, and the opportunities available to students to engage in the types of social interactions that are fundamental to engineering design. A fundamental issue evident in each of these topics was a tension between the need for teaching staff to plan activities and support for students in advance on one hand, and the open-ended, unpredictable nature of the student projects on the other. The results from this chapter are summarized here, and are used to further develop the pedagogical framework, which will in turn be used to modify the learning environments in future phases. A third column has been added to the framework in Table 4.5 to record features of the learning environment that relate to the knowledge categories and theories. Problematic aspects of the courses that require further attention in future research phases are highlighted in bold font.

Design Processes and Strategies

All teams were observed rehearsing design behaviours described in Chapter 3, in particular problem-solution coevolution and attempts to manage uncertainty. Students appeared to become more comfortable using intuitive judgement as a result of their experiences in the courses. All courses used assignments to guide students through a particular design process, combined with feedback and coaching to provide opportunities for flexibility within those processes. A fundamental tension has been identified between the methodical and flexible aspects of the courses. In the observed cases, a top-down, breadth-first structure combined with regular design review meetings appeared to align most closely with the objectives contained in the framework. Episodes of local task optimization were observed, during which students focused their efforts on immediate assigned tasks with little attention paid to their relationship to overall design or learning goals. This behaviour appeared to be at least partly caused by problematic aspects of the learning environment. Providing clear information about the process followed in the course, such as a detailed syllabus document, was identified as a potential means of addressing this issue.

Design Models

Students were observed to engage in sketching and drawing without being instructed or required to do so, particularly during the early stages of the courses. However, the amount of physical modelling undertaken by teams seemed to be related to introductory sketch modelling activities during which students were encouraged to build rapid low-fidelity prototypes using low-cost materials. The teams that participated in these activities appeared more likely to subsequently engage in physical modelling throughout their projects. The use of such exercises is therefore proposed as an addition to the pedagogical framework. The importance

Table 4.5: Pedagogical Framework for OATPB Courses

Design Knowledge	Guiding Theory	Learning Environment Feature
Strategies	*Strategic Nature of Learning*	
• Learning strategies • Design strategies • **Task optimization strategies**	• Metacognition • Reflection • Alignment of tasks and learning goals	• Overview of course process
Process	*Cognitive Apprenticeship*	
• **Flexible-methodical process** • Problem-solution coevolution • Tolerating uncertainty	• Coaching • Modelling • Articulation • Reflection	• Methodical: assignments and milestones • Flexible: coaching via regular review meetings
Models	*Social constructivism*	
• Sketching • Prototyping	• Guided discovery	• Introductory sketch modelling exercise • High-fidelity prototyping • Facilities
Design Knowledge Reuse	*Cognitive Flexibility Theory*	
• **Precedents** • Fixation	• Multiple representations • Contextual information • Concepts linked to precedents • Emphasis on interrelations • Knowledge assembly	• Concept precedents • Detail precedents
The Social Nature of Design	*Fostering a Community of Learners*	
• Role of language • Team roles • **Inter-team communication** • Distributed cognition	• Dialogic base • Distributed expertise • **Communities of practice** • Multiple zones of proximal development • Instructor guidance	• Regular meetings • Assignment of individual responsibility • Access to stakeholders • **Access to engineering communities of practice**

of high-fidelity prototyping as a learning experience was identified. Supporting students' prototyping activities through providing access to the required materials and facilities was identified as a difficulty for teaching staff, in part due to the open-ended nature of the courses which made predicting resource needs in advance impossible.

Design Knowledge Reuse

Student teams made extensive use of design precedents during the problem definition and concept design stages of the courses, both to suggest potential solution concepts and to identify "competing" designs to circumvent. These types of precedents are here termed "concept precedents." The amount of information that students needed about such precedents was minimal, and documentary sources such as online patent databases appeared sufficient. However, during the later stages of their projects the teams struggled to access more detailed knowledge about the design and manufacture of precedents. This lack of access presented an obstacle to learning as it impeded students' ability to rehearse analogical reasoning and transfer of knowledge from one context to another. The type of detailed knowledge required by students during these stages of the courses is here termed "detail precedent" knowledge. Students' difficulty in accessing detail precedents was closely related to a lack of access to engineering communities of practice.

Social Aspects of the Courses

All courses successfully provided opportunities for students to rehearse the types of social interactions that are essential to design knowledge. Minimal guidance was required to encourage teams to adopt behaviours observed in the literature, including deferral of disagreement and the invention of a shared language. The type of terminology adopted by teams, and the implications of that terminology for how they thought about their designs, appeared to be related to the students' level of domain experience. The courses also allowed learners to rehearse interacting with clients and stakeholders and to learn about the role of such interactions in guiding the technical aspects of design. However, all courses were characterized by a lack of sufficient access to more experienced engineers, and in particular there were minimal opportunities to participate in engineering communities of practice. This issue was related to the open-endedness of the courses, which made it unfeasible for teaching staff to predict the knowledge needs of students in advance. Finally, the amount of inter-team communication observed was minimal, and may be due to the wide variety of design problems and solutions tackled by students, which often meant that there was no direct link between one project and another.

Next Steps

The following Chapter describes attempts to address many of the issues raised during this chapter, in particular the problems of access to design knowledge and experience. Project themes, closely related to the work of local research groups, are introduced in Course A and Course B in an attempt to connect students with more experienced designers and researchers. Chapter 5 also describes attempts to apply aspects of the learning environments from Courses A and C to that of Course B. The chapter thus explores the feasibility of transferring lessons from one context to another, and of scaling successful methods to meet the needs of larger student cohorts.

Chapter 5

Research Phase 2

The objective of this thesis is to develop a pedagogical framework for open-ended, authentic, team- and project-based (OATPB) engineering design courses. In Chapter 3, the initial embodiment of the framework was developed through a review of the literature on design practice and theories of learning. The framework consists of essential aspects of design knowledge that may serve as objectives guiding the development of learning environments. For each aspect of design knowledge a corresponding learning theory was identified; these theories are intended to provide guidance on achieving the learning objectives. In Chapter 4, this framework was used to guide an exploration of three OATPB courses. The results of the research highlighted issues in the design of learning environments, in particular a tension between the flexible and methodical aspects of the design process, a lack of access to detail design precedent knowledge, and a lack of access to engineering communities of practice. The pedagogical framework was expanded to record features of the learning environments that appeared to align with the learning objectives and theories, as well as to highlight issues that require further attention.

This chapter describes the second of three phases of empirical research in educational settings. Two courses were selected for exploration in this phase. Modifications were made to the learning environment of each, guided by the pedagogical framework, and the results of these modifications were observed. The chapter begins by describing the changes to the learning environments as well as the research methods used in each context. In subsequent sections, the experiences of students and teaching staff are again described and interpreted in relation to the pedagogical framework. Particular attention is paid to those aspects of the courses that were identified as problematic during the previous phase. The chapter concludes by further expanding the framework to reflect the results of the research, as well as identifying topics of focus for the third phase of research.

5.1 Context

Courses A and B were selected as the research sites during this phase. The selection of courses was partly one of convenience: these contexts offered opportunities for greater influence to be exerted over aspects of the learning environment. However, the courses were also selected due to their similarities and differences. Both courses shared a similar teaching philosophy and course process, but they differed significantly in terms of number of students, available resources, and overall context. Thus, one of the research objectives was to investigate whether

Table 5.1: Overview of the courses

Course code	A2	B2
Academic Year	2012-2013	2013-2014
Level	Mixed	Undergraduate
Type of projects	Electromechanical	Mechanical, Electronic, and Software
Duration of project	15 weeks	21 weeks
Number of students	16	61
Number of teams	4	10

similar teaching approaches and learning activities, informed by the pedagogical framework, could be applied in two very different contexts. A second research objective was to explore the use of project themes as a means of providing access to engineering communities of practice. Themes linking student projects to each other and to the work of engineering research groups were introduced in both courses. In doing so, the hope was that these research groups would serve as communities of practice in which the students could participate. The following sections describe the theme introduced in each course as well as other changes to the learning environments. Table 5.1 contains a summary of information about the courses.

5.1.1 Course A2

During the second phase of research, the overall format of Course A remained unchanged. Again, four teams of students worked with four clinicians to develop solutions to unmet clinical needs. The class was composed of four graduate and twelve undergraduate students. A top-down, breadth-first process was imposed on the student projects through milestones and assignments, and the weekly review meetings between each team and the teaching staff provided opportunities for coached deviations from this process. As before, the course culminated in a showcase at which students presented their designs and demonstrated their final prototypes to an invited audience.

The major change in the learning environment of Course A during Phase 2 was the introduction of a technological theme. The focus of the course became medical applications of soft robotics technology. Soft robotics is a field of research that studies the use of low-modulus,

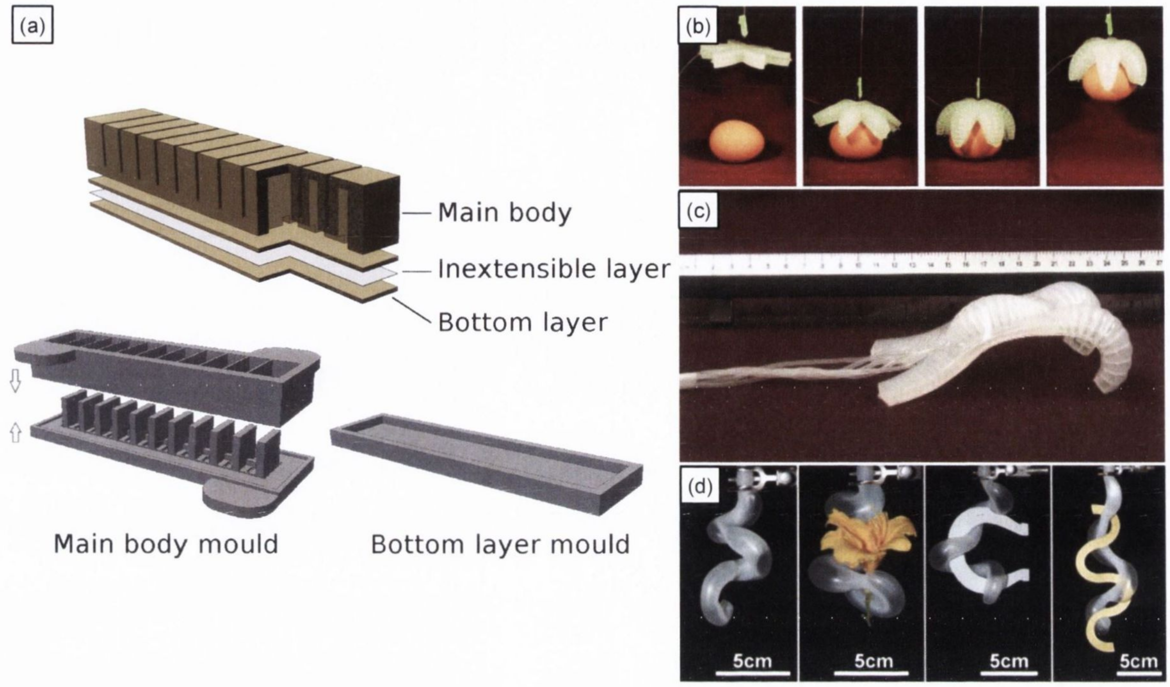


Figure 5.1: A variety of configurations of the PneuNets soft pneumatic actuator: (a) Schematic of an actuator and the moulds used in its fabrication; (b) A soft robotic grasper (Ilievski et al., 2011); (c) An ambulatory quadruped (Shepherd et al., 2011); (d) A robotic tentacle (Martinez et al., 2013).

often hyperelastic, materials in the design of electromechanical devices. An example of a soft robotic component is shown in Figure 5.1. This fluidic actuator consists of an elastomeric body with an embedded layer of inextensible but flexible material, such as paper or fabric. The body of the actuator is formed using a 3D printed mould, and contains chambers linked by a central channel. When the air pressure inside these chambers is increased, they expand resulting in an elongation of the entire body. However, one side of the body is constrained from expanding by the inextensible material, resulting in an overall bending motion. By varying the morphology of the actuator and the configuration of inextensible reinforcements, a variety of complex motions can be achieved using only air pressure as input. Figure 5.1 shows four variations on the same type of actuator.

Soft robotics was selected as a theme in Course A2 for two reasons. First, soft robotics is of interest in medical applications as it enables compliance matching, or the design of devices that match the material properties of human tissue, thereby potentially reducing trauma or discomfort. Second, soft robotics research is an active area of research at Harvard involving a large number of faculty, postdoctoral researchers, and graduate students. These researchers are spread across multiple groups and academic disciplines and are involved in sharing knowledge across these boundaries. The selection of a soft robotics theme was intended to connect students with these researchers and thereby enable them to participate in a large and active community of practice.

In order to accommodate this change the approach to identifying candidate projects was modified. Instead of inviting clinicians to propose projects, the teaching staff sought medical problems related to tissue injury or patient discomfort. Clinicians in a variety of fields were consulted, including surgery, emergency medicine, and physical therapy. As before, eight candidate project-clinician pairs were identified and presented to the students, and team formation proceeded as before. The use of the theme was not intended to eliminate the open-ended aspect of the projects, and each student team was again required to define its own brief. Two of the teams pursued solutions that were not within the original definition of soft robotics as understood by the teaching staff. The remaining two teams made use of fluidic soft actuators, but did so in a way that was unexpected. Thus, the open-endedness of the course was maintained.

A series of labs was added to the schedule to introduce aspects of soft robotics such as mould design and fabrication techniques. These labs took place in the initial weeks of the course, in parallel to the students conducting needfinding and prior art research. One of these labs focused on the assembly of a fluidic control board, consisting of a miniature pump, a pressure regulator, solenoid valves, relays, a microcontroller, and pressure and flow sensors (Figure 5.2). This board was capable of operating most types of fluidic actuators and was intended as a tool to support prototyping and testing. Each team assembled one board; this activity was intended as an opportunity for students to learn basic electronics skills and to enable them to subsequently modify the board if required.

5.1.2 Course B2

Considerable changes were made to the project-based component of Course B during Phase 2. The duration of the project was increased so that the students had almost the entire academic year to develop their designs in parallel to the other course components discussed in Chapter 4. As before, the research focused solely on the project-based component of the course. To address the issues of clarity reported during Phase 1, a detailed syllabus document describing the weekly course activities and project milestones was provided to students. A condensed version of this syllabus is provided in Appendix F. An introductory sketch modelling exercise

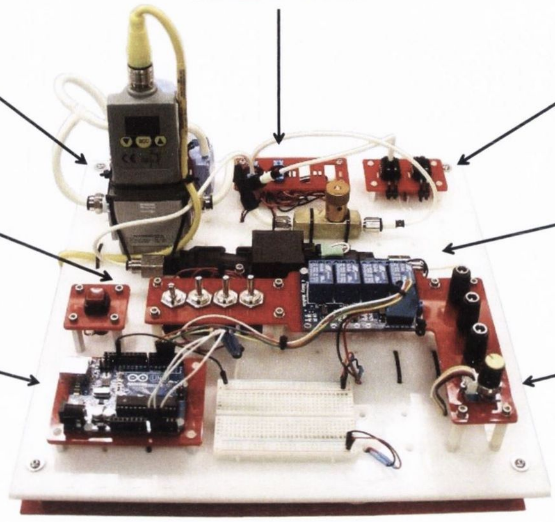


Figure 5.2: The fluidic control board provided to students in Course A2.

was used to encourage students to engage in physical modelling throughout their projects, and new materials and machine tools were made available to support high-fidelity prototyping. These tools included a CNC router, a hot wire foam cutter, and an acrylic strip bender. New lab activities were introduced to train students on the use of this equipment.

A project theme was also introduced in an effort to connect students with researchers. Student teams were required to design solutions to support successful ageing. Due to the phenomenon of population ageing in Europe, research to support successful ageing is a large and active field in Ireland. A variety of interdisciplinary research groups and centres are engaged in data collection and technology development aimed at improving quality of life for the elderly. Trinity College Dublin is home to many of these groups, and is also involved in collaborative projects with other institutions. Thus, a focus on projects related to successful ageing was intended to facilitate students in interacting with a wide variety of domain experts. As before, teams were required to recruit a stakeholder group and work with them to define a need. They were encouraged to include domain experts in this group, and were provided with details of research groups both at TCD and at other institutions.

More frequent milestones and deliverables were introduced in order to support the methodical aspects of the design process. To allow for flexibility within the process, weekly review meetings were added. During these meetings, five teams provided updates on their projects to the teaching staff and the other teams, who provided feedback on current progress and advice on subsequent tasks. Formal student presentations coincided with major milestones throughout the course, culminating in a public showcase during the final week.

5.1.3 Methods

Data collection during Phase 2 relied on methods that were largely similar to those used in Phase 1. As before, the role of the researcher in each course was that of teaching assistant. Fieldnotes were used to document weekly review meetings, lectures, lab activities, contextual interviews, and informal interactions with students. The new structure of Course B2 allowed a much greater level of access to students than was possible during the previous phase. Artefacts, including student documentation as well as photographs of sketches and prototypes, were collected. The "muddiest point" questionnaires were again used in Course B2 as a means of monitoring student understanding and identifying potential issues. Given the small number of students and substantial amount of contact time in Course A2, monitoring understanding and issues directly was possible. Thus, questionnaires were not used in that course, but were replaced with exit interviews with eight of the sixteen students, representing half of the members of each team. Data analysis was conducted as described in Chapter 2.

5.2 Results and Discussion

5.2.1 Design Processes and Strategies

With regards to the processes followed in the courses, the primary difference between Phases 1 and 2 were the changes to the structure and delivery of Course B. The introduction of regular milestones, weekly review meetings, and a detailed syllabus document were intended to clarify the course process for the students, and to address shortcomings in the amount of coaching available to teams. In many respects these changes were based on the efficacy of methods observed in Courses A1 and C1, and an objective of the research in this phase was therefore to explore whether methods from particular courses could transfer successfully to a very different context and a much bigger scale. Of course, this transfer involved making many modifications to suit the new context; it is not claimed that teaching methods could be universal and context-independent.

These changes appeared to have a positive impact on the course. Students were much clearer about the design process being followed and teaching staff were better able to monitor each team's progress and provide regular feedback. Coaching on such a scale was difficult, particularly given the limited time available in students' schedules. The simple weekly questionnaires, originally intended purely as a data gathering instrument, were in fact used to support coaching. Recurring questions and difficulties reported in students' questionnaire responses were identified and addressed during subsequent lectures. This did not replace the need for direct coaching of individual teams, but by answering general logistical or process-related questions during lectures it was possible to spend more time discussing particular aspects of each project during the weekly reviews.

Questionnaire responses were also used to guide adjustments to the learning environment during the course, and to involve students in making those adjustments. For example, in the early stages of the course it became clear that students were dissatisfied with the format of the weekly review meetings. Initially, these meetings were structured around informal presentations. Each team presented updates on their progress during the previous week to the teaching staff and four other teams. The teaching staff responded to each presentation and invited other students to contribute. The questionnaire responses highlighted some problems with this approach. For example, students felt that the format resulted in feedback focused on the quality of presentations rather than the quality of project work, and that attention was paid primarily to completed tasks rather than future directions and decisions. Furthermore, students were uncomfortable with all discussion taking place in front of other teams, and reported that they did not "want to ask too much in front of everyone." To address these problems, a class activity introducing concept generation and selection methods asked students to redesign the weekly review meetings. The students' "designs" were collected and used to guide modifications to the meeting format. The new format involved each team providing a two-minute update to the entire group, followed by the teaching staff spending time with each team individually. These changes appeared to address many of the issues raised by the students.

Grading

Comparing between the two courses studied in Phase 2, problems related to the tension between the flexible and methodical aspects of the course were particularly prevalent in Course B2. There were many logistical and contextual differences between the two courses that might account for the contrasting observations. However, a fundamental reason may be a seemingly subtle difference: the assignment of grades. In Course A2, students received a weekly qualitative "grade" summarizing the teaching staff feedback on their progress. A "check minus" indicated that team needed improvement, a "check" meant that their work was satisfactory, and a "check plus" was awarded when the team had made substantial progress during the preceding week. These feedback summaries were not directly tied to their final numerical grade for the course, which took account of their overall performance rather than a tally of weekly scores. In contrast, the teams in Course B2 were assigned numerical grades for each milestone, and these counted towards their final grade. In both cases the grades were intended to provide regular feedback to the teams and to allow the teaching staff to keep a record of student performance throughout the course.

The seemingly minor difference between grading methods appeared to have a major effect on student perceptions of tasks in each course. The survey and observation data from Course B2 contain repeated references by students to grades, while grades are never mentioned by Course A2. The fact that numerical grades were the most visible aspect of feedback from the Course B2 teaching staff appeared to signal to students that the attainment of high scores was the primary objective in undertaking any individual task, thereby creating perverse incentives. From the students' perspective grades appeared to be assigned almost every week based on adherence to the course process. This was an incentive to conform rigidly to that process and never deviate into exploring alternatives or taking creative risks, even if advised to by teaching staff. The finality of being assigned an immediate grade for a task meant that students had no reason to revisit that task. For example, if the teaching staff felt that a team's exploration of alternative solutions was insufficient, they would assign a low score for that week. For the students, the most important part of the task, the grade, had now been decided and there was nothing to be gained from spending more time exploring solution concepts. This is another example of the role of environmental cues in fostering local task optimization strategies among students. Thus, the data gathered during this phase appears to indicate that regular quantitative grading is poorly aligned with the learning objectives of OATPB courses, and that qualitative feedback is therefore preferable.

5.2.2 Design Models

An additional change to Course B during this phase was the introduction of a sketch modelling exercise at the beginning of the course. Before commencing their successful ageing projects, each team was required to design a novel bike stand and to build and document rough models demonstrating their design using household materials. The results of this change appear to confirm the observation during Phase 2 that introductory sketch modelling exercises encourage students to engage in more modelling throughout their projects. The effect of such a simple exercise seems remarkable. Compared to the previous student cohort, Course B2 students were more likely not only to engage in physical modelling, but also to create storyboards, produce videos, and incorporate music into presentations. It seems likely that such exercises signal permission to students to engage in activities that are typically absent from engineering coursework. Many participants in all observed courses had extracurricular interests in creative activities including digital art-making, photography, and filmmaking. Being encouraged to make rough models and freehand sketches apparently encouraged them to integrate these activities into their design projects. That being said, many students in Courses A2 and B2 did not see value in sketch modelling exercises, considering them "arts and crafts" and "not engineering."

As hoped, increased access to prototyping facilities and materials in both courses resulted in a greater number of prototypes produced and more attention paid to detail design and manufacturing issues. The selection of a technological theme for Course A2 allowed many of the teams' material and equipment needs to be predicted in advance and thereby addressed one of the previously identified obstacles to supporting student prototyping in OATPB courses. Furthermore, the provision of the fluidic control board was observed to be beneficial for two of the four teams. Access to the board allowed these teams to rapidly prototype and test a variety of actuator designs, and allowed them to focus on the development of their medical devices rather than dedicating time to designing and sourcing supporting hardware. However, the assembly of control boards by students did not appear to be a useful learning activity. Team members with practical electronics experience tended to take responsibility for this task and did not feel they benefited from it.

The addition of a lecture covering fundamental mechanical design principles seemed to encourage some Course B2 students to engage in more approximate analysis; however, for many teams in both courses analysis was either unfeasible or inappropriate. In particular, modelling soft robotics components is difficult even for experienced researchers, due to the use of hyperelastic materials with nonlinear behaviours (Lipson, 2013). As a result, only one team in Course A2 used modelling and analysis to guide their design. Some students felt that a lack of analysis meant that their project was "not engineering," again referring to "arts and crafts." The belief that all engineering projects rely on the use of mathematical models is at odds with the reality of design, which often relies on prototyping and testing as a more efficient method of guiding decisions in situations where creating analytical or numerical models would be too complex or time-consuming. This belief is potentially a result of the emphasis on analysis in engineering education. The misconception is troubling as it indicates that students are unaware that they are rehearsing engineering design knowledge, which is a barrier to the type of deliberate practice required for the development of expertise.

5.2.3 Design Knowledge Reuse

The objective of introducing course themes in both settings was to increase access to design knowledge by enabling students to interact with engineering communities of practice. Thus, students' retrieval and use of design knowledge was primarily a social activity, and is explored in the following section. However, Phase 2 also provided an opportunity to further investigate students' attempts to access design knowledge from documentary sources. This section describes some difficulties and successes encountered by students attempting to retrieve and use information about detail precedents from online databases.

Detail Precedents for Software and Electronic Design

During this research phase it was observed that students do in fact make extensive use of detail precedents from documentary sources when working on design tasks. However, these tasks are consistently related to software or electronic circuit design rather than mechanical design. Software source code is typically a set of text files, while electronic wiring diagrams are pictorial representations. Text and image files tend to be platform-independent, in that they can be viewed and manipulated using most computer platforms, and are therefore ideally suited to sharing via the Internet. Thus, an online culture of sharing code and circuit diagrams exists, and students draw on these examples when prototyping their own designs. In the observed cases of this activity, students did not seem to use such precedents for concept design or problem definition, but drew on them solely when attempting to implement a design. In order to understand how students use such detail precedents, and what effect this might have on their learning, contextual interviews were conducted with students working on electronic or software design tasks. Excerpts from one such interview are presented here.

The student is trying to use an Arduino microcontroller to read values from a flexion sensor, which exhibits a change in resistance as a result of angular deflection. She wants to embed the sensor in a soft bending actuator in order to monitor the actuator's deflection, but first she must figure out how to interface the sensor to the computer, via the Arduino. She is using a booklet of example Arduino projects as a source of guidance.

> R: Is there any project that seems relevant?
>
> S: Yeah... there's one for a force sensor with code and how to set it up... there should be one for the sliding sensor which is similar to this guy...
>
> R: Can you find that example in the book?
>
> S: Not in this which is surprising as I know we built one in [an electronics course] last year using this guide... Oh I think they changed it... It was a potentiometer... They update [the booklet] from year to year.
>
> [...]
>
> R: Are you following their diagram for the force sensor example?
>
> S: Yeah it seems like a good place to start. The LED brightness changes based on the pressure on the sensor, we could do the same for the flex sensor... or we could just read in the value instead...

The student demonstrates an understanding of the basic operation of the sensor, and can draw an analogy with examples in the booklet which deals with other types of variable resistor ("a force sensor" and "the sliding sensor"). The booklet contains a wiring diagram for connecting the sensor to the microcontroller pins, and source code for reading the voltage at the relevant pin. The student refers to the wiring diagram to connect her sensor, adapting it to eliminate unnecessary components including an LED.

> R: Which resistors are for the LED and which are for the sensor? Do you need these resistors?
>
> S: Oh I think that's right. We can just go straight to the pin.

The student connects the sensor to the Arduino, which is connected to a computer, and modifies the code in the booklet to read in the sensor value and display it in the serial monitor. She compiles and runs the code but nothing happens, and she has trouble finding the serial monitor window. She tries to figure out if there is something wrong with the circuit or the code, but cannot see a problem. Eventually she searches online for a solution and finds a website that explains how to open the serial monitor.

S: That's my procedure for any programming language. Go on Google and search something and scroll through the results. It works better for some languages than others... This is how I choose what language to use.

The student also searches for instructions on using a flexion sensor with Arduino. She finds an example wiring diagram which includes the resistor that she earlier thought was unnecessary. By following the diagram she is able to get the circuit and software working as intended.

R: Why is that resistor necessary?

S: [Looks at diagram, thinking] Well without the resistor the sensor is the only thing between the source and ground, so all the voltage has to drop over the sensor... You need another voltage drop between the sensor and ground so that the drop over the sensor can vary.

This brief episode concerned a relatively simple task which was part of a project focused primarily on the mechanical design and fabrication of soft robotic actuators; such electronic design tasks were a minor component of the student's work. However, the episode demonstrates some features of student use of detail precedents. The student considered herself a mechanical engineer with minimal practical electronics knowledge. However, she seemed confident in reasoning about precedents, drawing analogies between different types of sensors and displaying no hesitation in adapting the precedent circuit to her own needs. Her confidence seems to be based on her experience using similar approaches to software design; she has a "procedure" for finding and using precedent knowledge and bases design decisions such as the choice of programming language on the availability of documentation. Finally, she is capable of using precedents combined with trial and error to understand fundamental design principles; at the end of the episode she reasons about the requirement for the second resistor and arrives at an understanding of the basic principle of operation of a voltage divider. However, it is unclear whether this reasoning would have occurred in the absence of the researcher's questions.

Detail Precedents for Mechanical Design

The observations during Phase 2 indicate that students are comfortable using precedents in certain domains and are capable of learning design knowledge as a result. This is the case even when their experience in those domains is limited, as in the example above. An implication seems to be that design precedents, in addition to providing opportunities for students to rehearse analogizing and redesigning, can increase students' confidence to engage in detail design tasks. However, there were no observed cases of students using online detail precedent information for mechanical design tasks. During Phase 1 it appeared that this was due to a lack of access to the types of design knowledge required by students. In order to better understand students' perspectives on this issue, they were asked during the exit interviews about their use of software and electronic design precedents from documentary sources, and their experiences attempting to find similar documentation for mechanical design.

All of the students interviewed had experience modifying and synthesizing code or circuit designs retrieved from online databases. All interviewees were initially unable to identify equivalent sources of knowledge for mechanical design. When asked about online libraries of CAD solid model files, most students indicated that they were aware of such resources but did not consider them equivalent to the sources of precedent knowledge for software and electronic design. Only one student reported using CAD files obtained online as part of his design project; an extract from his interview is contained in Table 5.2. The student reported primarily using precedent CAD files not to support design tasks, but to support the creation of documentation. For example, when creating animations for use in a presentation, he retrieved examples that included similar animations and used these to understand the animation procedure. Rather than modelling an anatomical shape for use in the same presentation, he used one retrieved online without modification. The student attempted to modify solid models but found it difficult, and many times resorted to building models from scratch, using the downloaded file as a guide.

Students' attitudes to precedent CAD models are notably different to their views on electronic and software precedents. Most interviewees felt that access to such precedents was of limited use in supporting detail design tasks. This is due to fundamental differences between source code, wiring diagrams, and solid models. Logistically speaking, modifying source code is straightforward as it typically involves editing text files. Modifying a circuit design requires editing a two-dimensional representation, and can often be done mentally as in the example above. This is not to say that such tasks are conceptually easy or that the resulting products will function as intended, but the procedures involved in making changes are relatively straightforward.

Table 5.2: Student use of an online CAD library

R: What do you tend to use [the CAD library] for? Like individual parts or more complex systems?

S: I've only ever used it for motion studies or complex shapes. Not necessarily complex systems. For example when we were trying to find a liver shape and I didn't want to make it myself. And I think the other thing was that animation with the device going down and then bending... Finding examples that had motion studies where parts would change shape during the motion rather than just relationships between parts changing during the motion.

R: And how would you use that, like you'd download it and open it in [the CAD software] and try to see what they've–

S: Yeah... yeah. The documentation there was not nearly as good as it is for a lot of computer science stuff.

R: That's what I'm wondering: do you actually go through it and try to reverse engineer it or look for documents that explain the process?

S: Oh no usually I'll reverse engineer it.

R: How does that work?

S: So for the motion study ones usually I'll start by going frame by frame through the study and look at relationships that change. And then delete parts that I think are irrelevant until something breaks.

R: Have you ever taken anything and tried to modify it to a particular purpose?

S: Yeah I did that a couple of times for things for this course.

R: And how did you find trying to modify someone else's solid models?

S: I think it's hard because I don't think [the CAD software] is very intuitive the way it builds parts... It's harder I think to modify things in the process because you have to roll back until that specific part was created. And if there are relationships later on I think it's harder to change them. So a lot of times I'll try to reverse engineer and try to modify and if it doesn't work just recreate and just follow the steps as I roll back and then roll back in.

R: So kind of work from scratch as if that were–

S: Yeah as if it were a tutorial.

However, modifying a solid model is logistically difficult. Solid models are created through sequential steps of adding and removing features. Each step relies on morphological characteristics of features created in previous steps. Editing one element of a model can therefore "break" the entire model, that is, break the documentation itself. As a result, students felt that it was generally more straightforward to create models from scratch rather than modifying precedents. However, some students believed that explanatory documentation accompanying a precedent solid model would assist with making modifications, as often understanding the reasons for features of the model is the main source of difficulty.

A further limitation of solid models as design precedents is that they typically describe only the morphology of a design; information about parts, materials, and manufacturing processes used are omitted. The observed difficulties faced by students relate to precisely these details, and thus the availability of CAD files alone does not address the needs identified in Phase 1.

5.2.4 The Social Nature of Design

Project themes were introduced to both courses with the aim of connecting students to engineering communities of practice. In Course A2, the theme related to the type of technology expected to be used in most projects, while in Course B2 the common theme was the section of society whose needs the projects aimed to address. In other words, the teams in Course A2 shared a common solution domain, and the teams in Course B2 shared a common problem domain. This section compares the different types of project theme, and explores their effects on facilitating student-expert interactions.

In both courses, the use of themes was successful in connecting students with experts. In Course B2, eight of the ten student teams recruited at least one expert stakeholder, in addition to their user group, to provide input on their projects. These experts were typically clinicians with experience providing medical care for elderly patients. This was an improvement over Course B1, during which students' user groups consisted solely of non-experts. However, of interest here is the amount of interaction with engineering experts rather than expert stakeholders. Four of the ten teams interacted with engineering researchers working in the area of successful ageing. Some of the students were extremely enthusiastic about the opportunity to engage with more experienced engineers, with one team travelling to another county to visit a research group and tour their facility. However, while these interactions provided students with insight into the practice of engineering research, the experts consulted typically worked in the area of diagnostics and data gathering rather than design. As a result, their role in the student projects was closer to that of expert stakeholders, and they typically provided guidance on problem definition, feedback on proposed solutions, and information about concept precedents. Lack of access to detail precedents thus remained an obstacle for the teams. As in Phase 1, the students relied on the knowledge of teaching staff to acquire detail design knowledge, and the wide range of designs presented challenges for teaching staff in attempting to connect teams with relevant domain experts.

In contrast, the technological theme used in Course A2 resulted in all teams interacting with engineering communities of practice engaged in designing technology relevant to the student projects. These communities were composed of doctoral and postdoctoral researchers primarily working in the field of medical device design. Access to these experts addressed many of the problems identified during Phase 1. Through participation in a community of practice the students gained access to detail precedent knowledge including design principles, examples of soft robotic component designs, fabrication processes, and testing methods. The more experienced engineers provided guidance on adapting precedents to new contexts, and explained the rationale for previous design decisions. Teams used this knowledge to adapt and synthesize elements of previous designs and combine these elements with their own original work. The student interactions with researchers consisted of informal meetings, email correspondence, and practical demonstrations in labs and workshops.

The most common type of knowledge shared in these interactions related to prototyping or fabrication procedures. In mechanical engineering, detail design is closely related to manufacturing methods, and the students primarily sought to understand the methods used in detail precedents in order to comprehend the design itself. The soft robotic components that students used in their projects relied on multistep moulding procedures, and many students did not understand a component design or its principle of operation until they had completed the required moulding process themselves.

The students' acquisition of detail design knowledge was typically a protracted process involving multiple interactions with experts interspersed with self-directed attempts at applying the knowledge to their particular problem. During their meetings with experts, students were often unable to explicitly pose questions, and instead spent time explaining the context of their problem and proposed solution. Experts responded to this contextual information with suggestions of possible precedents, and engaged the students in discussions about potential implications of particular design decisions. In other words, the discussions rarely consisted of straightforward information transfer. This pattern has been observed in interactions between design experts and novices in the aerospace industry (Ahmed and Wallace, 2004; Deken et al., 2012).

Table 5.3 contains an example of a meeting between a student and an expert. In this brief excerpt the discussion covers topics including related commercially available devices, medical procedures, previous design experiments conducted by the expert, materials, fabrication methods, and potential mechanism designs. The problem context appears to suggest a range of possible precedents to the expert, perhaps indicating that her design knowledge is organized around "contexts of applicability" (Bransford et al., 2000, p. 31). The student clearly contributes to the conversation by suggesting alternatives and identifying potential issues, rather than passively receiving information. In doing so, he is beginning to participate in and contribute to a community of practice. In fact, by the end of the course some teams had begun contributing knowledge back to the research groups by sharing their own novel fabrication methods or design variations.

However, students' appropriation and modification of design precedents was not always successful. One week after the meeting described in Table 5.3, the student's team was facing difficulties implementing the expert's fabrication procedure. Rather than returning to the expert to discuss the problems, the team decided to invent their own method, a method that had been explored and discarded by the research group months previously. Convincing the students to consult with the expert again required multiple attempts by a member of the teaching staff. The problem was eventually resolved when a team member observed the expert following the procedure. The team's reluctance to discuss their problems with more experienced engineers appeared to be based on a desire to invent their own method. This echoes findings by Busby and Lloyd (1999, p. 139) that designers sometimes associate "self-esteem with doing original design work, not adapting past designs."

Overall, the use of the soft robotics theme in Course A2 facilitated the types of interactions with engineering communities of practice that were identified as lacking during Phase 1. Comparing between the two approaches used in Phase 2, the adoption of a technological theme seemed preferable to that of a problem domain theme. The only observed disadvantage of the approach taken in Course A2 was the time commitment required of the experienced engineers. Much of this time was spent holding introductory meetings during

Table 5.3: Excerpt from a discussion between a student and a domain expert

A student (S) is meeting with a graduate student (E) who has extensive experience in the medical device industry. The student team has decided on their solution concept, and is working on the mechanism details and a prototyping plan. The course lecturer has advised the team to make use of an actuator fabrication technique that E uses in her research. E has explained the process and provided a box of parts including actuator moulds and custom jigs, and has shared solid model files that students can modify to make their own moulds. S uses the opportunity to discuss an unrelated problem that his team is facing:

S: We need a way to anchor the device to the tissue, but the anchor has to come through from the other side before being deployed so we were thinking of using a balloon... like a donut that you can push through the hole and then inflate and it acts as the anchor.

E: We have made our own balloons before by making wax cores and dipping them in elastomer. Then you melt the wax and you're left with a balloon... The other option is an off-the-shelf balloon. I have a catalogue that I can send you... But yeah I think we have been able to resist 5N of pull-out force with the [elastomer] balloon...

S: Would it be viable to make something out of nitinol [a shape memory alloy] and cast it in elastomer?

S sketches the solution his team has been considering, and outlines some of the issues they think they will face, in particular the delivery of the anchor through the hole. E explains the approach that many existing devices use in similar situations:

E: When you're going in through a catheter, fold and roll is the best way. It's what they do for angioplasty balloons.

[...]

E: But for this I'm not sure a balloon would have as good fatigue life as nitinol.

[...]

S: I didn't think too much about how durable the balloon would need to be.

E: Another device has a 3D coil that you can push out to the height you want.

S: With the nitinol I'd be worried about the size and strength of the linkages.

E: No, you'd just make it all out of one piece of nitinol. There would be no linkages... I have a device upstairs for delivering cardioplegic agents. It's a shaft with a rubber balloon at the end.

E shows S some commercially available medical devices that might help the team in thinking about mechanisms to solve their anchoring problem, and provides company names and part catalogues where the students can find more information.

which the researchers shared basic background information about particular designs or fabrication processes with students. Subsequent discussions tended to be more brief as the participants had a shared understanding of the background information. Thus, it would be beneficial to identify alternative means of sharing this background information with learners.

5.3 Conclusions

This chapter has described the second phase of research in OATPB courses. An objective of the research described in this chapter was to explore the use of a course theme to connect students with engineering communities of practice while retaining the open-ended nature of the projects. A second objective was to observe the effects of modifying features of certain learning environments (Course A and Course C) and applying them in a very different context (Course B). All changes to the learning environments were intended to address issues identified during Phase 1, such as a lack of clarity about course structure among students and a lack of access to detail design precedents and engineering communities of practice. The aim throughout this thesis is to develop a pedagogical framework for OATPB courses by comparing theories and results from the literature to the experiences of students and teaching staff in these courses. This section summarizes the results from the second phase of research with reference to this pedagogical framework. Additions to the framework in Table 5.4 are underlined, while topics that remain problematic are again highlighted in bold font.

Design Processes and Strategies

The introduction in Course B2 of a more structured process with regular deliverables and a detailed syllabus document providing a course overview appeared to address the issues of clarity identified in Course B1 and led to an overall improvement in project quality. New weekly review meetings and simple weekly questionnaires were used to monitor student progress and difficulties and support coaching of teams. Coaching remained an issue given the large class size, but the feasibility of adopting modified teaching approaches from a very different context was demonstrated. "Muddiest point" questionnaires were found to be effective as a means of monitoring student understanding and identifying issues in a large class. However, the use of regular quantitative grading was identified as an obstacle to encouraging flexibility and encouraged task optimization strategies that were at odds with the overall learning goals. Qualitative grades are therefore proposed as a preferable means of providing feedback on assignments.

Design Models

The addition of a sketch modelling exercise to Course B2 confirmed that it has a positive effect on the amount of prototyping carried out by teams, and demonstrated that the exercise is well-suited for use in large classes as it does not rely on access to equipment or facilities beyond household items. In both courses, improved access to prototyping equipment, materials, and space supported an increase in detail design and prototyping activity. The use of a general hardware control board in Course A2 supported some teams in building and testing functioning prototypes; however, the assembly of the board was not a useful learning activity for students. Teams engaged in mechanical design projects in Course B2 were observed to engage in mathematical modelling to guide their design, but in Course A2 the soft robotics focus made this unfeasible for most teams.

Design Knowledge Reuse

In Course A2, the selection of a course theme focused on a particular class of technology (soft robotics) supported reuse of detail design precedent knowledge. This knowledge was primarily accessed through social sources, and focused predominantly on fabrication procedures. Students used this fabrication knowledge as a way to understand precedent designs before adapting these designs for use in their project. Students' use of online databases of software and electronic design was explored. It was found that such sources lower barriers to entry by allowing novices to engage in analogical reasoning to transfer designs from one application to another, and in reverse engineering designs in order to understand fundamental principles. However, a lack of equivalent resources for mechanical designs was highlighted. Students found that online libraries of CAD solid models were of limited utility for learning design; the only interviewee who used these resources did so primarily for producing documentation rather than to supporting design problem-solving.

The Social Nature of Design

The introduction of course themes in both courses led to an increase in interactions between students and experts. In Course A2, this primarily involved students participating in engineering communities of practice. Students learned about detail design precedents through social interactions with more experienced engineers, and students were observed to actively participate in such interactions rather than passively receive information. In Course B2, the students made connections with multiple problem domain experts, including engineering researchers in some cases. This provided teams with knowledge about concept precedents and allowed students to rehearse interacting with clients and other design stakeholders. Comparing between the courses in terms of the pedagogical framework, the use of a technological theme was preferable for enabling participation in engineering communities of practice. However, the demands on experts' time were much greater in Course A2, and this may represent an obstacle to scaling this approach, or even to sustaining it in a small class.

Next Steps

A substantial amount of experts' time was spent in early meetings providing the students with background, declarative knowledge on which to build subsequent interactions. This type of knowledge could be recorded and provided to students in advance of their interactions with experts, which would enable the discussions to focus on more complex procedural knowledge, while also reducing the demands on experts' time. Furthermore, a lack of online databases of mechanical design precedent knowledge has been identified as an additional reason for students' difficulties in accessing domain knowledge. The following chapter attempts to address these issues by developing an online database of soft robotics design precedents for use in the third phase of research. The chapter also describes the development of a research instrument intended to augment the qualitative data by measuring the effects of OATPB courses on students' design knowledge.

Table 5.4: Pedagogical Framework for OATPB Courses

Design Knowledge	Guiding Theory	Learning Environment Feature
Strategies	*Strategic Nature of Learning*	
• Learning strategies • Design strategies • **Task optimization strategies**	• Metacognition • Reflection • Alignment of tasks and learning goals	• Overview of course process • Qualitative feedback rather than quantitative grading
Process	*Cognitive Apprenticeship*	
• **Flexible-methodical process** • Problem-solution coevolution • Tolerating uncertainty	• Coaching • Modelling • Articulation • Reflection	• Methodical: assignments and milestones • Flexible: coaching via regular review meetings • Monitoring understanding via "muddiest point" questionnaires
Models	*Social constructivism*	
• Sketching • Prototyping	• Guided discovery	• Introductory sketch modelling exercise • High-fidelity prototyping • Facilities
Design Knowledge Reuse	*Cognitive Flexibility Theory*	
• **Precedents** • Fixation	• Multiple representations • Contextual information • Concepts linked to precedents • Emphasis on interrelations • Knowledge assembly	• Concept precedents • Detail precedents from documentary and social sources
The Social Nature of Design	*Fostering a Community of Learners*	
• Role of language • Team roles • **Inter-team communication** • Distributed cognition	• Dialogic base • Distributed expertise • Communities of practice • Multiple zones of proximal development • Instructor guidance	• Regular meetings • Assignment of individual responsibility • Access to stakeholders • Access to engineering communities of practice via a technological theme rather than a problem theme

Chapter 6

The Development of New Teaching and Learning Resources

The objective of this thesis is to develop a pedagogical framework for open-ended, authentic, team- and project-based (OATPB) engineering design courses. An initial framework was developed in Chapter 3 by combining results from the literature on design cognition with learning theories from the fields of educational psychology and social anthropology. The framework was further developed in Chapters 4 and 5 based on the results of two phases of qualitative research in OATPB courses. The research conducted during these phases identified problematic aspects of the learning environments of these courses, including a lack of access to documentary and social sources of detailed mechanical design knowledge. In Chapter 5, aligning student projects to the work of local research groups was found to provide access to social sources of the required knowledge. However, a potential concern with this approach was the amount of time required for experienced researchers to share their knowledge with students, which may serve as a deterrent to participation for these researchers.

It was observed that many of the initial interactions between students and researchers were dedicated to sharing the detailed declarative knowledge which was a prerequisite for subsequent discussions that focused primarily on more advanced procedural knowledge. It was also observed that students regularly make use of online databases containing detailed design information related to electronic and software design, but that equivalent resources for mechanical design either do not exist or are insufficient to meet students' needs. This chapter describes an attempt to address both of these issues by developing an online database of detailed mechanical design information. Such a database would reduce the amount of time during expert-novice interactions dedicated to sharing declarative knowledge, and thereby reduce deterrents to participation by researchers. In keeping with the theme of Course A, the resource developed in this chapter focuses on soft robotics. However, its development may serve as an example for other types of mechanical design knowledge databases.

This chapter also describes the development of a data collection instrument for use in the next phase of research in OATPB courses. Thus far the research has focused on the analysis of qualitative data describing the experiences of participants in these courses. The results have yielded insights on aspects of the learning environments, but it has not been possible to directly evaluate the effects of course design on students' knowledge. Assessing design knowledge is difficult, and as a result there is no generally accepted method for evaluating the efficacy of teaching methods in design. The research presented in this chapter attempts to address this issue by developing and testing a set of concept questions related to aspects of design knowledge identified in previous chapters. The resulting instrument will be used to supplement the qualitative data gathering during the third phase of research.

The chapter begins by describing the background to and development of the database of soft robotics design knowledge. User tests intended to ensure the clarity of the database contents are discussed, and a description of the structure and content of the resulting website is provided. The remainder of the chapter focuses on the development of the concept questions for design. An initial set of questions is developed and pilot tested. The results of testing inform the development of the instrument that will be used in the next chapter.

6.1 The Soft Robotics Toolkit

In course A2 it was observed that students make use of online collections of detail precedent knowledge related to software and electronic design. The aim of the Soft Robotics Toolkit (SRT) is to create a comparable resource to support soft robotics design by recording expert knowledge in such a way that it can be retrieved and used by novices. As the SRT is inspired by resources in electronic and software engineering, a review of these resources will be useful. In particular, the success of open source software and open source hardware are taken as a starting point for developing the SRT.

Open source software (OSS) is computer software provided under a license that allows users to run, study, modify, and redistribute the software source code as they wish. OSS projects such as the robotics operating system (ROS) provide a modular and reconfigurable platform to support the rapid implementation of new designs (Quigley et al., 2009). OSS has been successful in the software industry, and a large body of work has sought to understand this success and draw general lessons from it (e.g., Lakhani and Wolf, 2003; Osterloh and Rota, 2007). An increasing number of researchers and practitioners have proposed that the success of OSS could be replicated in other industries (Hope, 2004; Lerner and Tirole, 2004). An example of such a replication is open source hardware (OSH), in which design information related to "tangible artefacts – machines, devices, or other physical things" is shared under a license that allows others to modify, use, and redistribute it (OSHWA, 2012).

In the previous chapter, excerpts from a contextual interview described a student's use of the Arduino microcontroller, a project that combines OSS and OSH in an educational tool originally developed for use by design students. The Arduino is an electronics platform intended to support rapid prototyping and testing of embedded computing designs, and has become extremely popular in engineering departments. The Arduino's success is due in large part to an active online community of users who share wiring diagrams and source code, which students use as detail precedents. In fact, the success of the open source approach in general is due to the erosion of boundaries between users and producers. When a large amount of users make small modifications to a design and these changes are accumulated, it leads to rapid progress in the development of a technology (von Hippel, 2005).

A necessary component in developing such a resource may therefore be a community of user-producers. Such a community may address the knowledge acquisition problems commonly encountered in research on expert systems and information resource management. For decades, research in these fields has focused on recording the knowledge distributed throughout large organizations. However, eliciting knowledge that is often tacit and held by a small number of research subjects has proved to be a challenge (Wagner, 2006). Wagner proposes that open source approaches, in which a large number of users engage in dialogue via a documentary database, may provide a solution to these difficulties. A large number of contributors with varying levels of expertise, engaged in reviewing each other's work and asking and answering questions, may be effective at gradually shaping a knowledge database.

The challenge then becomes engaging soft robotic researchers to contribute expertise and build a community around the resource. The growth of soft robotics as a research field is a relatively recent phenomenon, and there are many open challenges that must be addressed in order for the field to develop (Lipson, 2013; Majidi, 2013). Soft robotics researchers have acknowledged a need for shared design tools and standards to ease knowledge transfer (Lipson, 2013; Trimmer et al., 2013). The proposed toolkit could serve as a platform to meet these needs. Framing the toolkit as a resource to support the soft robotics research community, rather than solely as an instructional tool, may provide the incentive required to build a community of user-producers. This approach has been successfully used to create research tools in other disciplines, including OpenWetWare in synthetic biology and usefulChem in chemistry (Bradley et al., 2011; Williams, 2008).

A further challenge to be addressed is that taking an open source approach to mechanical design is not straightforward. In Course A2 it was observed that students rarely make use of resources such as online libraries of solid model files. This is because mechanical design information is different to software or electronic design documentation. OSS involves sharing source code as text files that can be downloaded and compiled by any user with a basic understanding of software. OSH relies on the existence of a relative small number of standard components, including resistors and microcontrollers, and fabrication processes such as soldering and circuit board etching. However, as reported by students in Phase 2, mechanical design files, such as solid models, alone are rarely useful. Mechanical design is concerned with particular morphologies that depend upon factors external to the design itself. The parameters of even a simple three dimensional shape, such as a rectangular cuboid, can be varied infinitely in response to the environment in which the design will be used. Therefore, using a precedent design inevitably involves making modifications. Modifying a solid model file is a complicated task, interoperability between different CAD environments remains an issue, and information about how to actually realise a design cannot typically be inferred from the documentation. In Phase 2 the students required a wide range of contextual information in order to make use of detail mechanical precedents.

As a result, open source mechanical projects typically involve sharing a wider range of information, including models, drawings, bills of materials, and written fabrication instructions. Examples of such projects include the RepRap, a low-cost 3D printer, and the OpenHand, an underactuated robotics hand (Holland et al., 2010; Ma et al., 2013). However, these projects have a very particular focus. Whereas ROS and Arduino can support software and electronic design for a wide range of applications, similarly broad platforms to support mechanical design are rare. This is because traditional mechanical design typically involves specialized parts customized to suit a particular application. Mechanical hardware such as motors, gears, shafts, and bearings cannot be straightforwardly transferred from one application to another.

In contrast, the nature of soft robotics makes it ideally suited to the development of a broad design platform. For example, the hardware required to operate fluidic soft devices (including pressure source, regulator, valves, and microcontroller) is largely interchangeable between one system and the next with little to no customization. Therefore, a common hardware control platform like that used in Course A2 could support a range of applications including surgical, wearable, locomotion, and manipulation systems. The behaviour of soft robotic devices is determined by the morphology of custom-made actuators and sensors that are typically made from low-cost elastomers cast in moulds. These moulds can be affordably produced due to the increased availability of rapid prototyping technologies such as 3D printers and laser cutters, and once a mould has been created it can be used repeatedly to produce multiple components. An online database of mould part files, design guidelines, and

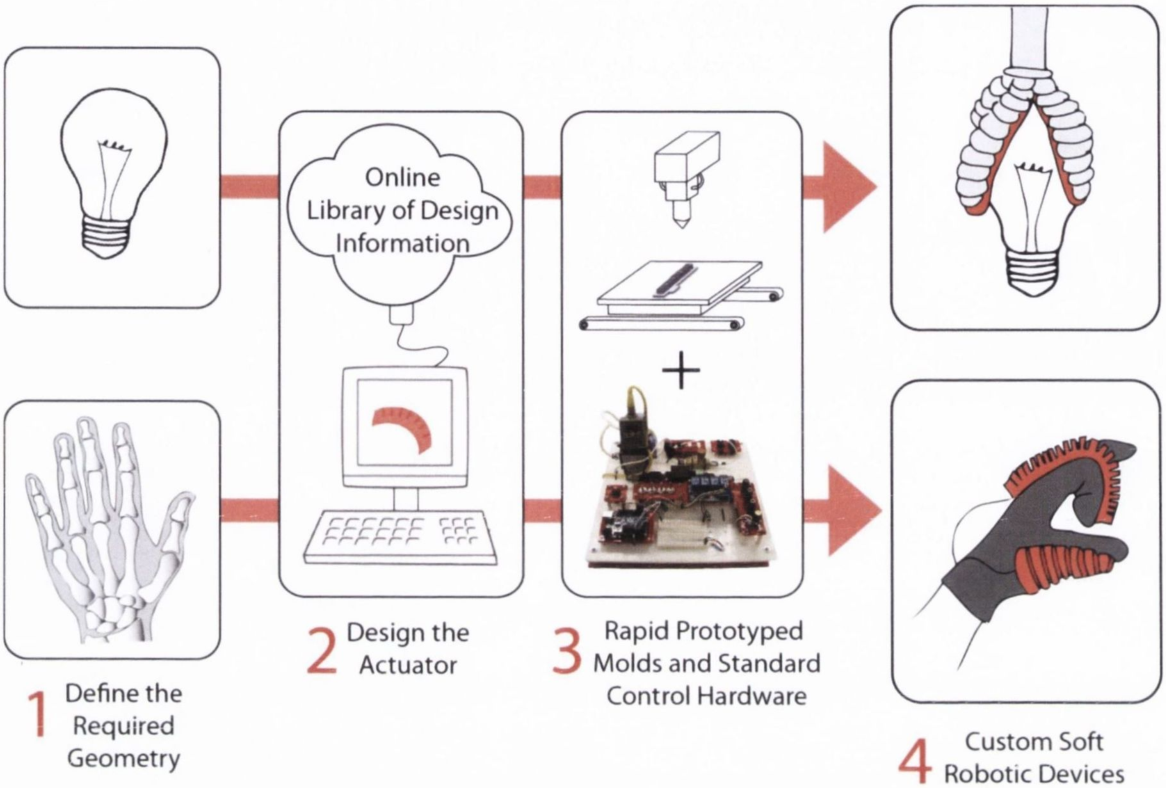


Figure 6.1: Schematic depiction of the design process that would be enabled by the proposed resources (Holland et al., 2014).

fabrication protocols describing the casting process could therefore support a broad range of design activities. Figure 6.1 contains a graphical description of the type of design process that such a database could support.

The Soft Robotics Toolkit (SRT) was therefore conceived of as a public online database of design information, which researchers and designers can both contribute to and make use of. While inspired by the concept of open source, the SRT itself is not completely open source, in that it is not required that all content contributed to the site be shared under an open source license. Welcoming material that is protected by patents but shared for educational or research purposes, rather than applying restrictive requirements regarding licensing, is more conducive to building a broad community. The following sections describe the development and initial testing of the resource, before giving an overview of the current embodiment of the SRT.

6.1.1 Developing the Soft Robotics Toolkit

Initial Draft

Creating content for the SRT required recording detailed design information about soft robotic actuators and sensors, hereafter termed "soft components." Based on the observations made during Course A2, four categories of design information required by students were identified:

- Detail design information, including principles of operation, instructions for creating solid models, and guidelines on modifying the design;
- Fabrication information, including bills of materials, mould preparation, and detailed casting and assembly instructions;
- Modelling guidelines, such as examples of analytical and numerical models; and
- Methods for characterizing components through testing.

It was decided that the toolkit entry for each component would contain material addressing each of these four categories. Many students in Course A2 did not gain a satisfactory understanding of a component's design until they had completed the fabrication process. Thus, material for the fabrication section was given priority during initial compilation of information. One of the components used during Course A2, the PneuNets ("pneumatic networks") bending actuator, was chosen as the subject of the first documentation set (Ilievski et al., 2011).

The fieldnotes collected during the course, and in particular the observations recorded during expert-novice interactions, was sufficiently detailed to allow fabrication processes to be recreated without seeking external input. The fabrication process was decomposed into steps, and for each step a verbal explanation was written and a video demonstrating the step was made. Supplementary images, including labelled photographs and diagrams, were also created. The material was collected in a Microsoft PowerPoint file, with each slide corresponding to a single step in the protocol. The format was chosen for its ability to embed multimedia content. When completed, the protocol consisted of 31 slides describing the fabrication process from start to finish. Figure 6.2 shows an example slide from the set.

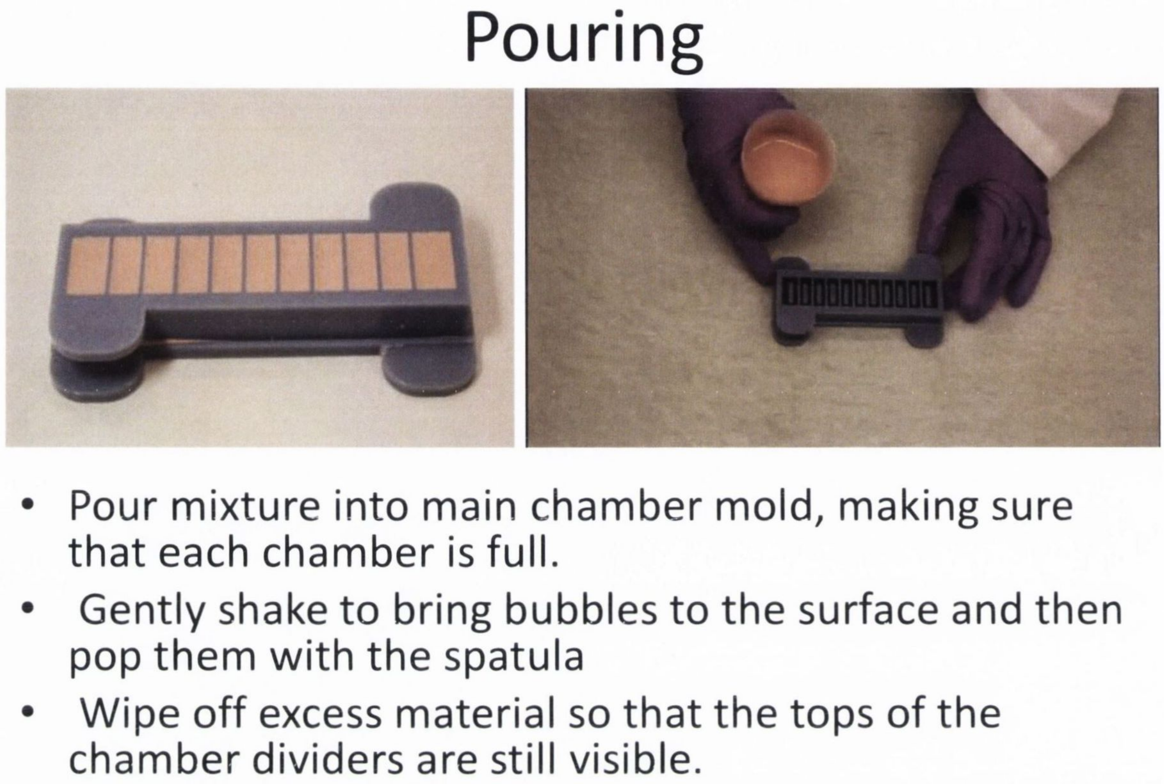


Figure 6.2: An excerpt from the protocol used during user testing.

User Testing

As an educational resource, the aim of the SRT is to provide learners with comprehensive information on detail design precedents in order to scaffold their interactions with experts. Thus, it is essential that the information is sufficiently clear and comprehensible to novices. To ensure that no specialized engineering knowledge was required to understand the documentation, four volunteers from non-engineering backgrounds were asked to follow the procedure and provide feedback on its clarity.

During the tests the participants were provided with all of the equipment and materials required to build a PneuNets bending actuator, including 3D printed moulds, and the fabrication protocol was displayed on a laptop computer. In each test, a single participant completed the protocol over the course of one hour. Two researchers were present throughout each test, and the participant was asked to think aloud while carrying out the task. One researcher answered any participant questions, prompted the participant to think aloud when necessary, and controlled the protocol, advancing the slides when requested by the participant. The other researcher recorded fieldnotes describing the process. Participant comments and feedback were noted on a printed copy of the protocol, with particular attention given to comments relating to the clarity of the documentation.

The overall feedback on the protocol was positive, and every participant successfully built an actuator within one hour. The four tests resulted in a detailed list of suggestions for improving the protocol, most of which focused on particular basic details. Proposed improvements included rewording sentences to be more clear, changing the speed of the instructional videos (increasing the speed in some cases, and decreasing it in others), and providing "before and after" photographs so that watching the videos is optional. The participants were consistent in their feedback, with similar comments from each at every step of the process. In particular, participants highlighted the need to explain the rationale for each step; students found it difficult to understand what was being described without understanding the reason for doing it.

Further Development

The feedback was used to refine the fabrication protocol to improve clarity, and answers to recurring participant questions were incorporated to ensure that future users could follow the protocol without external assistance. The updated protocol was used as a template to guide the development of fabrication protocols for other types of soft component. Using the fabrication sections as foundations, material for the other three sections (design, modelling, and testing) were developed. For example, solid modelling tutorials were created for the design sections following a similar structure of discrete multimedia steps, each containing an instructional video, a verbal explanation, and labelled screenshot images. This is in contrast to most online solid modelling tutorial videos, which typically describe an entire procedure in a single video. The intention in using this structure for the tutorials was to allow users to progress at their own pace and to allow for different learning styles.

Documentation of the additional component types was achieved primarily through collaboration with experienced researchers involved in developing soft component technologies. In many cases, the researchers contributed to the SRT while also drawing on its contents to enhance their own projects. One such project focused on the development of a soft robotic glove intended to augment hand rehabilitation for individuals with functional grasp pathologies (Polygerinos et al., 2013). The first version of this glove (Figure 6.3) consisted of PneuNets bending actuators which assisted the fingers with grasping tasks. To optimize actuator designs for the application at hand, the project team developed finite element method (FEM)

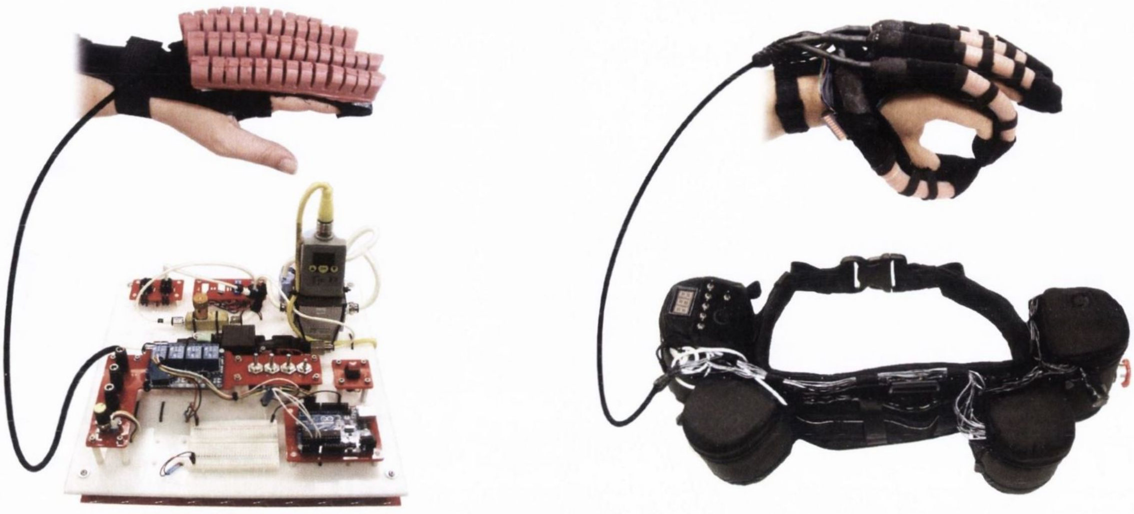


Figure 6.3: The evolution of a soft robotic orthosis: initial version consisting of PneuNets actuators and the control board used by Course A students during Phase 2 (left); second version consisting of fibre-reinforced actuators and a wearable control belt (right). (Polygerinos et al., in print; image adapted from Holland et al., 2014).

models for PneuNets, which were documented and added to the toolkit. In turn, they used the control board component of the toolkit to test actuators and validate these models and also used designs documented in the toolkit to create new actuators for the glove, which could more accurately mimic the behaviour of the fingers and thumb by combining bending, twisting and extending motions (Polygerinos et al., in print). The project team later returned to the control board, modifying it and reducing the number of components to create a more user-friendly, portable version in the form of a control belt (Figure 6.3). These improvements were in turn incorporated back into the design of the toolkit control board, reducing its cost and complexity. The point to note here is that the SRT seems capable of supporting the type of iterative interactions required to build the user-producer community necessary for the growth of the resource.

6.1.2 Soft Robotics Toolkit Overview

This section describes the structure, content, and intended uses of the toolkit website that resulted from the sequence of development, testing, and collaboration with soft robotics researchers described in the preceding section. At the time of writing, the SRT website[1] (Figure 6.4) contains 101 pages documenting six types of soft component and two versions of

[1] http://softroboticstoolkit.com/

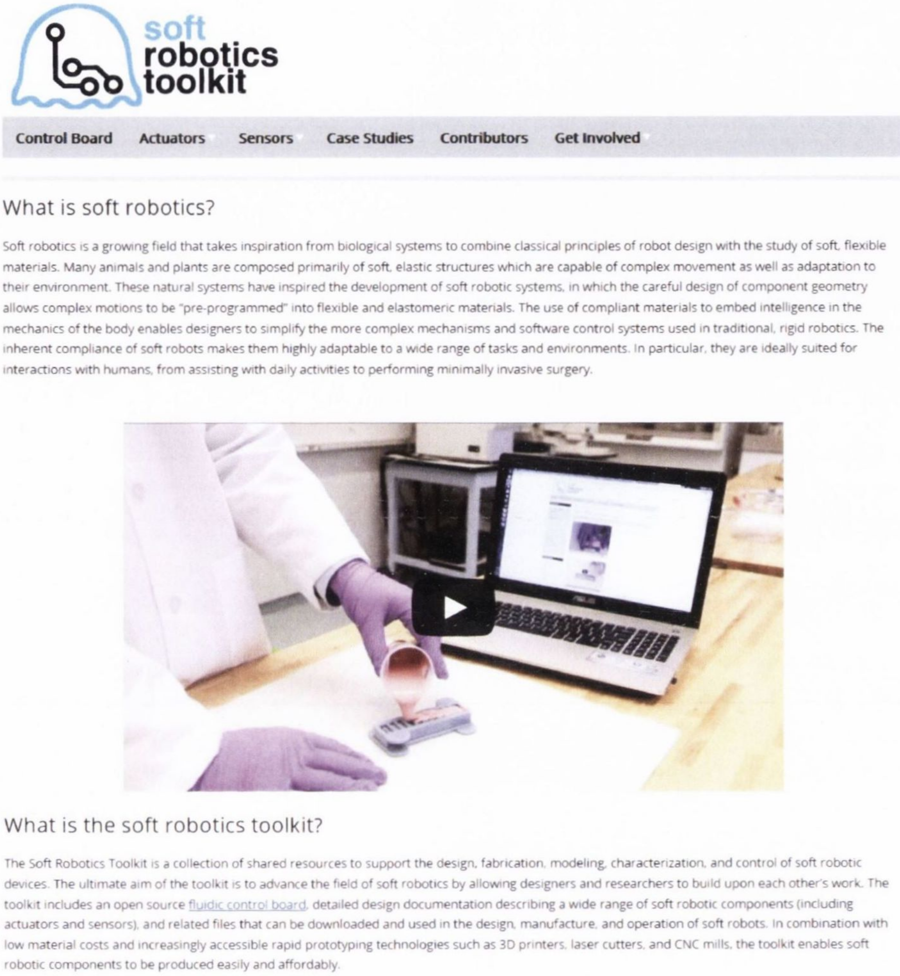


Figure 6.4: The Soft Robotics Toolkit website.

the fluidic control board. As discussed previously, the documentation for each component is organized under four categories: design, fabrication, modelling and analysis, and testing. This section describes the documentation for an example soft component, the PneuNets bending actuator, as well the general fluidic control board.

PneuNets Bending Actuator

Design The Design section describes a particular configuration of the actuator, complete with downloadable solid models and engineering drawings of the component and related moulds. These files are complemented with tutorials for designing mould parts in a solid modelling environment (SolidWorks, Dassault Systèmes) (Figure 6.5). A user with limited mechanical engineering experience can follow the tutorials to design a complete component from start to finish, while more experienced users can refer to the tutorial to modify and

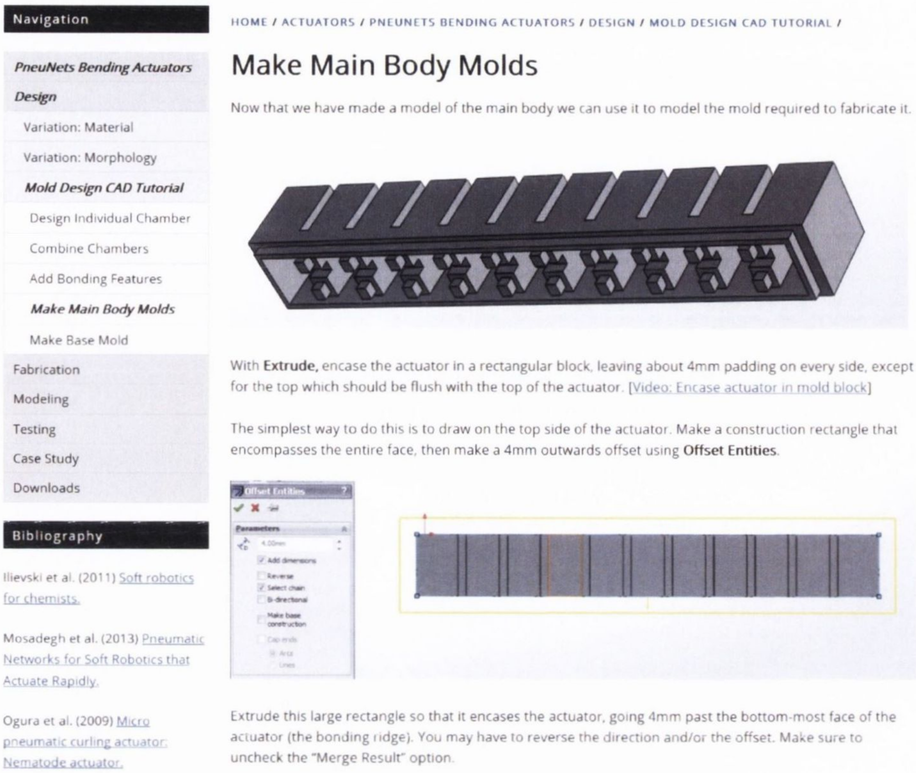


Figure 6.5: The *Design* section of the PneuNets bending actuator documentation set. The screenshot shows an excerpt from a CAD tutorial.

customize the downloaded CAD files to suit their own application. Students in Course A2 indicated that access to documentation explaining the steps taken in creating a solid model made it easier to modify that model. The Design section also contains information on material selection, general design principles, and discussions of possible design modifications to vary the actuator's performance. The content is based on the observations of student teams in Phase 2, in particular the type of information they sought from more experienced soft robotics researchers. A collection of case studies provides an overview of how other developers have used the component. Since soft robotics allows for infinite customization, these case studies provide insight into the design considerations that need to be addressed for specific applications. The case study section for each component contains an overview of the design problem and solution, with links to published articles containing more in-depth information.

Fabrication The Fabrication section contains all of the information required to build the actuator. Bills of materials, with links to suggested suppliers, assist users in procuring the required parts and materials. For parts that are not commercially available and need to be

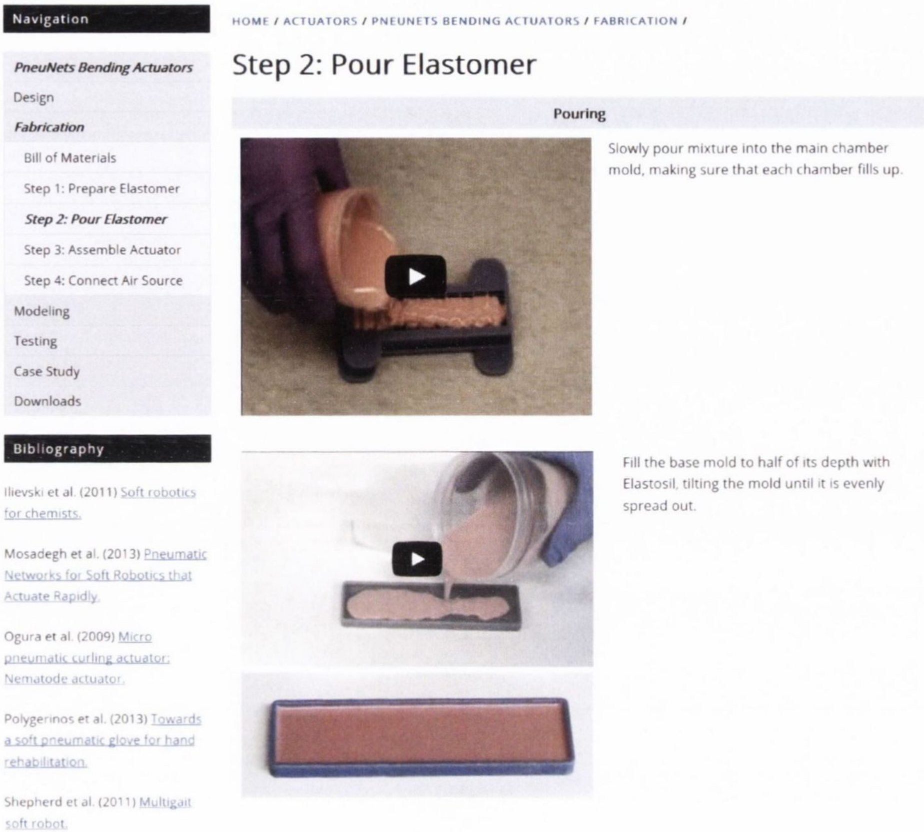


Figure 6.6: An excerpt from a multimedia fabrication protocol.

custom-made, the provided CAD files can be used to manufacture parts on a 3D printer, laser cutter, or CNC mill. Detailed multimedia protocols, as refined through the user testing, describe the steps involved in preparing moulds, casting parts, and assembling the soft component. Where appropriate, alternative methods of building the actuator are described, and the strengths and weaknesses of each method are discussed so that users can make an informed choice about which procedure best suits their needs. Each step of the process is described through verbal descriptions, annotated images, and videos (Figure 6.6).

Modelling and Analysis Predicting the performance of a soft actuator (such as force output in response to a given pressure) prior to manufacture is non-trivial due to complex morphologies, non-linear elastic behaviour, and multiple degrees of freedom (Lipson, 2013). Both learners and researchers require support to model and analyse their designs. Towards this end, the Modelling and Analysis section contains general guidelines for analysing the actuator. Descriptions of both analytical and numerical modelling approaches are provided along with related FEM input files and scripts. Tutorials provide a step-by-step description

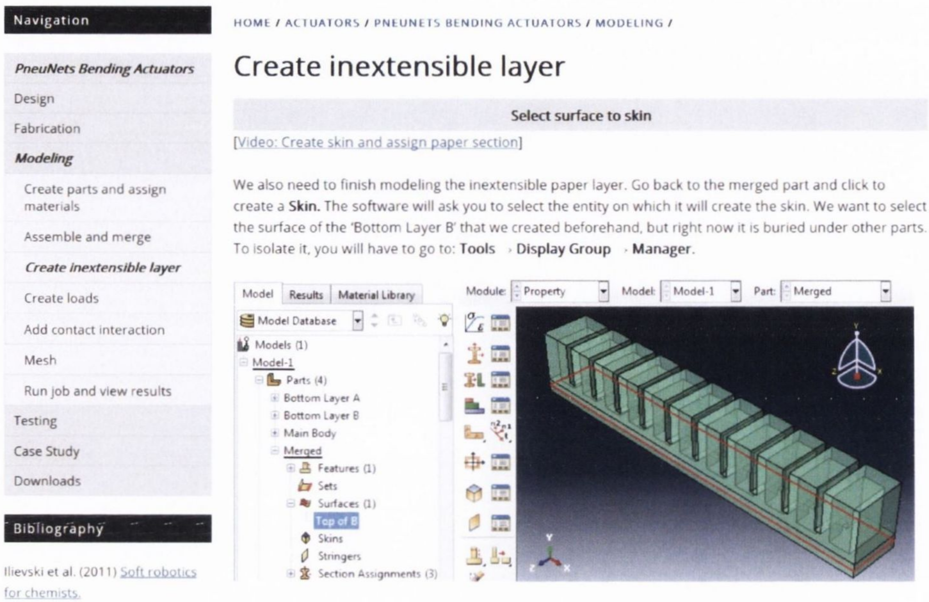


Figure 6.7: An excerpt from a tutorial demonstrating the use of finite element method (FEM) analysis to predict the behaviour of the actuator.

of using FEM software packages to conduct numerical analysis of one configuration of the actuator (Figure 6.7). Users can follow these tutorials to learn about the software and the modelling considerations particular to soft systems so that they can subsequently analyse their own designs.

Testing In order to understand the behaviour of soft components, as well as to validate FEM and analytical models, researchers rely on experimental data. During Course A2, most student teams relied on empirical testing more than modelling to guide their designs, but had difficulty designing and conducting experiments. To assist both types of user in the design of experiments, the toolkit contains examples of empirical tests that have been carried out by other students and researchers. These examples describe the experimental setup, the type of data that resulted, and how that data was interpreted. The experiments described include fatigue strength tests, force and displacement characterization, and motion studies. Users can modify the examples to guide their own experiments. Many of the experiments described in the toolkit make use of the SRT control board discussed in the next section.

Control Board

As mentioned previously, much of the hardware required for the operation and control of soft fluidic systems is interchangeable between one system and the next. The website contains

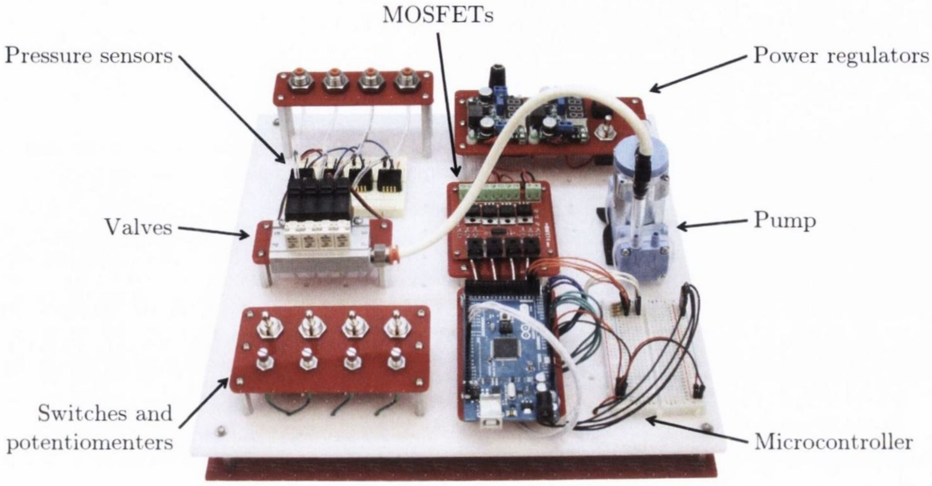


Figure 6.8: Version 2 of the fluidic control board.

documentation for two versions of an open source fluidic control board, intended as general purpose tools that can be used for a range of applications. Version 1 is identical to that used by students in Course A2. Version 2 is an improved design that reduces the cost and complexity while improving functionality by allowing the user greater control over the output pressures of the system. The updated board consists of a microcontroller (Arduino Mega), a pressure source, MOSFETs, solenoid valves, and pressure sensors (Figure 6.8). These components can be controlled manually via the included potentiometers and switches, or programmatically via the microcontroller. The boards can be used to implement closed loop control, and the documentation contains source code for PID control for particular actuator and sensor combinations that can be downloaded and run on the microcontroller.

The base of the control board, a perforated sheet of acrylic, acts as a "mechanical breadboard" and allows users to reconfigure the assembly or add new components. An electronic breadboard enables the addition of further sensors. For example, one student team in Course A2 added a gyroscope module to track the orientation of the tip of their actuator during testing. The control boards enable "plug and play" of soft devices across a range of applications, allowing proof of concept prototypes to be rapidly assembled, tested, and demonstrated. Given the modular nature of the board, its cost depends on the needs of the user. The cost of parts required to build the complete version documented on the website is $800. In the future, toolkit users will be invited to share details of their custom feedback controllers on the toolkit website to support accurate control over device behaviour.

6.1.3 Summary

This section has described the development and the resulting structure and content of the Soft Robotics Toolkit. The toolkit contents have been tested for clarity and its use by researchers has been observed. However, it is not possible to anticipate whether and how students in OATPB courses would make use of this type of resource. Thus, the use of the SRT by students is explored in context in the next phase of research. The SRT is intended to be used to support, rather than replace, social interactions between students and more experienced engineers. The following chapter explores whether the toolkit can be successfully used in this way.

6.2 Mechanical Design Concept Questions

In the research conducted thus far the focus has been on understanding student experiences in project-based design courses. In particular, the emphasis has been on using observations, surveys, and interviews to explore activities in these courses with reference to a pedagogical framework based on the design studies and learning theory literature. Principles to guide the design of learning environments have been identified, with emphasis on particular activities that are assumed to be beneficial for student development. However, there has been no attempt to directly examine the learning outcomes of these activities. Thus, this section describes the development of a collection of concept questions intended to probe students' design knowledge. It should be emphasized that the aim of this work is not to develop a standardized test for design, or a tool for assigning grades. Rather, the intention is to create a research tool to supplement other data gathering approaches in order to better explore the effects of interventions and thereby guide improvements to teaching and learning.

6.2.1 Background

Evaluating the effects of design education is difficult. In a review of 273 research articles describing engineering design courses, Turns et al. (2006) found that 40.7% of articles either did not provide any evaluation of effectiveness or did not refer to any data to support conclusions. Of the articles that included some reflection on what worked well and what needed improvement, 12.4% mentioned the difficulty of judging effectiveness. In general, the most common approach to evaluating both student learning and course or intervention efficacy is to focus on the product of student activity, in particular the quality of the design or the project documentation. Typically this assessment of quality is guided by the use of a rubric, often based on guidelines from accreditation bodies (e.g. Pierrakos and Watson, 2013). Assessing the product of student work is undoubtedly useful, and is traditional in most fields of formal education (e.g., essays, lab reports). However, a focus on product alone in design education risks missing important insights on student learning. Consider a student team whose design fails to meet functional requirements. For some students, this experience may provoke reflection leading to important lessons; for others it may have no effect beyond reducing their enthusiasm for design. These outcomes are significantly different, yet a focus on product has no way of differentiating between them. Clearly, additional evaluation approaches are required. This section reviews potential methods of assessing design knowledge.

"Self-efficacy" refers to an individual's belief in their own ability to complete tasks or achieve goals. Carberry et al. (2010) and Masi (2009) have developed instruments for measuring students' design self-efficacy. Carberry and colleagues validated their instrument by comparing respondents' self-efficacy scores with their level of experience, and found that the instrument was capable of differentiating between those with more or less design experience. Measures such as this are useful for examining the outcomes of experiential learning, and will be incorporated into the instrument being developed here. However, for the purpose of this research a method for probing knowledge is also required.

A common approach to measuring creativity is the use of divergent thinking tests. The most influential tests of divergent thinking are those developed by Guilford (1956) and Torrance (1966). Both tests ask participants to generate a list of ideas in response to a prompt, and the answers are evaluated based on the variety and originality of ideas. These tests can provide insight on subjects' concept generation abilities, but fail to capture other important aspects of design such as problem framing, solution evaluation, and detailed implementation (Zheng et al., 2011).

Closed-ended instruments composed of multiple choice questions have been used to assess knowledge of design process strategies. For example, Sims-Knight et al. (2005) developed a computer simulation in which students could advise a fictional design team by selecting options from a list of possible courses of action. Multiple choice problems like these, which usually have a single correct solution, have the advantage of being easy to score in a consistent and objective way. However, they are of limited use in inherently open-ended fields such as design.

Answers to open-ended questions can be more challenging to assess but are more appropriate for gaining insight into design knowledge. Many open-ended approaches involve asking students to describe or comment on the design process. Frank and Strong (2010) asked students to describe the steps they would take to design a solution to one of three given problems. Bailey and Szabo (2006) asked students to critique a proposed design process. These approaches test students' declarative knowledge of design process principles, for example by asking students to describe the elements required for effective teamwork (Okudan et al., 2007). However, rote memorization of an idealized design process is a trivial undertaking; performing design is another matter.

Attempts have been made to combine these different approaches in a single instrument. For example, Okudan et al. (2007) developed the Comprehensive Assessment of Design Engineering Knowledge instrument (CADEK), a collection of closed-ended, open-ended, and self-rating questions intended for use in introductory design courses. A major drawback to this and many of the methods discussed above is that they are time-consuming for both students and educators. In order to provide real-time and ongoing feedback that can influence teaching and research, the ideal instrument would consist of short questions focused on understanding, capable of being delivered via short in-class exercises.

An example of such an approach can be found in physics education, where educators have redesigned courses guided by the use of assessment tools such as the Force Concept Inventory, a collection of questions that test student understanding of fundamental mechanics concepts (Hestenes et al., 1992). In the Peer Instruction approach described by Crouch and Mazur (2001) classes are structured around concept questions that students answer individually and in groups. Student responses to these short exercises provide educators and researchers with insights into how students are thinking and whether they are achieving learning goals. Efforts to develop concept inventories for engineering education have to date focused on engineering science subjects which are well-suited to closed-ended, well-defined problems (e.g., Prince et al., 2012). Concept questions for design education would more likely be open-ended, ill-defined problems with no unique correct answer.

The ideal instrument for this research would consist of self-efficacy and creativity measures combined with open-ended concept questions that focus on particular aspects of design knowledge. Previous research has attempted to develop these types of concept question. For example, Shah et al. (2012) have been developing a battery of tests to assess a range of design skills. To date, an 8-item instrument focused on divergent thinking has been developed. However, the test is not yet available to researchers or educators. Diefes-Dux et al. (2010) have developed open-ended engineering questions as well as a rubric to guide evaluation of responses. However, their work emphasizes engineering management rather than design.

Therefore, there is a lack of knowledge assessment instruments available to researchers and educators in engineering design. The remainder of this chapter describes the initial development and testing of a collection of concept questions for design. Based on the results of a pilot study, an instrument for use in the third phase of research is developed.

6.2.2 Instrument Development

The objective of the work described here was to develop a range of simple design-related questions that could be used in an exploratory pilot test, with the intention of identifying questions with an appropriate level of difficulty that were capable of differentiating between respondents with more or less design experience. The initial development and testing of the instrument focused on creating concept questions related to specific design tasks. The tasks were drawn from the results of the previous phases, and related to the types of activities that have been identified as important in design education. Previous research which proposed types of knowledge that design courses should aim to teach, discussed in Chapters 1 and 3, was also used to identify potential question topics. Thirteen topics were identified as candidates for inclusion in the instrument (Table 6.1).

Short problems were developed for each topic. Where appropriate, questions were drawn from the work of other researchers and educators, for example Mahajan's (2010) work on estimation. One of the guiding principles of this thesis is that design is a highly context-dependent activity, which presents difficulties in trying to design short, decontextualized problems. In an effort to make the questions as realistic as possible, actual problems encountered by students during the previous phases were used as the basis for questions. Real problems from public design challenges were also used in an effort to maintain some level of authenticity. For example, OpenIDEO[2] is an online platform for crowdsourced and collaborative design, run by design firm IDEO. The website is organized around "Challenges," in which a general problem, typically related to a social issue, is posted by a partner organization. Site users are invited to submit proposed solutions. The community of users rates each other's submissions and suggests improvements. A challenge proceeds through stages of research, design, and

[2]https://openideo.com/

Table 6.1: Candidate question topics

Problem decomposition
Making estimates
Modelling
Evaluating information
Visual/spatial reasoning tasks
Visual communication
Assessing feasibility
Knowledge and understanding of mechanisms
Analogical thinking
Design of experiments
Failure modes
Part selection
Manufacturing process selection

evaluation; at the end of each stage a subset of the remaining designs is selected to proceed to the next stage. An OpenIDEO challenge and four users' proposed solutions were used as the basis of a problem that asked respondents to evaluate and select between concepts. This provided an external measure against which to assess answers: participants' answers could be compared to the evaluations of the OpenIDEO community.

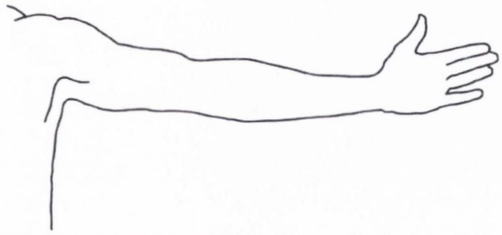
Seventeen problems were developed for the pilot test instrument. Many of the problems addressed more than one topic. The example shown in Figure 6.9 requires participants to create a mathematical model and to estimate quantities. For each question a simple rubric was developed, with a binary pass/fail rating for each topic. Note that in the example shown in Figure 6.9 the rating for each topic covered by the question is independent; it is possible to pass one while failing the other. The complete instrument is provided in Appendix G.

6.2.3 Pilot Study

Procedure

The aim of the pilot study was to gain some insight into the utility of the concept questions in order to identify the most useful types of problems for inclusion in the instrument to be used during Phase 3. For a question to be useful it must be intelligible to students, it must be neither too easy nor too difficult, and it must be capable of discriminating between different levels of knowledge or experience. Such a question could then be used to identify more and

You are designing a wearable device to assist with lifting tasks. Create a mathematical model of the arm in the position shown below, and use it to estimate the torque that must be applied at the shoulder to hold the arm in this position.



Code	Rubric	0	1
1B	Provided a mathematical model		
1C	Guessed quantities		

Figure 6.9: An example question and rubric from the test instrument used during the pilot study.

less effective educational design experiences, and thereby guide the improvement of learning environments.

In order to evaluate the utility of the questions, thirteen volunteers were recruited from TCD and Harvard. The volunteers ranged in experience from engineering undergraduates to postdoctoral researchers with industry experience. The volunteers were asked to spend 40 minutes completing the instrument. Each page of the instrument contained one problem with space for rough work and solutions, and a comment box to elicit feedback. Participants were asked to use the comment box to note any issues with the problem, such as a lack of clarity.

When the instruments had been completed and returned, each was marked with a random identifier to allow blind scoring. The comments identifying issues with the questions were noted, and the rubric was used to grade each response on a pass/fail basis. A binary marking scheme was used so that the results could be analysed using classical test theory. In particular, item analysis was used to identify the difficulty and discrimination of each question (Kline, 2005). When undertaking item analysis, each question on a test is allotted a difficulty score and a discrimination score. Counterintuitively, the difficulty score is the proportion of all respondents who answered a question correctly. A high difficulty score indicates that the majority of respondents answered correctly. (A more appropriate term would therefore be the "easiness score.") A difficulty score of 1 is too easy, as every participant answered it correctly, while a score of 0 is too difficult. A question with a score of either 0 or 1 is of no use as its inclusion on a test has no effect on the relative overall scores of respondents. When creating tests it is desirable to include questions with a range of difficulty scores between 0 and 1 to accommodate different levels of ability among respondents.

The discrimination score is a measure of how likely a question is to discriminate between high-performing respondents and low-performing respondents. To calculate discrimination, the respondents are divided into three groups based on their overall test scores. The third of respondents with the best overall scores is considered the high-performing group, and the group with the poorest scores is considered the low-performing group. The discrimination score for a given question is then the proportion of the low-performing group who answer the question correctly subtracted from the proportion of high-performing group who answered to question correctly. The discrimination score for the question is a value between -1 and +1. A negative score is assumed to indicate that the question is flawed, as the low-performing group has performed better than the high-performing group on this question. A discrimination score of 0 indicates that the question cannot differentiate between the two groups. A discrimination score of 1 means that every member of the high-performing group answered correctly while none of the low-performing group did. As with difficulty, any collection of questions should include a range of discrimination scores between 0 and 1.

Results

Once the blind scoring of responses was complete, the identifiers were used to associate participants' responses with their levels of experience. As would be hoped, the high-performing group was composed of the more experienced participants and the low-performing group was composed of undergraduate students. Thus, the discrimination score in this case is a measure of the ability of a question to differentiate between levels of design experience. The mean difficulty and discrimination scores for each problem topic are plotted in Figure 6.10. One topic, failure modes, had a negative discrimination value, meaning novices performed better than experienced engineers. Design of experiments, which has been observed as a recurring issue in the courses, received a discrimination score of 1, indicating that performance on this question was heavily dependent on level of experience. Manufacturing process selection and estimation problems also performed well at discriminating. The question related to part selection appears to be too difficult, with only one response receiving a passing score.

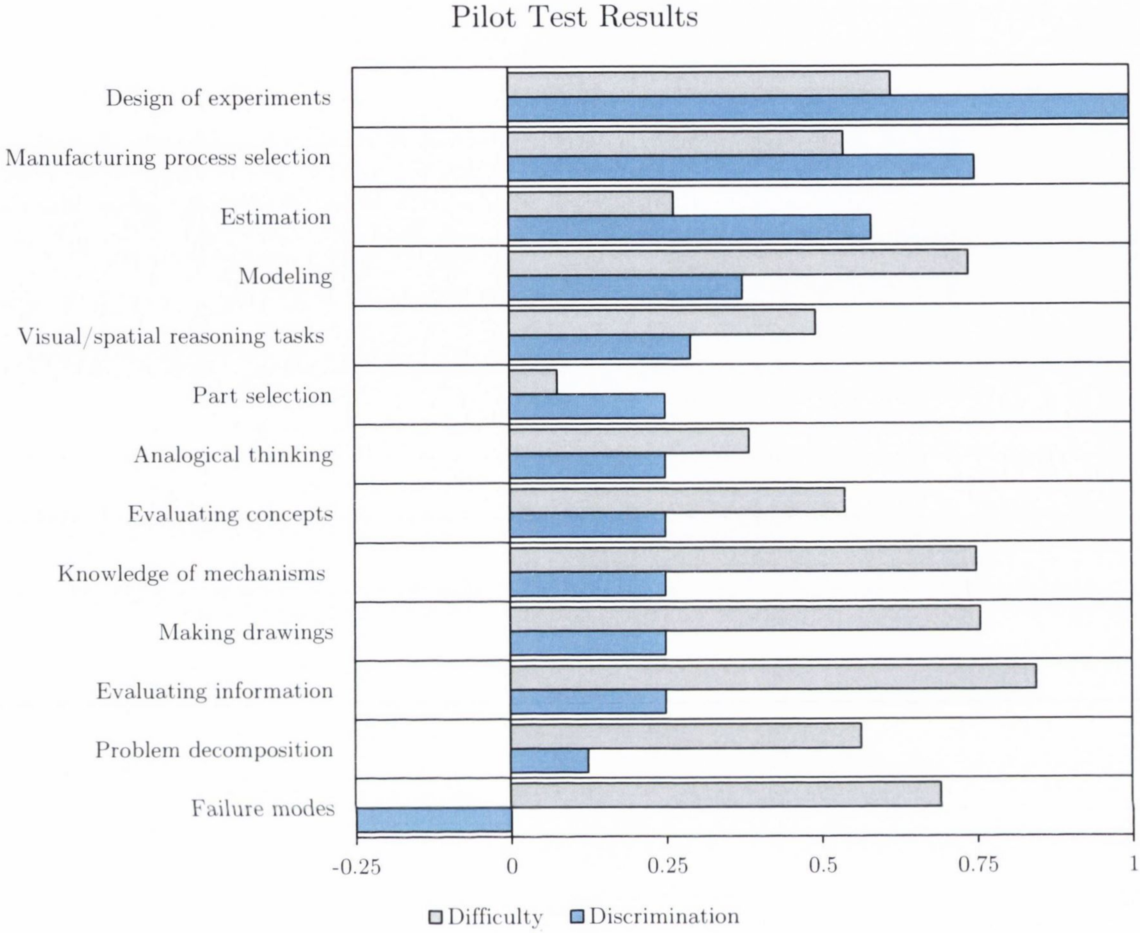


Figure 6.10: The difficulty and discrimination scores for each of the candidate question topics.

Some patterns emerge from the participants' comments. The questions on part selection and visual communication were seen as too complicated and time-consuming to complete within the allotted time. The problems related to modelling, estimation, and analogical thinking were unpopular, with participants of all levels of experience objecting to their ambiguity. These questions are perhaps the most dissimilar to typical engineering textbook problems. For example, the estimation questions deliberately do not include the information required to calculate an answer and instead require participants to guess quantities. As discussed in Chapter 4, this is an activity that is typically ignored, or even discouraged, in traditional engineering education, which may explain the unpopularity of these questions.

6.2.4 Refining the Instrument

The exploratory pilot study provided some insight into the types of concept question that may be appropriate for use in the third phase of research. Based on the participants' feedback, the difficulty and discrimination scores, and the results of the previous research phases, three problem topics were selected for use in the updated instrument. Evaluating and selecting between concepts, designing tests, and selecting approaches to prototyping have been recurring issues across all courses observed. The corresponding problems (concept evaluation, design of experiments, and manufacturing process selection) received appropriate difficulty and discrimination scores. Furthermore, participant feedback did not indicate any significant issues in understanding or attempting these problems.

The resulting instrument contains five questions. Four of the questions were developed to align with the course theme: medical application of soft robotics. The concept evaluation problem presents two solutions to a medical problem and asks students to evaluate each and indicate the concept they would choose to pursue if working on the project. The presented concepts are real, commercially available designs that attempt to address the same medical problem (trauma during endoscopy), each using a different "soft" approach. The prototyping question presents a soft actuator design and asks students to explain how they would go about building a prototype. This is also a real design, and the question includes a hyperlink to a video explaining its operation (Steltz et al., 2009). The design of experiments problem asks students to outline the tests they would perform to evaluate a particular soft actuator design for use in a "pick and place" robotic arm. Again, the question is based on a real actuator and application. The instrument is intended as a take-home test, and authentic design problems and solutions are used so that students may gather additional information to guide their responses if they wish, as they would do when working on their own design problems. To ensure that these questions did not relate directly to any of the students projects in the course, the problem details were defined after the candidate projects for Course A3 had been selected.

In addition to these three questions, the instrument includes a self-efficacy measure and a creativity test. One question from the self-efficacy instrument developed and validated by Carberry et al. (2010) asks participants to rate their belief in their current ability to perform a range of design process tasks (Figure 6.11). The creativity test is a variation on Guilford's Alternative Uses Task (Guilford, 1956) in which participants are asked to list as

Q1. Rate your degree of **confidence** (i.e. belief in your current ability) to perform the following tasks by recording a number from 0 to 100.
(0 = cannot do at all; 50 = moderately can do; 100 = highly certain can do).

	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Conduct engineering design	○	○	○	○	○	○	○	○	○	○	○
Identify a design need	○	○	○	○	○	○	○	○	○	○	○
Research a design need	○	○	○	○	○	○	○	○	○	○	○
Develop design solutions	○	○	○	○	○	○	○	○	○	○	○
Select the best possible design	○	○	○	○	○	○	○	○	○	○	○
Construct a prototype	○	○	○	○	○	○	○	○	○	○	○
Evaluate and test a design	○	○	○	○	○	○	○	○	○	○	○
Communicate a design	○	○	○	○	○	○	○	○	○	○	○
Redesign	○	○	○	○	○	○	○	○	○	○	○

Figure 6.11: An item from the self-efficacy instrument developed by Carberry et al. (2010).

many potential uses as they can think of for a common object (such as a brick or a paperclip). The test is intended to measure divergent thinking, which has been found to be a reliable indicator of creative potential (Runco and Acar, 2012). The responses are evaluated on 4 components: fluency (number of ideas), originality (compared to responses in the overall data set), flexibility (number of different idea categories), and elaboration (amount of detail provided). In the variation used here, the students are asked to list uses for the soft bending actuator described in Galloway et al. (2013). This modification is an attempt to examine domain-specific creativity: rather than asking students to generate uses for an arbitrary object, it may be of interest to examine whether extensive design experience with a type of component results in more or less ideas for alternative uses. Finally, a detailed rubric was developed to guide analysis of the responses. The contents and weighting of the rubric were developed in consultation with other members of teaching staff in Course A. The complete instrument and the associated rubric are provided in Appendix H.

6.2.5 Summary

This section has described the development of a data collection instrument intended to measure aspects of students' design knowledge. A range of candidate questions was developed and a pilot study was used to evaluate the difficulty of each question as well as its ability to differentiate between levels of experience. The pilot study also gathered feedback from participants which identified the shortcomings of certain questions. Based on these results, a five-item test of design knowledge was developed for use during the next phase of research. The test consists of three modified questions from the pilot study instrument, and two questions taken from the literature. The updated instrument primarily focuses on soft robotics applications as it is intended for use in an OATPB course dedicated to the design of soft robotic devices. However, the general format of the questions could be applied to any type of mechanical design.

Chapter 7 describes the third phase of research in OATPB courses. This phase focuses on one course, and involves the use of the resources developed in this chapter. The SRT is used to support students' design activities, and the data collection instrument is used as a pre-test and post-test in an attempt to measure the effects of the course on students' design knowledge.

Chapter 7

Research Phase 3

This chapter describes the third and final phase of empirical research in open-ended, authentic, team- and project-based (OATPB) engineering design courses presented in this thesis. The objective of the thesis is to develop a pedagogical framework to guide the design of learning environments for OATPB courses. Chapter 2 described the philosophical and methodological underpinnings of this research, in particular an abductive approach to combining theory and practice. In this view, theory is used to guide action, and the results of action are used to refine theory. Thus, throughout the thesis the pedagogical framework is used to inform the design of learning environments, and the resulting experiences of learners and educators are used to refine the framework.

In Chapter 3, the initial content of the framework was developed through a review of the literature on the psychology and practice of design. The review identified four categories of knowledge essential to design: design strategies and processes, design models, design knowledge reuse, and the social nature of design. A learning theory corresponding to each of these categories was identified through a review of educational psychology and social anthropology research. The empirical results from studies of design were thus paired with theoretical perspectives on the social and situated nature of knowledge and learning.

Chapters 4 and 5 described qualitative research conducted in OATPB courses. The results of the research were described and interpreted in terms of the four categories of design knowledge that form the basis of the pedagogical framework. Problematic aspects of the learning environments were identified, including a tension between the flexible and methodical elements of design and a lack of access to domain knowledge and communities of practice. Chapter 5 described efforts to address some of these issues and found that the use of a technological theme aligned with the work of local engineering research groups provided a means of connecting students with engineering communities of practice.

However, it was observed that an obstacle to sustaining or scaling this approach was the requirement of a substantial time commitment from the members of these communities of practice. It was further observed that much of this time was dedicated to explaining declarative background knowledge as a foundation for subsequent interactions that focused on more advanced procedural knowledge. Thus, Chapter 6 described the development of a database containing declarative and background knowledge related to a particular technological theme: soft robotics. The content of the database was drawn from observations of student-expert interactions and further developed in collaboration with these experts. Initial testing demonstrated that the content was sufficiently clear for use by novices. Chapter 6 also described the development of a research instrument intended to measure certain aspects of design knowledge.

This chapter describes the use of this database and research instrument in an OATPB course, and further explores issues raised in previous chapters. The objectives of the chapter are to:

1. Gain further insight into the tension between the methodical and flexible aspects of design in OATPB courses;
2. Examine the role that a documentary source can play in supporting students' interactions with engineering communities of practice;
3. Understand the role of access to communities of practice in OATPB courses; and
4. Explore the potential for using open-ended conceptual questions to measure changes in design knowledge.

The chapter begins by explaining the modifications made to the learning environment and the research methods used. As before, the results of the research are described and discussed in terms of the categories of fundamental design knowledge identified in Chapter 3. Finally, the implications of the results for the pedagogical framework are discussed.

7.1 Context

Course A3 was selected as the sole focus of research during this phase in order to allow a closer examination of many of the issues identified during previous phases, and in particular to examine the relationship between the Soft Robotics Toolkit (SRT) and the students' access to soft robotics experts. Most features of the learning environment were retained from the previous iteration of the course; this section describes the key modifications made.

The student cohort consisted of five graduate and eight undergraduate students working in four teams, each with a different clinician. The course deliverables and milestones remained unchanged. Templates for each deliverable were provided to support documentation efforts, and in particular to encourage the use of the "wiki" webpages to keep a record of student work. The general soft robotics theme was also maintained, and a wider range of "soft" technologies were considered as potential sources of inspiration for students. When identifying candidate design problems an effort was made to more closely align each project with the work of a particular research group. The number of guest lectures was greatly increased, with at least one external expert visiting the classroom each week.

The most notable change was the introduction of the SRT and the addition of related lab activities. Four introductory labs drew on material from the website and exposed students to a variety of precedent designs and fabrication procedures, while familiarizing them with the structure of the website and providing training on the use of workshop equipment. For example, in the fourth week the students built an underactuated finger using shape deposition manufacturing (SDM). This activity introduced students to design work conducted by a student team during the previous phase, the activities of a local research group, and a specialized manufacturing approach.

SDM involves successive cycles of subtractive manufacturing, in which a CNC mill is used to machine a mould, and additive manufacturing, in which the resulting mould is filled with polymer (Figure 7.1) (Binnard and Cutkosky, 2000). This approach allows the creation of more complex shapes, consisting of multiple materials and embedded components, than would be possible from a traditional moulding procedure. The soft, underactuated fingers shown in Figure 7.1 are examples of components made using this technique. These fingers were developed by a student team in Course A2, drawing on the work of an engineering research group at Harvard, as atraumatic manipulators for use in surgery involving delicate tissue (Gafford et al., 2014). The compliant joints allow the fingers to conform to a wide variety of shapes, and embedded pressure sensors provide feedback about contact force to the surgeon.

The lab activity during the fourth week introduced the students to these topics and required them to build their own SDM finger, which served as an opportunity to train the students on the use of CNC mills. The time required to complete fabrication of a finger is typically days, as the poured polymer must be allowed to cure before subsequent machining can take place. Thus, it was not possible to cover the entire process during the lab period. The students were required to complete the process outside of formal teaching hours, using the SRT as their guide. Thus, the SRT supported learning activities that were not feasible during previous phases.

This approach was taken in each of the introductory labs: students were introduced to a particular technology and fabrication process, the activity provided training on the use of

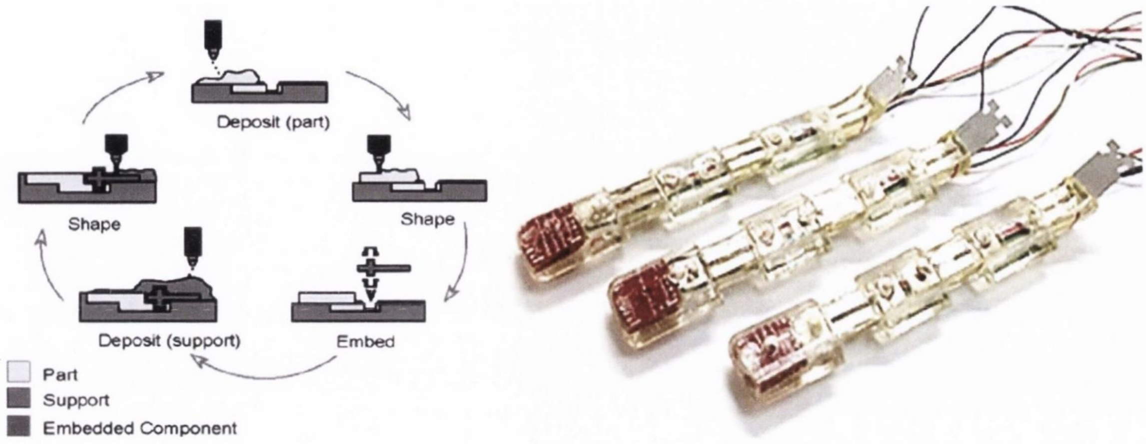


Figure 7.1: An overview of the shape deposition manufacturing (SDM) process (left) (Dollar and Howe, 2006) and the SDM fingers designed by a previous Course A team (right).

workshop or lab equipment, and the SRT was used to allow students to complete the task independently. As before, these structured lab sessions took place in parallel with the teams' problem definition activities; the pre-planned lab sessions ended when teams began focusing on concept design, and lab periods were used for self-directed project work with assistance from the teaching staff. Table 7.1 contains an overview of the course milestones and lab activities.

7.1.1 Methods

The methods of gathering qualitative data were identical to those used during the previous phase. Fieldnotes were used to document weekly review meetings, contextual interviews, teams' working meetings, and activities during lab periods. Contextual interviews took place in computer rooms while students created CAD solid models and in labs and workshops while teams fabricated prototypes. Upon completion of the course, exit interviews were conducted with eleven students. These interviews were used to discuss trends observed during the projects and thereby served as member checks, or opportunities to discuss students' opinions regarding emerging interpretations (Wallendorf and Belk, 1989). Again, the analysis of the qualitative data followed the process described in Chapter 2.

In contrast to previous phases, quantitative data gathering methods were used to provide an alternative perspective on students' experiences. Weekly questionnaires asked students to rate how helpful they found each of 12 aspects of the learning environment in a given week, and were used to record each team's use of resources and their opinions on course activities. Figure 7.2 shows an example item from this questionnaire, and the entire instrument is provided

Table 7.1: Overview of milestones and lab activities in Course A3

Week	Milestone	Lab activity
1	Individual research reports Project selections	Lab and workshop safety training
2	Research plan	PneuNets bending actuator Pneumatic artificial muscle Open-loop control using SRT control board
3	Prior art review	Fibre-reinforced bending actuator Laser cutter training
4	Design brief and mission statement	SDM Finger CNC mill training
5	High-level concept presentation	Sensors and signal processing Closed-loop control using SRT control board
6		Unstructured
7	Concept presentation	Unstructured
9		Unstructured
10		Unstructured
11	Design review presentation	Unstructured
12		Unstructured
13		Unstructured
14		Presentation practice
15	Working prototype Final presentation Final paper	No lab

Course A3 Weekly Questionnaire

Project Group:___________________________ Date:__________________

Please rate how helpful you found each of the following resources and activities while working on your design project during the past week.

	Did not use	Not at all	To a limited extent	To a moderate extent	To a great extent	To a very great extent
Soft Robotics Toolkit website	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5

Figure 7.2: An excerpt from the weekly questionnaire.

in Appendix C. Questionnaire responses were anonymous but included team identifiers. To ensure that the students did not feel coerced into participating or into distorting their ratings to please the teaching staff, a research assistant who was not part of the teaching team collected the questionnaires each week and shared only general class ratings with the primary researcher; the team identifier data was not shared until completion of the course.

A website analytics service (Google Analytics) was used to record statistics about visits to the SRT website during the course. The aim of collecting this data was to identify patterns in students' use of the resource as a means of triangulating the data from students' weekly ratings and the qualitative observations. For the duration of the course, password protection was used to ensure that only students could access the site. Teaching staff used a browser plug-in to avoid their website visits being included in the analytics data. The data collected contained no identifying information.

Finally, the pre- and post- test developed in Chapter 6 was used in an attempt to measure the effects of the course on aspects of students' design knowledge. In the second week of the course, when teams had been formed and projects selected, and again at the end of the course when the final design had been submitted, each student was asked to complete the test as a voluntary exercise. The grading of the responses to the pre-test (N=13) and post-test (N=11) was conducted simultaneously and was guided by the rubric in Appendix H. The grading of responses to the modified Guilford's alternative uses task (Q.2) followed the standard procedure for assessing this type of creativity test. Each response was assigned four scores, corresponding to fluency (number of ideas), flexibility (the number of idea categories), elaboration (the amount of detail provided) and originality (the number of ideas that are unique among the entire data set). During grading the researcher was blind to whether a given response was collected at the beginning or end of the course as each response was marked with a random 3-digit identifier. When grading was complete, the identifiers were used to associate scores with the pre-test and post-test. A Welch's t-test was used to compare the scores on each and a P-value < 0.05 was considered statistically significant.

7.2 Results and Discussion

7.2.1 Design Processes and Strategies

A recurring issue throughout the observations thus far has been the challenge of balancing methodical and flexible design process strategies. In all of the courses observed, assignments and milestones have been used to provide a methodical structure, and review meetings have been used to support flexibility by identifying opportunities for deviation from the methodical process. The third phase of research was used to gain more insight into the challenge of achieving balance between these two elements of the design process.

Figure 7.3 shows the average weekly student rating of course activities and resources related to process and structure. Lectures and assignment templates, plotted in grey, represent the pre-planned and methodical aspects of the course process. Review meetings and lab sessions, plotted in blue, represent the flexible coaching elements of the course. The interesting pattern to note here is that students exhibit a preference for the latter. The lab session, in which students carried out self-directed design tasks with coaching from the teaching staff, was consistently rated more useful than the lecture, during which the teaching staff discussed predetermined topics related to the design process. Similarly, the review meetings, which involved guidance on current project tasks, were rated more helpful than the assignment templates, which guided teams through prestructured tasks. Thus, the students exhibited a preference for activities that were more open-ended and contingent upon particular circumstances. Even within the labs, the initial weeks involved pre-planned activities which were rated less helpful than the remaining unstructured practical session. This preference is potentially related to findings from multiple domains that indicate novices prefer to follow a depth-first approach to problem-solving. However, it is perhaps a surprising result among engineering students, whose education typically emphasizes systematic and rule-based procedures.

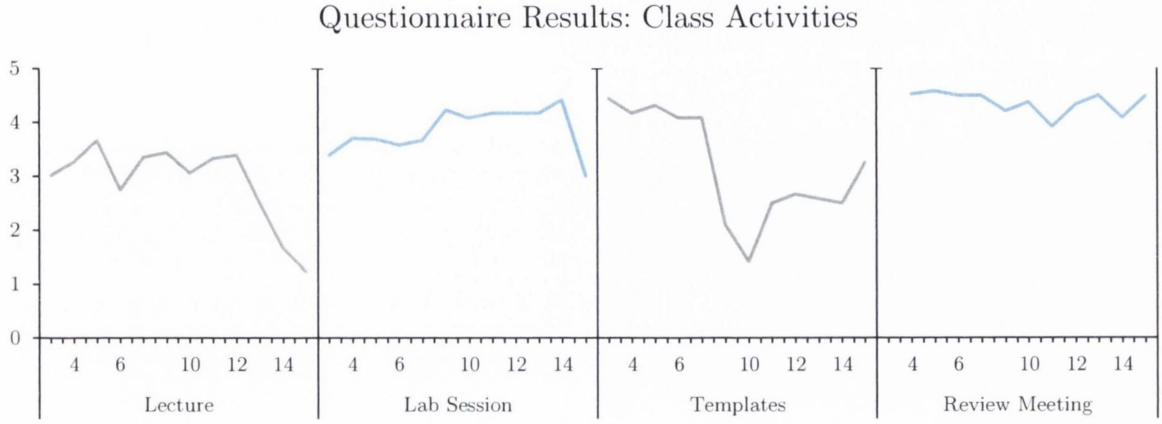


Figure 7.3: Average weekly rating of the helpfulness of course activities and resources related to design processes and strategies.

The qualitative data confirms this trend. Some teams felt that the process was overly restrictive and prevented sufficient exploration of potential solutions. These were teams whose projects involved greater levels of uncertainty, and students who identified clear goals early in the course found the methodical structure beneficial. Table 7.2 contains interview quotes illustrating the variety of student experiences regarding assignments. For the teams faced with high levels of uncertainty, the timing of the assignments did not allow sufficient opportunity to engage in depth-first explorations before being asked to make decisions. Among these teams the phenomenon of immediate tasks undermining overall goals was again evident. Interestingly, all members of Team 3.4 were aware that they were engaging in a strategy of local task optimization and explicitly blamed this upon the timing of the assignments.

In fact, this team appeared to have faced more process-related difficulties than any other team observed in Course A during the three phases, and their experiences may therefore yield insight into the tension between methodical and flexible strategies. The team was not working on a soft robotics project, and understandably felt themselves to be at a disadvantage compared to other teams. Their project was characterized by a high level of uncertainty, with neither teaching staff nor student team having a clear idea for an appropriate direction during concept design. Therefore they needed to engage in depth-first explorations before making a decision. At the end of the course they felt that engaging in prototyping and testing earlier in the course would have been beneficial, but felt that the imposed structure, and in particular the milestone assignments, were too rigid to allow this. However, the observation data indicates that their difficulties, while partly due to the imposed methodical structure, were primarily caused by problems of communication and expectations. During the concept

Table 7.2: Student perspectives on course structure and assignments

Team 3.1

S: I don't think [the assignments] were a distraction. I think they helped... forced us to document what we were doing and kind of show us what we needed to get out of our research

Team 3.2

S: I feel like there was an emphasis throughout the course on "this is the design process, these are the steps, we're in step 1 now, now we're in step 2, and you can't do step 3 until we've done step 2." And this sort of regimented schedule... which I can appreciate, but I think it was also the source of a lot of frustration for me personally and other people...

R: Do you think it would be better to have a structure where the assignments were more spaced out to allow for more exploration?

S: I'm kind of conflicted in that I think there's a lot of value in coming up with an idea, testing it, playing around, saying "oh that doesn't work, OK we need to change this," going back and redoing concepts. So that spaced out structure works in that sense but then obviously at the end when you're trying to finalize a prototype you've a lot less time. And I think even now, iterating at the end I felt like it was sort of rushed and we could have done a lot more, like iterated a couple more times. But I think in general it's an aggressive amount of stuff to fit into a semester-long course so I don't think there's necessarily a good answer for that.

Team 3.4

S: I think those assignments mean well, and there's always that feeling to help the course be as guided as possible and the whole design process be as guided as possible. But there's this kind of issue of– you spend so much time on [the assignments] that you actually do nothing on the other stuff... I know that in a course you need to keep everyone guided on where they're going but definitely having graded deliverables, students will spend a lot more time on those deliverables because they're graded and they want them to look nice and things. And they kind of miss out on what they should be focusing on.

design phase the teaching staff repeatedly asked to see prototypes of concepts before the team made a decision. That is, the teaching staff requested that the team engage in depth-first explorations. The students tended to disregard these requests, apparently operating under the reasonable belief that the course assignments and milestones took precedence. This indicates that in order for the review meetings to enable flexibility, it must be made explicit to students that the guidance received during coaching can supersede the predetermined course timetable and that teams would not be reprimanded for disregarding the assignments when so advised.

Students' Design Process Self-Efficacy

The engineering design self-efficacy instrument developed by Carberry et al. (2010) was used to measure students' beliefs in their own design abilities at the beginning and end of the course. Carberry and his colleagues validated the instrument by comparing the responses of 202 individuals with varying levels of design experience. They found that the mean engineering design process (EDP) self-efficacy score for the group with intermediate-level experience (composed of engineering undergraduates and non-engineers with science backgrounds) was 60.50 ± 22.63, while that of the experienced group (composed of professional engineers, engineering faculty, and engineering graduate students) was 82.47 ± 12.44.

The self-efficacy scores from Course A3 are plotted in Figure 7.4. The mean EDP score at the beginning of the course was 69.42 ± 17.57, and at the end of the course was 86.64 ± 10.44. Comparing these to the results from Carberry et al. (2010), at the beginning of the course the students' self-efficacy was slightly above the average intermediate score, which is to be expected given the presence of graduate students in the group. At the end of the course, the mean self-efficacy was comparable to Carberry's experienced group. A significant increase was observed in all items ($P < 0.05$). The most substantial gain was observed in the "Redesign" item, potentially as a result of the extensive use of precedents throughout the course. The scores reflect only the students' opinions of their own abilities. While these opinions may be inaccurate, the results indicate that, from the students' perspective, the course represented a substantial design experience that significantly increased their level of engineering design process confidence.

Students' Design Knowledge

The pre- and post-test developed in Chapter 6 was used to examine the effect of the course on students' design knowledge. As can be seen in Figure 7.5, students showed improvement

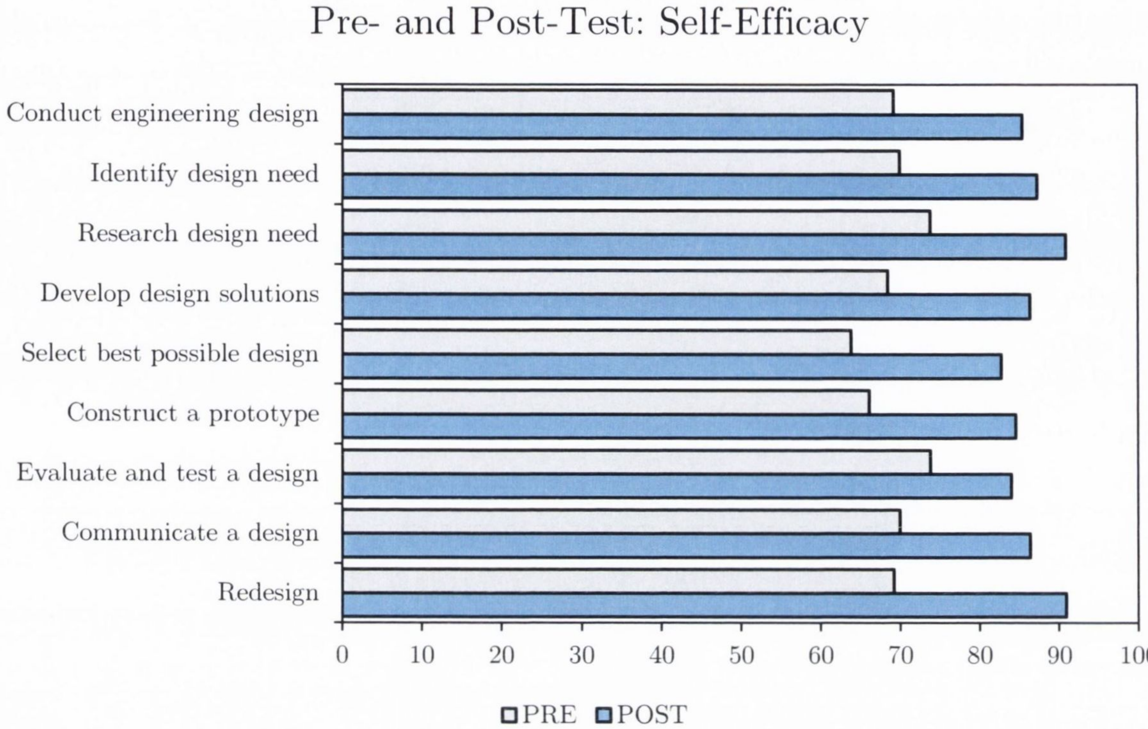


Figure 7.4: Students' self-efficacy scores at the beginning and end of the course.

on all but one of the measures. However, the only significant gain occurred in responses to the fabrication question ($P < 0.05$). This is perhaps unsurprising given the emphasis on procedural knowledge related to detail design and fabrication in the student projects, the learning resources, and the initial labs. However, with such a small sample size and subjective scoring of responses, it would be inappropriate to make any major claims about the results of the pre- and post-test. Furthermore, a potential shortcoming of the test was raised during the exit interviews. Participation in the test was completely voluntary and performance had no influence on course grades, meaning that there was no incentive for the students to exert effort in answering the questions. The following student quote illustrates this point:

> It's quite long, and I think at the end of the course you might find people not filling out... you might not see the results you expect just because people are like "Well I've already done this, you want me to list all these things again and maybe a few more," you know? So yeah, I would watch out for biased results or something.

The instrument may be of limited utility as a research tool only, and may have to be included as a course requirement in order to ensure meaningful results. However, at the very

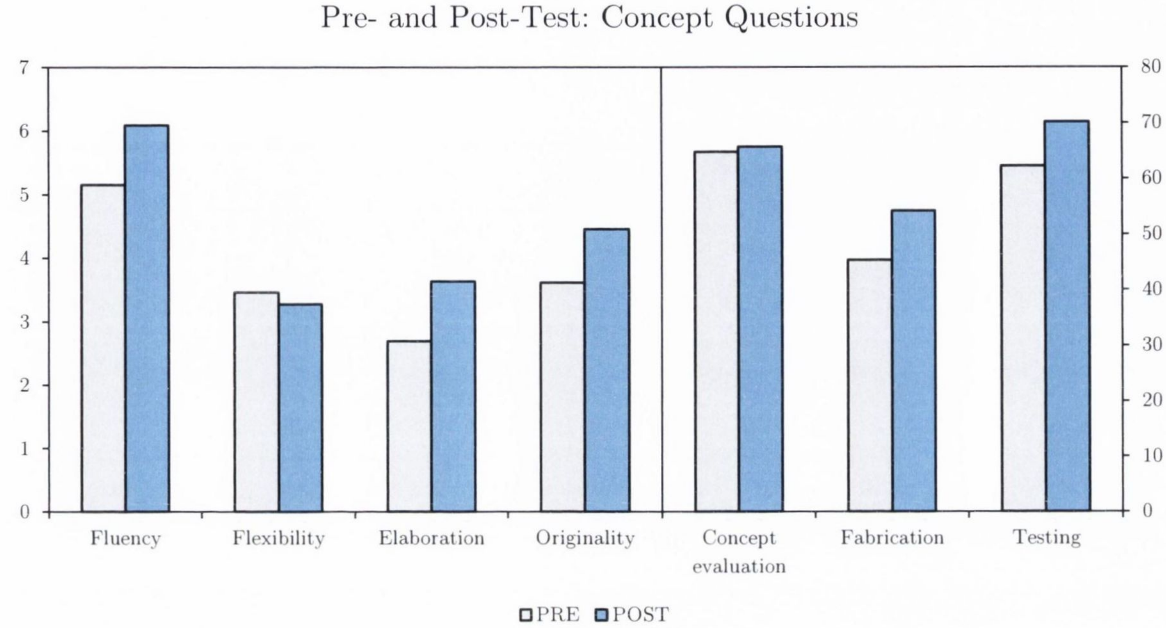


Figure 7.5: Mean scores of students' responses to the concept questions at the beginning and end of the course.

least this study has indicated that it is possible to measure changes over time in students' design knowledge.

7.2.2 Design Knowledge Reuse

As in previous phases, the student teams conducted comprehensive background research and prior art searches to define their problem and identify possible solutions. In addition, concept precedents were drawn from previous course projects, from interactions with domain experts, and from the Soft Robotics Toolkit. However, these sources were more often used as sources of detail precedents. As in the previous phase, students used experts to learn more about particular component designs, manufacturing approaches and material selection. The primary difference in this phase was the use of the SRT and the introductory labs to provide basic background information on a range of detail precedents. The objective of introducing these elements was to reduce the demands on experts' time by providing the students with the contextual information required for effective interactions in advance of their meetings with experts. In this respect the SRT appears to have been successful. The teams who drew on precedents documented on the SRT site continued to interact with the relevant engineering experts, but their discussions tended to be of shorter duration and to focus more on advanced aspects of the technology in question.

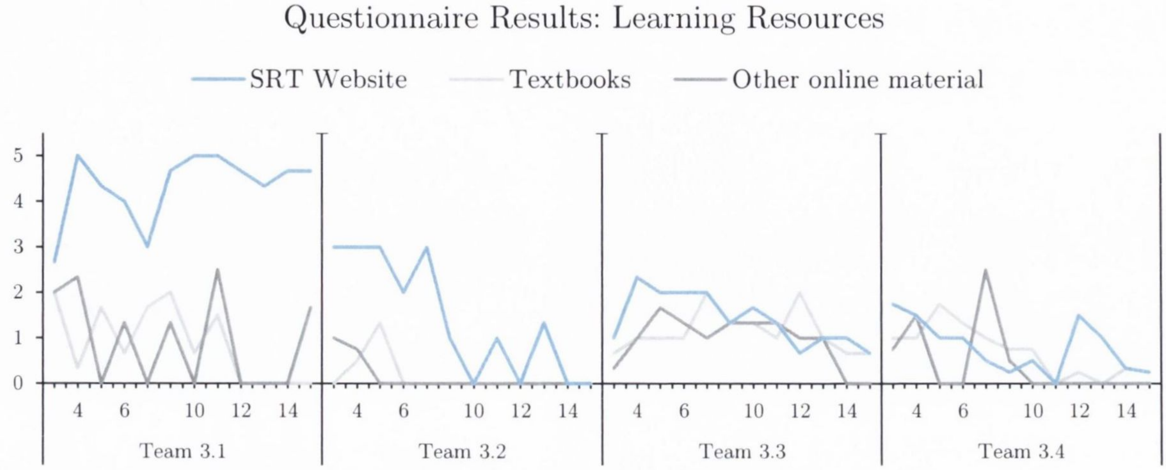


Figure 7.6: Weekly questionnaire results indicating how helpful each team found various learning resources.

Figure 7.6 shows each team's weekly ratings for the SRT, textbooks, and other online documentation. Team 3.1 clearly relied more heavily on the SRT compared to other teams, and as a result their interactions with experts tended to be regular brief discussions of specialized topics rather than longer meetings discussing background information. Team 3.2 based their actuator design on material from the SRT, and the website and introductory labs enabled them to identify and design the appropriate actuators early in the process. The remainder of their project focused on other aspects of the design problem, such as how to design wearable devices composed of fabric and other topics that the toolkit did not address. Team 3.3 relied on soft component technology that was not documented on the site and therefore required longer meetings with experts to cover the background information. However, even in this case the students reported that use of the SRT during the introductory labs introduced them to materials and casting processes required for their subsequent work. Team 3.4 did not find their needs served by the SRT and relied more heavily on social interactions, in particular to learn about materials and fabrication processes.

Although in general it is rated more useful than both textbooks and other online resources, the ratings for the SRT are quite low for all teams except Team 3.1. Two primary reasons for this were observed. First, the initial labs, based on material from the SRT, successfully introduced the topics to students and often the teams did not need to revisit the material subsequently. Second, the distributed expertise within teams meant that often only a single team member focused on soft component technology while their teammates specialized in other areas of the design. This served to reduce the average rating as the material was not applicable to most team members. Overall, access to the SRT was observed to be beneficial, for example in supporting the initial lab activities, each of which would otherwise have required multiple weeks to complete. Many of the students who did not find it helpful for their particular projects expressed enthusiasm for the concept nevertheless, and suggested improvements and additions to the site.

Among those students whose projects made use of the content of the SRT, it enabled independent work on design and fabrication tasks. These students reported that these sections of the site were the most useful for their needs; they did not engage in substantial amounts of testing and modelling and therefore rarely consulted that material. The website analytics data plotted in Figure 7.7 reveals patterns in how the SRT was used. At the beginning of the course students made a large number of brief visits to the site to seek information related to lab activities. During concept design the amount of visits decreased. At the beginning of the detail design stage of the projects, student visits were of much longer duration as they began using the website to support independent work such as the creation of mould CAD files and the fabrication of early prototypes. Towards the end of the course some teams were still using the same fabrication methods, but had internalized the procedure and had modified it to suit their purposes. As a result, both the number of visits and the average visit duration remain low during the final weeks of the course.

The overall pattern appears to be that the SRT was used at the beginning of the course as a source of basic information, and some teams used this information in framing their problem and generating initial solution concepts. During detail design the SRT was then used as a source of detail precedent knowledge, and the peaks in average visit duration correspond to the stage of the course when students spent most time interacting with engineering communities of practice. This seems to indicate that the SRT was useful in supporting the interactions between novices and experts, which was the primary objective of introducing it to the course.

Cognitive Flexibility Theory and the SRT

One of the fundamental principles of cognitive flexibility theory is the need for multiple knowledge representations when learning knowledge related to open-ended problem solving. Concepts, principles, and theories should be presented from multiple perspectives and in multiple contexts so that learners can reason about those aspects of knowledge that are transferrable between situations and those that are context-dependent. An assumption in the design of the SRT was that each type of component technology was a particular representation

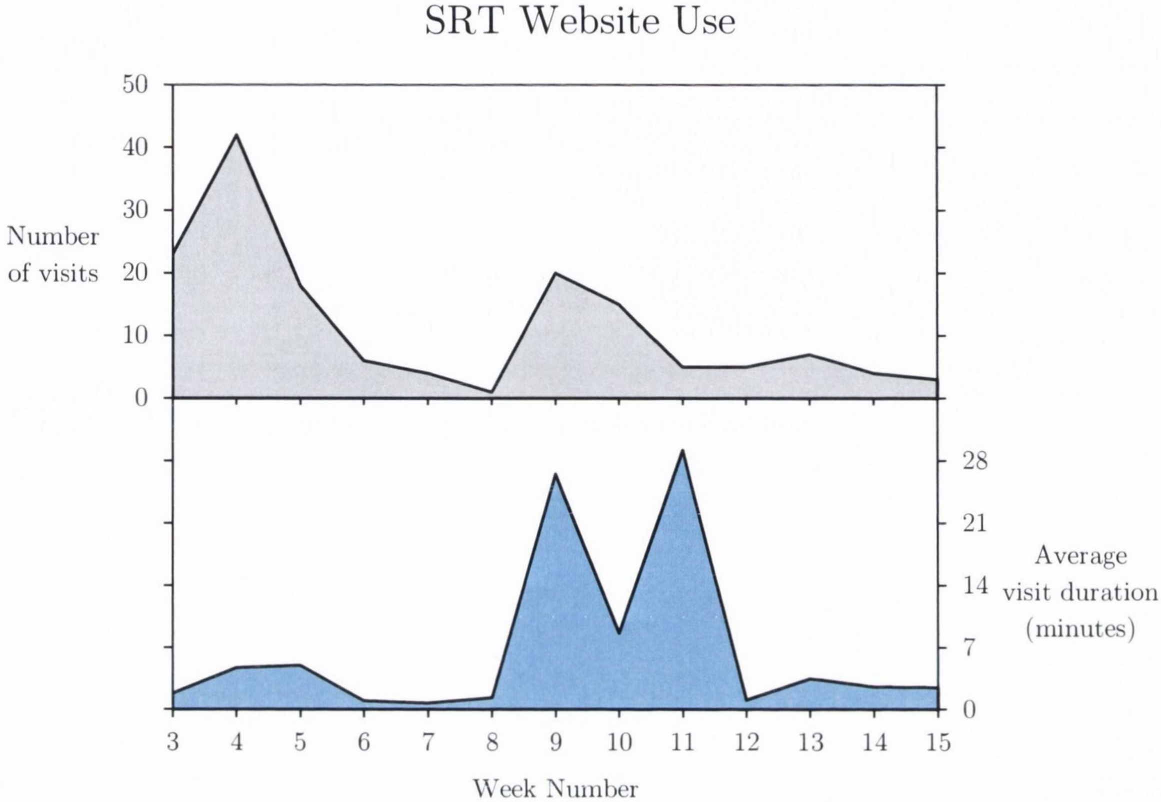


Figure 7.7: Website analytics data for the Soft Robotics Toolkit showing the use of the site by students throughout their design projects.

of the fundamental concept of "morphological computation," or the attainment of complex behaviour through mechanical design rather than through sophisticated software or electronic control systems. For example, fluidic soft robotic actuators can achieve complex motions involving multiple degrees of freedom, using simple fluid pressure as an input. An actuator's behaviour is based primarily on structural, morphological, and material properties, rather than any external intelligence.

It was assumed that exposing students to multiple specific examples of morphological computation would support them in implementing the concept in their own designs. However, this assumption proved to be flawed. The concept of morphological computation is so broadly applicable, and the examples provided in the SRT so dissimilar, that it was difficult for students to transfer design knowledge from one context to another. They may have grasped the fundamental concept, but it was of little assistance in learning the detailed procedural knowledge required to significantly modify a precedent design. For example, Team 3.1 based much of their design on a modified version of an actuator documented in the SRT. When making these modifications to the actuator's design the team referred to the tutorials and protocols on the website. However, the fact that only one instance of this actuator was documented made it impossible for them to discern those features that were specific to this instance and those that were related to the general principle of operation of the actuator type. In particular, the rationale for many steps in the procedure or features of the design remained unclear to the team. As a result, these students requested that variations on each tutorial and protocol be added, and suggested that this could be accomplished by recording the modifications made by students in each year of the course (Table 7.3). The implication is that, rather than thinking of the entire toolkit as a collection of instances of a single fundamental concept, each component type should be considered as a collection of concepts and principles, to be learned through multiple representations. For example, the section of the website documenting the PneuNets bending actuator should contain multiple examples demonstrating the design principles and fundamental principle of operation of this class of actuator.

Recording student work, as suggested by members of team 3.1, is in fact one of the goals of the SRT. Most of the examples currently documented on the website draw on the work of students in Phase 2. A long-term goal for the SRT is to encourage knowledge sharing between teams, as inter-team communication has remained minimal throughout the three phases. However, recording student work is difficult. During the three phases of research each team in Course A was provided with a "wiki" webpage hosted on Harvard's campus-wide virtual learning environment. Teams were encouraged to use their wiki to record their progress, and teaching staff often referred to the webpages during weekly review meetings. One of the aims of introducing template documents during this phase was to encourage a standardized approach to creating documentation for the wiki. However, student use of this resource was limited, and most teams saw the wiki simply as a means of sending completed assignments to the teaching staff. Students rarely consulted other team's wikis, and rarely recorded material that was not part of a specific assignment.

When asked about their use of the wiki, many teams felt that the environment was difficult to use and preferred to share documents using third party solutions. Team members typically spent so much time together in person that their need to share documentation online was minimal. Furthermore, many students felt that documentation tasks were a distraction from their design projects (Table 7.3). This last point is problematic. Documentation is an essential

Table 7.3: Student perspectives on documentation

Team 3.1

S1: Maybe if we put up some of the previous teams' work and how they modified the protocol it would help future teams. [...] I think a general protocol with caveats, even if you just keep the current protocol and say "If you would like to modify into a rectangular geometry this would be helpful." Just little tips like that.

S2: Not this year but next year have each team write up content for the website of what they did, what worked, and what didn't work [laughs]. And then just put it up there. If you want to look at it you ask. "Hey R we have this problem" and you're like "Well, you know team X had that problem last year, go look at their portion of the website and you'll see."

Team 3.2

S: There was nothing specific about the wiki that made it useful, it could have been done with any other sharing thing like Dropbox, Google Drive, whatever. In the past wikis have been very useful for me in other projects.

[Opens laptop and shows the website used in a previous team-based project]

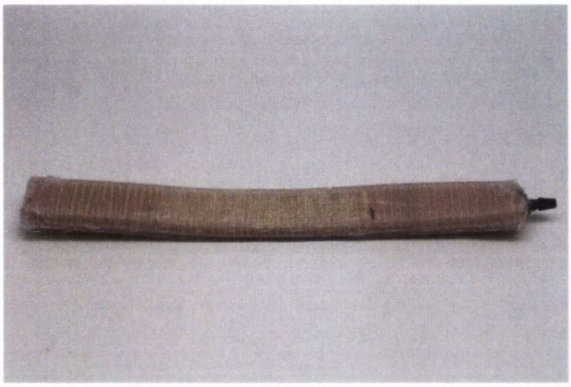
R: What were the differences between the way that course expected you to use it and the way this course did?

S: ... Now that I think about it, because I spent so much time in person with my team, there wasn't as much that had to be communicated digitally. Versus with that other project we were in and out of the lab, often not all five people could be there at the same time so it was immensely useful to be able to update everything in one place, everyone goes there and looks at it... Whereas for us, a lot of our stuff was physical and I wasn't going to take pictures at every single step of the way. And because I saw them so often that communication was just much easier to do in person.

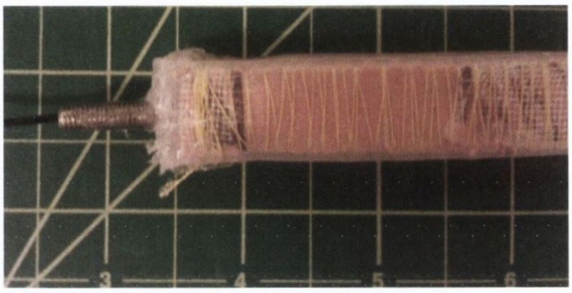
Team 3.3

The thing is [updating the wiki] also takes time away from the projects. So keeping the website updated you have to put effort into that in addition to the project. So I think we sort of left it by the wayside a little bit, because it seemed like it was more important to get things done on the project rather than– Especially since we still were documenting things but it was easier to do it on a Google doc or whatever.

Capping



Barbed Vent in Actuator Made with Pin Molding Method - Does not leak up to 40 PSI without SilPoxy. Adding SilPoxy to the hole before inserting the barb produces the best seal after two days - Actuator pops before leaking at that joint.



Glued Vented Screw Capping - Very likely to leak between the screw threads and elastomer - not reliable in our experience.

Figure 7.8: An example of detail design documentation produced by a student team.

part of engineering design activity, particularly in heavily regulated environments such as the medical device industry. Thus, encouraging students to develop good documentation practices may be beneficial. However, medical device engineers typically have access to sophisticated version control systems that lower many of the barriers to documentation, unlike the more rudimentary solutions available to students. Future development of the SRT website may benefit from reference to research on knowledge organization systems in industry.

Despite the general reluctance to producing documentation in addition to that required for assignments, upon completion of the course one team did voluntarily update their wiki with information that could be added to the SRT. This consisted of photographs and videos documenting attempted actuator designs, each with a caption describing the strengths or weaknesses of the approach. Figure 7.8 shows an example of the work uploaded. Identifying methods of encouraging other teams to share lessons like this throughout the duration of the course may lead to increased inter-team communication in future years.

SRT Control Board

Two preassembled control boards were available for use by the teams. In the initial weeks, the boards were used to support labs on control systems engineering and on sensor signal conditioning. Students were encouraged to use the boards as they saw fit in their projects and extra components were provided to enable teams to make modifications to the pre-built boards, or to build their own customized control system if necessary. During this phase,

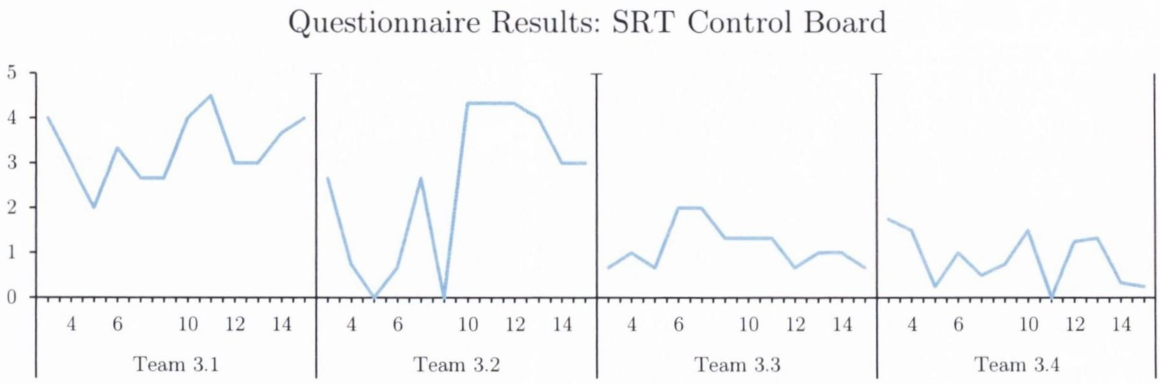


Figure 7.9: Weekly questionnaire results indicating how helpful the SRT control board was to each team.

the control board was again directly relevant to two teams' projects (Figure 7.9). Teams 3.1 and 3.2 used the board primarily as a platform for testing and demonstrating their design concepts. As before, access to the boards enabled the teams to focus on the design of their devices rather than the support hardware. Team 3.2 made extensive modifications to the control board, guided by the associated documentation on the SRT website. As is apparent from Figure 7.9, this occurred during the latter half of the course, in parallel with the prototyping of their device. The result was a control system customized for use with their final prototype. The board's portability was convenient when travelling to demonstrate their design to clinicians and user groups. The team member who took responsibility for the control board modifications felt that, without the provision of the preassembled board and the online documentation, this task would have been beyond the scope of the course. Team 3.1 relied less heavily on the board and made no modifications, as demonstration of their design required only basic manual control. Furthermore, the miniature pump included on the board did not provide enough fluid pressure to fully actuate their final prototype, and they instead relied on a larger air compressor for use in final testing.

7.2.3 The Social Nature of Design

In Phase 1 it was observed that one of the major obstacles to providing useful learning experiences in OATPB courses was a lack of access to engineering communities of practice. In Phase 2 course themes were used to connect students with research groups in an effort to overcome this obstacle. The resulting interactions seemed beneficial for students' learning, and during Phase 3 attempts were made to provide a greater number of connections between learners and experienced engineers. Projects were more deliberately aligned with the work of particular research groups, and more frequent guest lectures covering a wider range of topics were provided. Combining these approaches allowed space for teams to explore alternative solution technologies rather than being constrained to work with only one predetermined research group. For example, the attempt to align Team 3.4 with a particular research group was unsuccessful due to the project taking an unexpected direction, but guest lectures introduced topics relevant to their design and enabled students to make unplanned connections with a community of practice. Thus, the combination of provisional project alignment and a large variety of guest lectures preserved the open-ended nature of the course while allowing support to be planned in advance.

Figure 7.10 provides an indication of how each team interacted with different types of experts throughout the course. The general pattern is that, as expected, the teams relied on interactions with their clinicians primarily in the early stages of the process while interactions with expert engineers predominated in the later stages. Team 3.4 consulted experienced engineers during concept design and again during detail design, while Team 3.1 was in regular contact with a particular researcher throughout their project. The overall trend in how teams interacted with engineering communities of practice indicates that students used these interactions to access detail precedent knowledge, and concurs with observations from the previous phase and from the literature that highlight the role of social sources in tackling problems related to detail design (Ellis and Haugan, 1997; Milewski, 2007). Thus, the problems of access in OATPB courses, identified during Phase 1, appear to have been addressed in a repeatable way during Phases 2 and 3.

There are two potential drawbacks to connecting engineering students to more experienced peers. The first is that easy access to domain knowledge may prevent students from tackling complex problems on their own and therefore have a negative impact on their learning. However, the observation data contains multiple examples of students being required to overcome challenges in adapting precedent knowledge to suit the context of their particular problem. Comparing between the six student cohorts observed in this thesis, it may be the case that those with access to engineering expertise engaged in more complex problem-solving rather than less; one of the primary challenges the other teams faced was simply finding information, which is a logistical rather than conceptual problem. The second possible issue is that students may acquire an understanding of a very specific technological field but fail

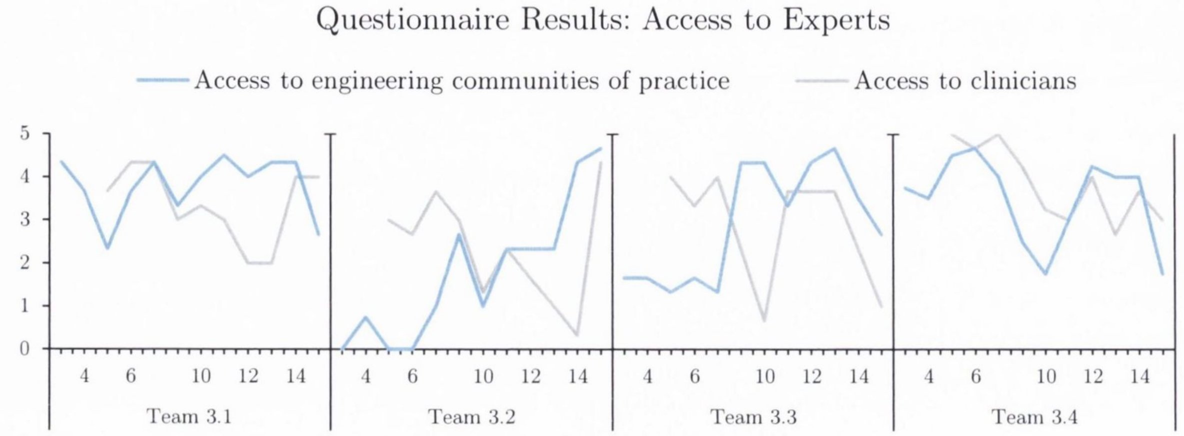


Figure 7.10: Weekly questionnaire results indicating how helpful each team found having access to experts.

to learn more fundamental knowledge about design practice. The social nature of design, and the role of interactions with more experienced peers in developing the social knowledge required for design, was not explicitly addressed in the course. Some students saw general educational value in these interactions while some did not (Table 7.4). The latter group viewed interacting with more experienced peers primarily as a means of accomplishing a particular task rather than as a learning opportunity. As a result, they may have benefited less from their experiences in the course. Thus, it may be necessary to make explicit the pedagogical rationale for connecting students with engineering communities of practice.

Finally, a conceivable problem in developing and sharing a resource like the SRT is that it could be perceived as a surrogate for these social interactions in design education. Rather, it is intended as a resource to support such interactions. The background information contained in the toolkit provides a common ground on which to base communication. By capturing much of the explicit knowledge about previous designs it enables discussions between experts and novices to focus on more subtle or tacit aspects of the experts' knowledge. The plots in Figure 7.10 and student quotes in Table 7.5 demonstrate that the teams were using the SRT to support rather than replace access to engineering communities of practice. It may be necessary to make the intended role of the toolkit explicit for other educators so that it is not applied to other learning environments without attention paid to the pedagogical framework that informed its development.

Table 7.4: Student perspectives on interacting with experts

Team 3.1 on problem-solving:

> It was helpful if you were open-minded enough to take all these ideas and convert them into what you need specifically for your project rather than getting bogged down in "He said do this" and not being able to take that and adapt it to your particular situation. [...] I guess if I was really desperate I would go to [the expert] and ask him how to do it but if I wasn't I would prefer to sit here and find my own way to do it.

Team 3.2 on learning outcomes:

> I think just having the experience of interacting with so many different other people for this one project made me a lot more receptive to the idea of asking for help and also– Again I think with a lot of these things it's that I'm more conscious of these things now. It's not like I didn't know that I could ask for help before, it's more that I'm much more aware that this is a very helpful thing and I've seen first-hand its benefits

Team 3.3 on learning outcomes:

> *R:* Do you think those interactions helped you to learn things that are useful to you beyond the course?
>
> *S:* I mean a lot of it was more specific to the project, but now I know how to make soft sensors!

Team 3.4 on learning outcomes:

> They were definitely helpful in terms of working with nitinol or whatever material we were working with, but also in the design process.

7.2.4 Comparison to Previous Phases

One of the challenges in improving OATPB courses, and one of the motivations in developing a collection of concept question to measure design knowledge, is that it is difficult to compare between one iteration of a course and another. A common approach taken is to use student satisfaction questionnaires to monitor changes in the course over time. At the end of each semester, all Harvard students are asked to rate various aspects of the courses they have completed and provide feedback on their experiences. As a means of evaluating OATPB courses, this approach is problematic as student satisfaction in these contexts may be influenced as much by their feelings about the success of their personal design projects as by any feature of the learning environment. Furthermore, the respondents to these questionnaires have no experience with previous iterations of the course and therefore are not capable of comparing one version of the environment with another. However, this thesis has relied pri-

Table 7.5: Student perspectives on the role of the SRT

Team 3.2

S: I think the level of information that was given to us was fine. I mean we still went and talked to plenty of people on our own because there are so many things that are going to be specific to your one project that it seems like it's highly unfeasible to try and make a module on the site for every single thing you need to do. And a lot of it isn't "how to do this." It's what does this researcher who has experience in this field think in general about your approach. That's not something you can present on a website.

Team 3.3

I saw it more as a starting place than "this is how you do everything forever"... It just sort of gave me the basics. I don't know if it could really replace the researcher interaction. [...] I don't think any of the teams were necessarily exactly copying the instructions from the website, you were adapting them to whatever project so there's always going to still be questions that you might have outside of that.

marily on the use of qualitative data, and subjective interpretation of that data, to compare between learning contexts. This approach is also susceptible to distortion, particularly when the researcher is actively involved in shaping the context being studied. Thus, this section examines the student satisfaction ratings from the three iterations of Course A described in this thesis. This is intended as another means of triangulating the data in order to improve the trustworthiness of the research.

In this questionnaire the students were asked to rate their satisfaction with four aspects of the course: the overall course, the coursework assignments, the feedback from teaching staff, and the learning materials provided. Figure 7.11 plots the average student satisfaction ratings from each phase of Course A. The overall trends apparent in these plots concur with aspects of the observations and interpretations presented in this thesis. The most substantial changes to the overall course occurred between Phases 1 and 2, when the focus of the course became medical applications of soft robotics. This corresponds to an increase in student satisfaction in all aspects of the learning environment. Between Phases 2 and 3, the overall course structure remained the same, resulting in identical average satisfaction ratings for both the overall course and the assignments. A reduction in satisfaction regarding the feedback from teaching staff during Phase 3 is very likely related to the problems faced by Team 3.4, as discussed above.

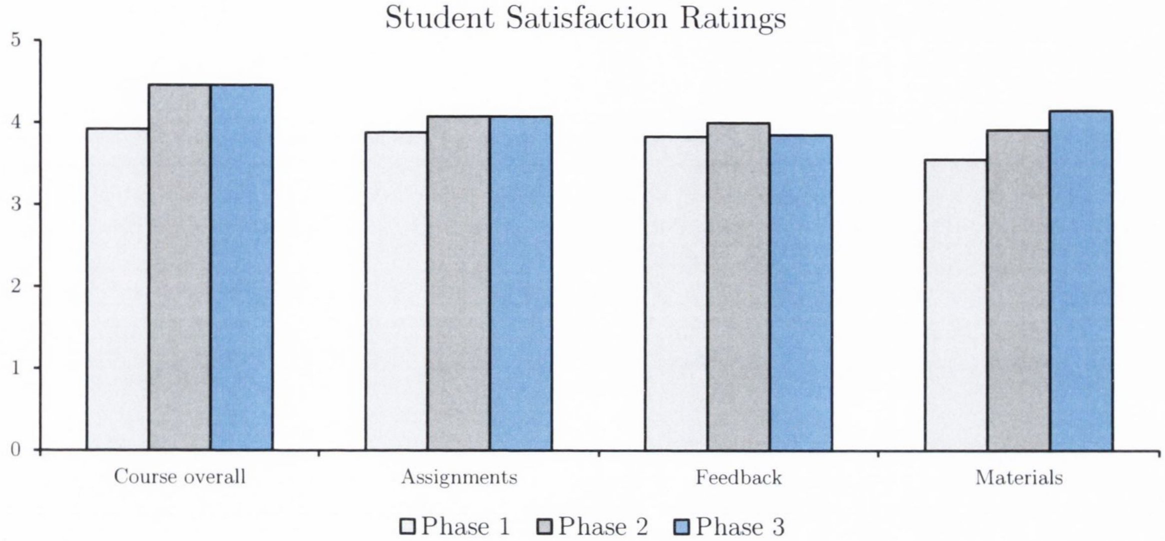


Figure 7.11: The mean student satisfaction with aspects of Course A for each of the three phases observed in this thesis.

The primary change in the learning environment between Phase 2 and 3 was the introduction of the SRT and a set of templates to guide the students' work, and the only increase in satisfaction during Phase 3 relates to the provided learning materials. Thus, these results appear to confirm some of the results from the qualitative research. However, this should not be taken as definite confirmation, as there are a wide range of factors that may influence students' satisfaction with the course, as mentioned above. In particular, during the three years the teaching staff became more experienced in the organization and delivery of Course A, and this may have improved the quality of the course in a variety of subtle ways.

7.3 Conclusions

This chapter has described the third and final phase of the research presented in this thesis. The research during this phase focused on investigating the use of a database of detail precedent knowledge in an OATPB course, and on exploring in more depth the experiences and perspectives of students related to some of the issues identified in previous chapters. Particular attention was paid to the tension between the flexible and methodical aspects of the design process, the reuse of design knowledge, and interactions between student designers and engineering communities of practice. This chapter also described the introduction of an instrument designed to test a variety of mechanical design skills, including concept generation and evaluation, prototyping, and testing.

The aim throughout this thesis has been to develop a pedagogical framework for OATPB courses by comparing theories and results from the literature to the experiences of students and teaching staff in these courses. This section summarizes the results from the third phase of research with reference to the framework. Additions to the framework in Table 7.6, based on results from the third phase of research, are highlighted in underlined font.

Design Processes and Strategies

Conflicts between task optimization strategies and both learning and design strategies were again evident in the actions of students. Interestingly, these students were aware of the conflict and felt that it was caused by features of the learning environment. The root cause of the observed issues appeared to be a high degree of project uncertainty combined with a lack of explicit permission for students to deviate from the overall course structure; although students were asked to engage in a depth-first exploration they appeared to consider these requests subordinate to the course milestones. This result implies a need to provide explicit permission to students to disregard milestones when appropriate. A potential approach to allow deviation while retaining overall structure may be to introduce secondary milestone deadlines, so that if a project requires more time spent on a particular task there is a formal mechanism to accommodate this and signal permission for students.

Pre- and post-test results indicated that completing the course positively affected students' confidence in their own design process abilities. Significant learning gains were only observed in one category: fabrication. However, shortcomings in the use of the test instrument purely as a research tool were identified. The results appear to indicate that it is possible to use open-ended conceptual questions to monitor changes in students' design abilities over time. However, testing on larger cohorts of students is required to confirm this.

Design Knowledge Reuse

The use of a database of detail design precedents was shown to provide much of the knowledge required by students during detail design and prototyping activities. This in turn was found to support interactions with engineering communities of practice by allowing many of the students basic information requests to be addressed in advance of meeting with experienced engineers. The database recorded information about the design, fabrication, modelling, and testing of soft robotic component technologies. The students whose work drew on the contents of the database reported that the content related to design and fabrication was more useful than that related to testing and fabrication. A shortcoming identified in the design of the database was the inclusion of only one instance of each category of component. Feedback from the students concurred with a fundamental principle of cognitive flexibility theory: multiple representations are required to facilitate transfer to other contexts and problems.

The Social Nature of Design

For a second time, the use of a course theme related to a particular type of technology was found to be beneficial in facilitating access to engineering communities of practice. Aligning student projects with particular research groups established connections that most student teams exploited. However, not all projects involved participation in the expected communities of practice. In order to retain the open-ended nature of the course it was necessary to recruit a wide range of guest speakers, which enabled unanticipated interactions between students and more experienced peers. The students' interactions with experts increased throughout the course, indicating that the teams accessed detail precedent knowledge through social sources, an observation which concurs with findings from the literature. A potential issue with students' perception of the role of communities of practice in the course was highlighted: some students saw access to domain knowledge solely in terms of the details of that knowledge, rather than as an opportunity to rehearse procedural knowledge related to analogical reasoning and the social nature of engineering design. This may be due to a failure of the environment to make these learning objectives explicit.

Table 7.6: Pedagogical Framework for OATPB Courses

Design Knowledge	Guiding Theory	Learning Environment Feature
Strategies	*Strategic Nature of Learning*	
• Learning strategies • Design strategies • Task optimization strategies	• Metacognition • Reflection • Alignment of tasks and learning goals	• Overview of course process • Qualitative feedback rather than quantitative grading • Explicit permission to deviate
Process	*Cognitive Apprenticeship*	
• Flexible-methodical process • Problem-solution coevolution • Tolerating uncertainty	• Coaching • Modelling • Articulation • Reflection	• Methodical: assignments and milestones • Flexible: coaching via regular review meetings • Monitoring understanding via "muddiest point" questionnaires • Open-ended concept questions as means of evaluating design knowledge
Models	*Social constructivism*	
• Sketching • Prototyping	• Guided discovery	• Introductory sketch modelling exercise • High-fidelity prototyping • Facilities
Design Knowledge Reuse	*Cognitive Flexibility Theory*	
• Precedents • Fixation	• Multiple representations • Contextual information • Concepts linked to precedents • Emphasis on interrelations • Knowledge assembly	• Concept precedents • Detail precedents from documentary and social sources • Database containing multiple representations of detail precedents
The Social Nature of Design	*Fostering a Community of Learners*	
• Role of language • Team roles • Inter-team communication • Distributed cognition	• Dialogic base • Distributed expertise • Communities of practice • Multiple zones of proximal development • Instructor guidance	• Regular meetings • Assignment of individual responsibility • Access to stakeholders • Access to engineering communities of practice via a technological theme rather than a problem theme • Anticipated connections via alignment of projects to research groups • Unanticipated connections via wide range of guest lectures

Chapter 8

Conclusions

This thesis has explored the learning environments of open-ended, authentic, team- and project-based (OATPB) engineering design courses. Such courses are an increasingly common feature of engineering education. However, there are obstacles to successfully introducing these types of project-based experiences to the engineering curriculum. Design learning requires a fundamentally different approach to instruction compared to that which has predominated in engineering programs traditionally. Many faculty members have limited experience with design, and still less with design education. While arguments in favour of introducing design experiences for students have been common, there is little by way of guidance for educators to indicate the types of knowledge that should be taught and the methods appropriate for doing so. Previous attempts to support educators suffer from a number of shortcomings, in particular a lack of explicit pedagogical principles and a focus on activities and behaviours rather than knowledge and understanding. Support for teaching often comes in the form of conference and journal papers written by and aimed at practitioners, however there is a disconnect between this material and results from design and education research.

Thus, the objective of this research has been to develop a pedagogical framework to guide educators in developing and improving learning environments for OATPB courses. The framework is also intended as a tool to support research in these contexts, by providing a lens through which to examine students' experience, based on both empirical and theoretical foundations. The initial version of the framework was developed in Chapter 3, which described results from a variety of empirical studies of design practice and in particular the types of knowledge that characterize design expertise. Four categories of fundamental design knowledge were identified: strategies and processes, models, knowledge reuse, and the social nature of design. These categories form the organizing structure of the framework, and are suggested as fundamental learning objectives for OATPB courses. The work of educational psychologists and social anthropologists was then used to identify a set of learning theories closely related to the types of knowledge essential for design. These theories were selected to act as guidance in achieving the proposed learning objectives. The framework was thus constructed as a matrix in which each essential aspect of design knowledge was paired with a theoretical perspective on knowledge and learning.

Chapters 4 and 5 described two phases of participant observer research in OATPB courses. The results were used to identify aspects of the learning environments that aligned with the learning objectives and theories contained in the framework, as well as those that presented obstacles to student learning. The observations revealed that students often engage in rehearsing aspects of design knowledge when given the opportunity. Problematic aspects of learning environments were identified as those that impede such rehearsals. Issues that were identified as particularly problematic include structuring courses in such a way as to facilitate deviations from a top-down, breadth-first strategy and providing access to documentary and social sources of detail design knowledge. Attempts to address these issues yielded further insights into learning needs and indicated potential improvements to learning environments.

Chapter 6 described the development of resources to be used in the third phase of research. The Soft Robotics Toolkit (SRT) is an online database of detailed knowledge relating to the design, fabrication, modelling, and testing of soft robotics components. It is intended as an example of the type of knowledge resource required by mechanical design students. The SRT was developed by recording the knowledge shared between experts and novices during the preceding phase of research in one of the courses. Collaboration with experts enabled this material to be elaborated further. Contents of the SRT were tested for clarity with volunteers from non-engineering backgrounds. The results of these tests were used to improve the SRT and to develop general guidelines to assist with the creation of further website content. Chapter 6 also described the development of a set of conceptual questions intended as a means of evaluating students' design knowledge. An initial instrument was pilot tested to identify the types of questions that were most useful in differentiating between levels of design experience. Based on the results of this test, a five-item instrument was developed for use during the subsequent phase of research.

Chapter 7 described the use of these resources in an OATPB course, and explored many of the issues previously identified in greater depth. Quantitative data was used as a means of supplementing and guiding the qualitative research. Methods of addressing problems in OATPB learning environments were validated, and issues that remained problematic were highlighted. The results of the research were used to improve the pedagogical framework by adding guidelines on the design of learning environments.

The primary contribution of the thesis is the pedagogical framework. The framework has been developed iteratively throughout the thesis, with certain aspects being revealed during each phase. This chapter begins by describing the complete framework that has resulted from the three phases of research. Limitations of the work presented in the thesis and potential directions for future research are then discussed.

8.1 A Pedagogical Framework for OATPB Courses

This section describes the pedagogical framework that has resulted from the research presented in this thesis (Table 8.1). The framework is intended as a tool for understanding, developing, and improving OATPB learning environments. It is not intended as a detailed course template, but rather a collection of principles to guide educators and researchers. It is also not intended as a final and stable model. The framework will continue to evolve through application in different contexts, and educators are encouraged to reflect critically upon its use, adapting elements to best meet the requirements of particular settings. The inclusion of learning theories is intended to guide such critical reflection; the aim of basing the framework on a theoretical foundation is to allow surface details to change while maintaining the underlying principles.

The framework could be used in combination with existing guidelines for engineering design educators, such as those discussed in Chapter 1. For example, the CDIO syllabus (Crawley et al., 2011) provides guidance on the development of engineering degree programs and can be used to define the relationship of design experiences to other courses. Thus, it addresses the general educational context. The pedagogical framework developed here provides guidance on the development of particular courses within engineering programs. Thus, it addresses the specific learning environment related to a given course. Finally, the Informed Design Teaching and Learning Matrix (Crismond and Adams, 2012) supports the planning and evaluation of specific activities within design courses; it addresses the details of student activity carried out within the contexts defined by the other guidelines. The pedagogical framework developed in this thesis is therefore conceived of as a contribution to an emerging suite of tools to support research and practice in engineering design education. The remainder of this section describes the complete current version of the framework.

Design Processes and Strategies

Design ability relies upon strategic knowledge. There is no single correct strategy, process, or heuristic that can be used to solve all design problems. Successful designers possess a "repertoire" of strategies which allow them to flexibly adjust their working process in response to aspects of the problem context, unexpected problems, or emerging solutions. Thus, the fundamental objective of OATPB courses should be to expose students to a variety of design strategies, and in particular strategies related to the overall process followed. The process

Table 8.1: Pedagogical Framework for OATPB Courses

Design Knowledge	Guiding Theory	Learning Environment Feature
Strategies	*Strategic Nature of Learning*	
• Learning strategies • Design strategies • Task optimization strategies	• Metacognition • Reflection • Alignment of tasks and learning goals	• Overview of course process • Qualitative feedback rather than quantitative grading • Explicit permission to deviate
Process	*Cognitive Apprenticeship*	
• Flexible-methodical process • Problem-solution coevolution • Tolerating uncertainty	• Coaching • Modelling • Articulation • Reflection	• Methodical: assignments and milestones • Flexible: coaching via regular review meetings • Monitoring understanding via "muddiest point" questionnaires • Open-ended concept questions as means of evaluating design knowledge
Models	*Social constructivism*	
• Sketching • Prototyping	• Guided discovery	• Introductory sketch modelling exercise • High-fidelity prototyping • Facilities
Design Knowledge Reuse	*Cognitive Flexibility Theory*	
• Precedents • Fixation	• Multiple representations • Contextual information • Concepts linked to precedents • Emphasis on interrelations • Knowledge assembly	• Concept precedents • Detail precedents from documentary and social sources • Database containing multiple representations of detail precedents
The Social Nature of Design	*Fostering a Community of Learners*	
• Role of language • Team roles • Inter-team communication • Distributed cognition	• Dialogic base • Distributed expertise • Communities of practice • Multiple zones of proximal development • Instructor guidance	• Regular meetings • Assignment of individual responsibility • Access to stakeholders • Access to engineering communities of practice via a technological theme rather than a problem theme • Anticipated connections via alignment of projects to research groups • Unanticipated connections via wide range of guest lectures

followed in courses should be "flexible-methodical" (Fricke, 1996). That is, the default process followed should be a methodical, top-down, breadth-first approach to problem-solving, but with the flexibility to allow student teams to deviate into depth-first explorations of potential solutions when appropriate. This thesis has confirmed the need for a flexible-methodical process by examining the experiences of teams who struggled with process-related issues.

The methodical aspect of the process may be achieved through the use of course milestones and deliverables. For example, in the early weeks of one of the courses studied in this thesis the student teams were expected to produce weekly documentation describing the results of their needfinding research or prior art searches. After this background research had been conducted they were required to define the project brief, by outlining a mission statement and set of functional requirements. During the concept design stage of the project the teams were expected to document the "top three" solution concepts considered, indicate their chosen concept, and justify this choice. Subsequent deliverables included a project plan, documentation of tests, and detail design presentations.

The flexible aspect of the process may be achieved through regular design review meetings. The role of the educator in these meetings should be guided by the theory of cognitive apprenticeship (Collins et al., 1991), which suggests activities intended to support learning of cognitive strategies and processes. Coaching involves providing feedback and guidance on student performance, or supplying hints while students complete a task. Modelling involves demonstrating aspects of a task so that students may observe the strategies used by an expert. Articulation requires students to explain their thought processes, and should be used to encourage reflection. These activities support the learner in engaging in metacognitive reasoning, or reasoning about their own knowledge and cognitive processes. This type of reasoning is characteristic of both effective learning strategies and successful design strategies.

In courses with a large number of students, it can be difficult to schedule sufficient time for thorough review meetings with each team. This thesis has found that simple weekly questionnaires, asking students to identify any difficulties they are facing in their projects and the main unanswered question they have about the course (the "muddiest point"), allow educators to monitor the activities and experiences of teams (Hall et al., 2002). Recurring difficulties or questions can be addressed during subsequent lectures. These questionnaires do not replace the need for regular review meetings, but allow general course issues to be addressed outside of meetings so that the reviews can focus on particular aspects of a team's project, thereby reducing the time required. The thesis has also described the development of a set of open-ended conceptual questions that may be useful for measuring students' design knowledge. Such questions could be used throughout a course as a further means of providing feedback on course efficacy and identifying topics that may require more attention.

An important issue highlighted throughout this thesis is the detrimental role that task optimization strategies can play in OATPB courses. When faced with regular short-term tasks learners will often adopt strategies to minimize the amount of time required to create the deliverable product (Scardamalia et al., 1994). For example, regular design milestones may result in students focusing their efforts on producing satisfactory documentation rather than on conducting the work that is supposed to be documented. Studies of learners' task optimization strategies have typically focused on the performance of schoolchildren completing reading comprehension or written composition tasks. Interestingly, this thesis has found that college students sometimes engage in similar behaviours.

Three aspects of OATPB learning environments have been identified as contributing to the use of task optimization strategies. In one of the courses studied during Phase 1, the students were not provided with information about the process being followed. As a result, it was difficult for them to link immediate task-related goals with overall project or process goals, resulting in a focus on the former to the detriment of the latter. In one of the courses observed during Phase 2, frequent numerical grading of student deliverables overemphasized the immediate tasks, again causing some students to focus their attention on the sequence of short-term tasks rather than the overall process. In this case, the use of grades also discouraged deviation from a methodical process and experimentation with alternative strategies. The use of qualitative grading in another course seemed less likely to encourage task optimization. However, even in an environment that provided students with detailed process information and used qualitative feedback rather than quantitative grading, task optimization behaviour was observed. An interesting finding in this case was that the team was aware of their behaviour and identified it as a problem, indicating that metacognition is not sufficient to overcome the issue. A cause of this team's problem appeared to be a lack of explicit permission to deviate from the imposed course schedule; even though teaching staff requested depth-first explorations in weekly review meetings, the students felt obliged to focus on the top-down, breadth-first milestones. This demonstrates that the flexible aspect of OATPB courses may be undermined unless it is made clear that students will not be reprimanded for deviating from the schedule. A contribution of this thesis is the attention drawn to the issue of task optimization strategies among students, and the identification of causes for its prevalence.

Design Models

Design engineers rely on a variety of models, be they mathematical, mental, physical, or graphical. Models are used to reduce uncertainty, and may represent the problem being tackled, the artefact or system being designed, or the process being followed. Students seem to naturally rely on graphical modelling throughout the process, from freehand sketching to the production of CAD solid models. The development of graphical modelling skills appears to be a largely independent process in which student teams experiment with media and techniques. However, review meetings should be used as a means of providing guidance on this experimentation, for example by encouraging students to consider alternative representations if detailed CAD models are not appropriate for their project.

An emphasis on CAD and mathematical models in engineering education results in a belief among students that engaging in other forms of modelling is "not engineering." The use of introductory sketch modelling exercises, during which students are required to design and build devices using basic materials such as cardboard and tape, has been found to encourage students to engage in more physical modelling throughout their projects. These activities also seemed to encourage other creative activities throughout the projects, including the use of videos and storyboards. It is proposed that sketch modelling activities signal permission to students to engage in activities that are not typically an aspect of engineering coursework and therefore tend to be viewed as "not engineering." These exercises can range in duration and complexity. In one of the courses studied, students were expected to spend two weeks designing and constructing a "paper bike" that could be used to transport a team member during a competition, using only cardboard and other paper products. In another, students were given 90 minutes during which to design and build as many mechanical graspers as possible using cardboard, string, and any other material they could scavenge.

The observations carried out in OATPB courses have highlighted the value of including detail design and high-fidelity prototyping experiences. Many issues related to a design do not become apparent to students until they attempt to implement it. This appears to be true for all types of projects observed, but particularly for those involving mechanical design. A conceptual understanding of manufacturing processes does not equip students with the knowledge required to design for these processes; they also require procedural knowledge resulting from producing prototypes or working with vendors to have parts made. Providing access to the resources required to support these activities is a major challenge for educators. Due to the open-ended nature of OATPB courses it is not possible to predict in advance the equipment, materials, or knowledge required for prototyping. This issue may be partially addressed through the use of a course theme, as discussed in the following section.

Design Knowledge Reuse

A substantial amount of design activity involves identifying and synthesizing aspects of previous solutions, or improving existing solutions through redesign. Successful design reuse requires extensive declarative knowledge related to precedents as well as procedural knowledge about how to make use of those precedents. Transferring elements of a solution from one situation to another requires an ability to identify the context-specific features of a previous design and reason about whether those features are appropriate for the problem at hand.

This thesis has identified two categories of design precedents: concept precedents and detail precedents. Concept precedents are primarily used during the problem definition and concept design stages of a project, both to inspire potential solution concepts and to identify existing concepts that the team wishes to avoid. Students are capable of accessing information about concept precedents with minimal support, and typically identify candidate precedents through prior art searches and needfinding research. Detail precedents are primarily used during the detail design and prototyping phases of projects, and relate to methods of realizing a particular concept. Detail precedents may include specific mechanisms, machine elements, morphologies, materials, manufacturing processes, electronic circuit designs, software algorithms, or programming techniques.

Access to detail precedents has been found to be essential for students' learning. However, providing the required access is difficult, particularly in mechanical design. Given the wide and unpredictable variety of projects involved in a typical OATPB course it is unlikely that course teaching staff would ever possess experience with all of the technologies relevant to students' designs. While detail precedents for electronic and software design are readily accessible from online databases, equivalent sources for mechanical design are rare. This thesis has demonstrated that it is possible to develop this type of resource for mechanical design, and has identified the types of knowledge that should be recorded in order to address novices' learning needs. In particular, it has identified that CAD files alone are insufficient, and that learners require detailed explanations of the procedures involved in designing, fabricating, modelling, and testing mechanical systems. These results may contribute to research on knowledge management (e.g., Deken et al., 2012) and on "open" phenomena, in particular open source hardware.

Cognitive flexibility theory is proposed as a source of guidance when providing students with detail design information. The theory was developed as an approach to teaching problem-solving in ill-structured domains such as engineering design (Spiro et al., 1992). It prescribes the use of multiple knowledge representations as a means of supporting analogical reasoning and transfer. Concepts, theories, and precedent cases should be examined in multiple contexts and from multiple perspectives to allow students to reason about the role of context in solving ill-structured problems (Jacobson and Spiro, 1993). The thesis has confirmed aspects of cognitive flexibility theory, and has afforded insights into applying the theory in the context of mechanical design. Providing multiple representations of a very broad design principle may result in examples that are so dissimilar that students are unable to make meaningful comparisons between them. Thus, precedent knowledge should be arranged around particular categories of device or mechanism, with multiple representations provided for each.

However, access to documentary sources of precedent information may not be sufficient to support design learning. Results from the literature indicate that design engineers also rely upon social sources, in particular more experienced peers, to retrieve information about detail precedents. Even when information is acquired from a documentary source, novices require input from more experienced engineers in order to interpret and use it (Demian and Fruchter, 2006). The lack of access to detail design information is therefore also related to a lack of access to social sources of domain expertise. As discussed in the next section, the use of a technological theme aligned with the work of local research groups has been identified as a means of addressing this problem.

The Social Nature of Design

Engineering design is a social process. It requires negotiation between multiple participants, each with their own technical perspective and personal preference. It relies heavily on the use and manipulation of language: designers create language that defines the direction of a project (Bucciarelli, 1994) and rely on "verbal sketching" and rhetorical skills to guide decision-making (Lloyd and Busby, 2001). Knowledge about a design project is distributed throughout and between teams, departments, and organizations (Busby, 2001). Members of design teams must have an understanding of team roles and an ability to judge when and how to share knowledge.

Guided by the Fostering a Community of Learners (FCL) model (Brown and Campione, 1994), the primary activity in OATPB courses should be dialogue on multiple levels: within teams, between students and stakeholders, and between teams and experienced engineers. Regular meetings, presentations, and large group discussions are therefore crucial. Individual team members should be encouraged to develop "expertise" in a given area and to rehearse interacting with other "expert" teammates in order to identify strategies for managing distributed cognition. Distributing specialized knowledge throughout the classroom creates multiple zones of proximal development, thereby facilitating a variety of learning potentials. However, students must be encouraged to meet regularly with their teammates rather than simply apportioning tasks and working in isolation. Given these conditions, students in OATPB courses appear to adopt many of the social behaviours of experienced designers, such as creating a project-specific language and exploiting strategies for resolving disagreement. In the observed courses, explicit coaching of these strategies was not required.

Situated learning theory suggests that all learning occurs as a result of participation in a community of practice, which is a group who share a domain of interest and engage in and identify with a common practice (Dennen and Burner, 2007; Lave and Wenger, 1991; Wenger, 1998). Novices learn through contributing to the practice of the group and through interactions with other community members. From this perspective, it is essential to examine the learning environment in terms of the communities in which learners are participating. This thesis has identified a lack of access to engineering communities of practice as a major obstacle to student learning in OATPB courses. As mentioned above, this is closely related to the issue of access to detail design knowledge.

The thesis has demonstrated a method of addressing this issue. The use of a course theme that aligns student projects with the work of local engineering research groups provides opportunities for students to interact with a wide range of domain experts. The use of a technological theme has been found to be particularly effective. While focusing on a particular problem area as the course theme also allows students to engage with experts, it can result in these experts acting as stakeholders rather than fellow practitioners. However, adopting a technological theme must not be done in such a way as to eliminate the open-endedness of a course. The approach described in this thesis involved the selection of a broad technological field, in which teams could pursue a wide range of trajectories, thereby preserving ambiguity for the students. Guest lectures from engineering researchers should be used to expose students to a broad range of topics, including technology unrelated to the theme. This allows for unanticipated connections and provides opportunities for teams to deviate from the theme while still benefiting from access to communities of practice. The use of a database of detail precedents, as discussed above, can support novice-expert interactions by providing the basic background information required for discussion of more specialized topics.

8.2 Limitations

By grounding the research firmly within methodological and theoretical traditions, substantial effort has been made to ensure the quality and trustworthiness of this research. The research objective has been achieved, and the work has provided insight into a novel but increasingly common educational context. However, it is important to acknowledge the limitations of the research presented in this thesis.

8.2.1 Data Gathering

Qualitative research in educational settings is inherently messy and is subject to multiple potential sources of distortion. In participant observation, the researcher is the instrument, and an examination of limitations must therefore begin with the role and biases of the researcher. The author of this thesis was trained as a mechanical engineer and not a social scientist, much less a qualitative educational researcher. While a tacit knowledge of engineering was of benefit in understanding the experiences and activities of students, a lack of experience with qualitative research methods resulted in a certain amount of trial and error. As discussed in Chapter 2, the questionnaires used in Course A1 suffered from a number of flaws and a different approach was used in subsequent courses. It is reasonable to assume that the gathering of participant observation data during Phase 1 similarly suffered from flaws. However, learning to collect fieldnotes has been a process of acquiring tacit, procedural knowledge, and it is therefore difficult to explicitly identify the changes in this aspect of data gathering throughout the thesis.

Evolving data gathering methods can be of benefit to the quality of research, as outlined by Wallendorf and Belk (1989). However, they may also undermine attempts to compare results between one case and another. It is possible that some of the results observed during Phase 3 were present in earlier phases, or vice versa, and that the evolving methods caused phenomena to be observed in one case but not in another. However, the consistent use of participant observation and data triangulation should act as a check against this.

The researcher's role as a member of teaching staff afforded a degree of access to students that may not have been possible otherwise. However, despite attempts to prevent students from feeling coerced into participation, it is extremely likely that the inherent power imbalance between teaching staff and students affected participation in the research. In particular, students who participated in interviews may not have felt free to express their true feelings about the courses. The use of anonymous surveys and the scheduling of interviews after completion of the course may have aided in counteracting this effect, but it is unlikely that it was eliminated completely.

8.2.2 Research Settings

The research focused on six student cohorts in three educational contexts. Thus, the degree to which the results, and in particular the pedagogical framework, may be transferred to other OATPB courses is unclear. The three contexts studied were very different, and it is hoped that this diversity increased the transferability of the framework. However, some unique aspects of the courses, and in particular Courses A and C, may represent limitations in the research. Educators may object that learning environments that can provide prototyping budgets of $2,500 or €5,000 (respectively) per team are extremely rare, and that the problems faced in such learning environments bear little relation to those in environments that suffer from a lack of resources. However, the inclusion of Course B provides some balance in this regard. Furthermore, beyond the recommendation that students be provided with some means of creating high-fidelity prototypes, no aspect of the pedagogical framework depends directly upon financial or other material resources.

A related limitation was the use of course themes as a means of connecting students with engineering communities of practice. The soft robotics theme proved to be particularly successful in this regard, but this may have been due to a serendipitous combination of an appropriate technology type and a large and active local research community. Thus, educators may struggle to replicate this approach in other institutions. However, fostering connections between student teams and external communities of practice could be achieved in multiple ways, and the particular approach followed in Course A is not intended as a general model. Furthermore, in settings where establishing social connections with communities of practice is impossible, the use of a resource such as the Soft Robotics Toolkit may allow the experience to be simulated. Although that is not the intention of the resource, if the choice was between access to the SRT with no social interactions on one hand and no access to detail precedents at all on the other, the former would be preferable.

8.2.3 Participants

The vast majority of the students observed in this research were Caucasian, male, and relatively affluent native English speakers. This is primarily due to a long-recognized lack of diversity among engineering students in Europe and the US. In terms of gender balance, the setting with the greatest diversity throughout the research was Course A, with the proportion of female students varying between 23% and 62%. However, the overall lack of diversity represents a limitation, particularly in terms of the transferability of the research. A consistent theme throughout the thesis has been the importance of context and of procedural knowledge acquired through experience. The range of cultural experiences present in a learning environment must therefore be considered, particularly if an aim of engineering education is to produce professional designers capable of practicing in a global economy.

8.2.4 Learning Outcomes

A fundamental assumption throughout the thesis has been that providing support for students to engage in rehearsing design knowledge is essential for meaningful learning to take place. While this assumption is in agreement with the dominant current theories about the nature of knowledge and learning, the research presented here cannot confirm that it applies to design education. It is not possible to compare the learning gains of the students in Phase 1 with those in Phase 3. This is primarily due to the difficulty in assessing design knowledge, and the thesis presented initial work towards the development of an instrument for measuring design knowledge. However, testing of this instrument has relied on small numbers of participants; large-scale testing and validation is required before it could be considered a reliable research tool. Furthermore, a concern in developing such an instrument is that it could be perceived as an objective measure of overall design ability. Such a reductive view of design could only be detrimental to the quality of design education.

8.2.5 Design Outcomes

It is perhaps unusual that a thesis exploring the experiences of 35 design teams has contained almost no description of the designed products. As discussed in Chapter 2, this was due primarily to concerns regarding participant privacy. However, a potential limitation of the research is the lack of attention paid to the relationship between learning environment and quality of student work. The decision to not consider design outcomes in the research is based on a number of assumptions. First, it is assumed that the quality of student work is an insufficient measure of student learning; the experience of producing an inferior design may lead to greater learning outcomes than that of achieving a successful product. Second, it is assumed that the role of the learning environment in student performance cannot be definitively established; a team may produce excellent work in spite of, rather than because of, features of the learning environment. Third, it is assumed that the diversity of projects within OATPB courses renders attempts to define universal criteria for success futile.

However, these assumptions may be unfounded. Many of the student projects achieved success according to external judgments of design quality. The 35 projects observed during the research have resulted in nine peer-reviewed publications, three provisional patent applications, two complete patent applications, four design awards, participation by a team in a business incubator program, and expressions of interest from two multinational corporations in licensing solutions. Considering these aspects of the courses, and in particular examining the role of learning environments in producing successful designs, may have yielded greater insight into the contexts studied.

8.3 Future Work

The research presented in this thesis aimed to develop a pedagogical framework for a particular type of project-based engineering design course. Out of necessity it has focused on a small number of research settings in order to observe the effects of learning environment on the experiences of students and educators. Further research is now required to evaluate the applicability of the framework to other OATPB courses. Such research should continue the process described here, in which the framework was developed and improved through application to learning environments. Of particular importance is the need to further explore methods of achieving an appropriate balance between the flexible and methodical aspects of the design process.

Furthermore, this work may form the basis of similar research in other types of engineering design courses. It would be beneficial to explore the learning environments of other course models and identify the salient similarities and differences. Many of the challenges encountered in OATPB courses may not apply to other contexts, or may be overcome in very different ways. For example, in the aircraft design program described by Thompson (2002), students participate in the project throughout the four years of their undergraduate degree. This is an elegant means of creating a community of practice; new entrants to the program have access to more experienced students, and the senior students obtain experience mentoring other engineers. This teaching model is very different to those described in the thesis, but it is a response to the same basic need of providing access to engineering communities of practice. Further research may result in a typology of courses with a pedagogical framework developed for each.

Monitoring the activities and abilities of students in project-based engineering design courses remains a significant challenge for educators, and an obstacle to making the type of iterative improvements described here. Qualitative investigations of learning environments are extremely time-intensive, and it is unlikely that many educators would have the opportunity to conduct in-depth explorations to identify problems and potential solutions. Thus, instruments to provide feedback on course efficacy would be beneficial. The thesis has included initial work towards the development of such instruments. Further research is required to improve and validate the concept questions developed in this thesis as well as the associated rubric.

The use of regular questionnaires has been found to be helpful in monitoring understanding and informing teaching. It may be beneficial to combine two of the approaches used in this thesis: the muddiest point questionnaires and the weekly student ratings. By providing a list of common design tasks and asking students to rate their recent difficulties related to each task, it would be possible to track the activities of each team throughout a course. The results could serve as a means of identifying teams that are struggling and may need to deviate from the course process. Furthermore, plots of a team's activities over time could be provided to the team to serve as a visual aid encouraging reflection on design processes and thereby enable metacognitive reasoning.

Finally, new learning resources are a common product of educational research. However, sustaining these resources is difficult and materials developed during doctoral research typically disappear upon completion of the project. This thesis has proposed a model for the Soft Robotics Toolkit that is intended to enable the resource to continue to grow beyond its initial development and testing. At the time of writing, the SRT has been shared with researchers and students beyond the context in which it was developed. For example, students from Harvard and the Indian Institute of Science, Bangalore are currently using the resource as part of a summer project on medical devices for low-resource environments. Academics in Irish universities are using the material on the website to train new graduate students. Soft robotics researchers from a range of US universities have been invited to use the toolkit and to suggest additional material. However, the feasibility of the model cannot yet be confirmed. Further work is needed in order to identify viable approaches to sustaining learning resources produced during educational research. While the knowledge gained as a result of developing such resources may be of interest to other researchers, the primary aim of work such as that presented in this thesis must always be to support educational practice.

8.3.1 Summary

This thesis has described a pedagogical framework for open-ended, authentic, team- and project-based (OATPB) engineering design courses. To achieve this, learning goals were identified through a review of the literature on design practice and cognition. An apposite learning theory was identified and validated for each learning goal. The framework was used to guide three phases of research and intervention in OATPB courses. The results of each phase were used to further develop the framework. The objective of this work has been to address a paucity of research connecting learning goals, learning theories, and implementation guidelines for design education. The resulting framework is intended as a tool to support both educators and researchers. While the framework will continue to evolve, this thesis provides a basis for future research on learning environments for engineering design. It also provides a foundation on which to improve the practice of design education.

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Appendix A

Course A1 Questionnaires

Course A1 Online Questionnaire 1

This short questionnaire is part of a multi-stage survey. The questionnaire is completely anonymous and should take between 5 and 10 minutes to complete. The responses of the class will be combined and used to generate the next round of questions, thereby giving you feedback on the opinions of your peers. We feel it is important that our research is as transparent as possible so that you can participate fully in helping us to improve engineering education. Thank you for taking part!

What issues or problems are you currently facing with your projects?
Please list any bottlenecks, annoyances, grievances, etc. Be as specific as possible.

What tools/methods are you using to test and demonstrate your design concepts?
This could include any software, physical or communication tools you have found useful.

Can you think of anything that would have helped you to identify design concepts, or would make it easier for you to prototype and test different approaches?

What engineering, science and math concepts are you using to perform initial analysis of your designs? Again, please try to be specific.

Are there any aspects of the design process that you find unclear?

Course A1 Online Questionnaire 2

In the previous survey, you and your classmates identified 48 issues and problems that you were facing in your projects. These issues were then clustered by theme and 30 common issues were identified. These are presented below. For each item on the list please indicate how significant a problem you felt it presented to you and your team.

In your experience in this course, how significant a problem did each of the following present to you and your team? (1 = Not significant at all; 5 = Very significant)

	1	2	3	4	5
Making decisions when information available is ambiguous					
Evaluating ideas					
Choosing between ideas that seem equally viable					
Access to ideas from people outside team					
Resolving conflict/disagreement within team					
Dividing workload within a small group					
Lack of knowledge about surgical procedures					
Getting to observe to surgical procedures					
Navigating the initial stages of the design process					
Defining the problem being addressed					
Deciding how to build prototypes					
Knowledge or skills required to build prototypes					
Time required to obtain parts and build prototypes					
Assessing usefulness of prototypes					
Access to resources (machines, parts, processes, etc) required for prototyping					
Working at small scales					
Deciding how to test ideas in the lab					
Access to testing equipment					
Assessing results from bench level tests					
Obtaining useful results from bench-level tests					
Knowledge of the underlying science required for modeling, analysis and evaluation					
Determining what type of analysis is required					
Modeling devices, in order to perform analysis					
Simulating surgical procedure and environment in the lab					
Material selection					
Obtaining materials					
Knowledge of manufacturing processes					
Budgeting					
Steep learning curve for software or physical tools					
Designing for usability					

Course A1 Online Questionnaire 3

In the previous questionnaire, you rated the significance of a list of issues faced in this course. The 5 issues which were considered most significant are listed below. For each, please give a brief description of any resources or approaches which proved useful in addressing it. Then, list anything that you think would help future students facing the same problems that you and your team faced. What information or physical or digital tools could we provide to help students overcome this issue? All responses are anonymous and we are interested in all ideas so "blue sky" suggestions are most welcome.

	How did you deal with this issue?	**What information or tools could we provide to help with this?**
Working at small scales		
Making decisions when information available is ambiguous		
Time required to obtain parts and build prototypes		
Material selection		
Evaluating ideas		

What issues have you faced in recent weeks, e.g. when dealing with vendors and working on your final prototype?

Appendix B

"Muddiest point" questionnaire used in Courses B1, B2, and C1

Course: **Date:**

This feedback form is part of a research project on improving engineering design courses. Please spend 2 minutes on the following questions. Your (anonymous) answers will help to improve the course – for the rest of the term and for next year. Thank you!

1. What difficulties or frustrations have you faced recently in your design project?

2. What is the main unanswered question you have about your project or about the topics covered in the last week? What is the muddiest point?

Appendix C

Course A3 Weekly Questionnaire

Course A3 Weekly Questionnaire

Project Group:__________________________ Date:__________________

Please rate how helpful you found each of the following resources and activities while working on your design project during the past week.

	Did not use	Not at all	To a limited extent	To a moderate extent	To a great extent	To a very great extent
Lecture and lecture notes	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Topics covered in guest lectures	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Lab session	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Weekly meeting	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Interacting with researchers in Harvard labs	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Interacting with clinician(s)	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Course iSite	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Assignment templates	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Soft robotics kit control board	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Soft robotics kit website	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
An engineering textbook	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5
Other online tutorials or documentation **Please specify**: ____________________	◯ n/a	◯ 1	◯ 2	◯ 3	◯ 4	◯ 5

General comments or clarifications:

____

____

Are there any resources not listed above that you found helpful for your project this week?

____

____

Appendix D

Informed Consent Forms

Consent Form: Development and Evaluation of Educational Resources for Mechanical Design

Purpose of the research: The research aims to evaluate the effectiveness of the educational resources that have been developed for this course, with the more general goal of better understanding student learning in project-based, open-ended engineering design courses and accordingly developing guidelines for improving the learning environments and resources in engineering education.

What you will do in this research: If you decide to participate, you will complete a take-home questionnaire, once at the beginning of the course and once at the end. Some of the questions will be about your engineering background and skills, while others are about the design process and soft robotics. There will also be short paper-based surveys, completed once a week during lecture, for evaluating the course resources used that week. Otherwise, the research is ethnographic and follows the normal curriculum in the class, with observational data in the form of field notes taken during weekly review meetings and lab sessions. The coursework your team submits (including design notebooks and materials on your team wiki) may be analyzed if you agree to participate in this research. You must be 18 or older to participate in this research.

Time required: The beginning and end questionnaires will take approximately 30 minutes to complete. The weekly in-class surveys will take less than 5 minutes.

Risks: The only perceived risk to participating is that you might feel as if it will influence your grade. To ensure this is not the case, we are collaborating with XXXXX, a research staff member in the Biodesign Lab (email: XXXXX@seas.harvard.edu), who is not a part of the teaching staff, and will keep all data confidential until the course has ended. The faculty and TFs will not know whether and how you are participating.

Benefits: There are no direct benefits, but this research will help improve future iterations of this course, and more broadly, improve engineering education, particularly design courses.

Confidentiality: The questionnaire data will not include any personal identifiers, but will include project group identifiers. The observation data will be recorded as field notes containing only project group identifiers. During analysis and reporting all identifiable information will be removed; only the researcher will have access to the link between identifiable and de-identified information and only for the duration of the data analysis. When research results are reported, no identifiable information will be included and responses will be aggregated and described in summary.

Participation and withdrawal: Your participation is completely voluntary, and you may refuse to participate without penalty or loss of benefit to which you may otherwise be entitled. You may quit at any time without penalty or loss of benefit to which you may otherwise be entitled.

To Contact the Researcher: If you have questions or concerns about this research, please contact: Donal Holland; 60 Oxford St, Suite 409, Cambridge, MA 02138; Email: donal@seas.harvard.edu.

Whom to contact about your rights in this research, for questions, concerns, suggestions, or complaints that are not being addressed by the researcher, or research-related harm: Committee on the Use of Human Subjects in Research at Harvard University, 1414 Massachusetts Avenue, Second Floor, Cambridge, MA 02138. Phone: 617-496-CUHS (2847). Email: cuhs@fas.harvard.edu.

Agreement:

□ **Yes**, I agree to participate in this study. The nature and purpose of this research have been sufficiently explained. I understand that I am free to withdraw at any time without incurring any penalty.

□ **No**, I do not agree to participate in this study. Any data related to my participation in this course will be deleted from the data set prior to analysis.

Print Name: ______________________________

Signature: ______________________________ Date: ______________

Consent Form: Development and Evaluation of Educational Resources for Mechanical Design

Purpose of the research: The research aims to evaluate the effectiveness of the educational resources that have been developed for this course, with the more general goal of better understanding student learning in project-based, open-ended engineering design courses and accordingly developing guidelines for improving the learning environments and resources in engineering education.

What you will do in this research: If you decide to participate, you will take part in one or more contextual inquiry studies and an exit interview. During the contextual inquiry study you will discuss an aspect of your project coursework with the researcher and demonstrate the use of related resources. The exit interview will be conducted upon completion of the course, and will involve the researcher asking you about your impressions of the course.

Time required: The contextual inquiry studies will take place during normal coursework activities, and the time taken will be decided by you. The exit interview will take about 40 minutes.

Risks: The only perceived risk to participating is that you might feel as if it will influence your grade. To ensure this is not the case, the TF conducting the research will have no influence over any student's grade. The course lecturer (who is solely responsible for assigning grades) will not know whether and how you are participating.

Benefits: During the contextual inquiry studies the researcher will be available to assist you with project-related activities. There are no direct benefits to taking part in the interview, but this research will help improve future iterations of this course, and more broadly, improve engineering education, particularly design courses.

Confidentiality: All information gathered will be kept confidential. When research results are reported, all personal identifiers will be removed. and responses will be aggregated and described in summary.

Participation and withdrawal: Your participation is completely voluntary, and you may refuse to participate without penalty or loss of benefit to which you may otherwise be entitled. You may quit at any time without penalty or loss of benefit to which you may otherwise be entitled.

To Contact the Researcher: If you have questions or concerns about this research, please contact: Donal Holland; 60 Oxford St, Suite 409, Cambridge, MA 02138; Email: donal@seas.harvard.edu.

Whom to contact about your rights in this research, for questions, concerns, suggestions, or complaints that are not being addressed by the researcher, or research-related harm: Committee on the Use of Human Subjects in Research at Harvard University, 1414 Massachusetts Avenue, Second Floor, Cambridge, MA 02138. Phone: 617-496-CUHS (2847). Email: cuhs@fas.harvard.edu.

Agreement:

☐ **Yes**, I agree to participate in this study, and agree to be audio recorded during the exit interview. The nature and purpose of this research have been sufficiently explained. I understand that I am free to withdraw at any time without incurring any penalty.

☐ **Yes**, I agree to participate in this study, but do not wish to be audio recorded during the exit interview. The nature and purpose of this research have been sufficiently explained. I understand that I am free to withdraw at any time without incurring any penalty.

☐ **No**, I do not agree to participate in this study.

Print Name: ______________________________

Signature: ______________________________ Date: ______________

School of Engineering, Trinity College Dublin

INFORMED CONSENT FORM FOR RESEARCH PARTICIPANTS

Information Sheet

Purpose of the Study. This study is part of a PhD research project. The study is concerned with the experiences of students in project-based design courses. The aim of the study is to improve design teaching.

What will the study involve? The study will involve completing anonymous weekly in-class questionnaires. Each questionnaire will take approximately 3-5 minutes to complete. As part of the research we will also conduct archival analysis of the team assignments submitted via Blackboard, and any coursework-related emails sent to the teaching staff containing student queries or problems on the course. Emails of a personal nature, or emails related to matters outside of the course, will not be analyzed.

Why have you been asked to take part? You have been asked because you are a student in [Course B].

Do you have to take part? No. Participation is voluntary and will have no effect on your grades. Even if you agree to participate now you have the option of withdrawing during the study. If you choose to withdraw at a later date, any data which is identifiable (e.g. archived emails) will be destroyed.

Will your participation in the study be kept confidential? Yes. We will ensure that no clues to your identity appear in the PhD dissertation or any resulting publications. Any extracts from what you say that are quoted in the dissertation or other publications will be entirely anonymous.

What will happen to the results? The results will be presented in the PhD dissertation. They will be seen by the PhD supervisor, a second marker and the external examiner. The dissertation may be read by future students. The study may be published in a research journal.

What are the benefits to taking part? Your participation will help improve to the course for current and future students. Questions raised on the surveys will be addressed in class to improve your learning experience. The course content will be redesigned for future cohorts of students to improve learning outcomes.

What are the possible disadvantages of taking part? We don't envisage any negative consequences for you in taking part. The only perceived risk to participating is that you might feel as if it will influence your grade. Your participation or non-participation will not influence your grade in any way. To ensure this, these consent forms will be collected by another PhD student, who is not a part of the teaching staff, and will keep all data confidential during the term. The teaching team will not know whether you are participating until after the course grades have been assigned.

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Any further queries? If you need any further information, you can contact the researcher, Dónal Holland (holland@tcd.ie) or the research supervisor, Professor Gareth J. Bennett (gareth.bennett@tcd.ie).

If you agree to take part in the study, please sign the consent form overleaf.

Consent Form

I..agree to participate in this research study.

The purpose and nature of the study has been explained to me in writing.

I am participating voluntarily.

I give permission for my assignment submissions and any coursework-related email queries sent to the course teaching staff to be analyzed.

I understand that I can withdraw from the study, without repercussions, at any time, whether before it starts or while I am participating.

I understand that anonymity will be ensured in the write-up by disguising my identity.

I understand that disguised extracts from my survey responses and emails may be quoted in the thesis and any subsequent publications.

Signed.. Date..................

Appendix E

Course A1 condensed syllabus document

	Lectures	Lab	Tasks & Project Milestones (due Tues of next week)
1	Welcome Course Overview and Logistics IP Overview **Clinician Presentations**	• Sign up for Lab Access • Solid Works: Part and assembly tutorials	<u>Tasks</u> • Sign up for machine shop and safety training: Feb 3rd at 9am and 1pm in Physics Machine Shop • Background research on presented clinical problems <u>Milestones</u> • SW parts and assembly files submitted
2	**Clinician Presentations** Students meet after class to form teams. FRDPARRC and strategies, concepts, modules	• Teams meet with course staff • Reviewing the Literature and Patents: Where to search and how to organize the data. • Overview of prototyping tools (Mill, 3D printer, Laser Cutter). One team member assigned to each.	<u>Tasks</u> • ***Research*** strategy options, and current standard of care and create preliminary list of questions • Schedule meeting for needs finding research <u>Milestones</u> • Top 3 project choices submitted • Safety training completed • Document understanding of presented clinical problem (template) • Mission statement (see examples) • Team Wiki's should be functional • Patent and Literature Review Complete with References (patent PDFs uploaded to Wiki)
3	Ethnography, Needs Finding and Problem Identification: *Guest Lecture* Fundamental Design Principles and Evaluation of Ideas	• User-Centric Design Process: Preparing for interviews and observations	<u>Tasks</u> • Choose and plan research methods for interaction with clinician • ***Ask*** your questions to one or more clinicians <u>Milestones</u> • Documented research methods plan • Documented results of research methods plan • Top 3 strategies selected, and described with their FRDPARRC tables completed
4	Sketching and sketch modeling. *Guest Lecture* Using modeling and experimentation to evaluate design concepts	• Sketching & Modeling: creating good sketches and physical models to illustrate concepts	<u>Tasks</u> • Build SW model and physical model for each of the strategies • ***Show*** strategies to clinician to get feedback <u>Milestones</u> • Document sketching, physical and SW modeling of strategies • Document in detail the feedback you got from clinician

5	Manufacturing and design for manufacture Material selection and machine elements **Teams' Strategy Presentations**	• Lab on developing concepts and determining whether modeling or experimentation is appropriate for evaluation	Tasks • Develop at least three concepts for how to implement the chose strategy • Create plan for evaluation of concepts Milestones • Best Strategy Selected with its FRDPARRC table complete • Summary documents for analysis / bench level experiments for concept selection
6	Actuators Sensors, Transducers & Instrumentation *Guest Lecture*	• Assist with model making both looks like and functional models • Support of use of manufacturing tools in teaching labs	Tasks • Build SW model and physical model for each of the concepts • Perform first order analysis or bench level experiments for concepts • ***Show and Play*** with your models with your clinician Milestones • Document sketching, physical and SW modeling of concepts • Document in detail the feedback you got from clinician • Top 3 concepts selected, described with their FRDPARRC tables and solid models
7	Transmissions **Teams' Concept Presentations**	• Lab on finalizing selected concept and identifying different modules of device	Tasks • Identify the different modules, including Most Critical Module (MCM), for the best concept and assign responsibility Milestones • One page documents summarizing analysis / bench level experiments for concept selection • Best Concept Selected with its FRDPARRC table complete • Detailed schedule to completion uploaded
8	Spring Recess	Spring Recess	Milestones • Take a break, climb a mountain or jump in a lake! But if you are behind, get you and schedule aligned.
9	Interfaces: Fit/Adhesives Advanced Solidworks and engineering drawings *Guest Lecture*	• Lab to support MCM engineering analysis and creation of full SW model (tolerancing etc for MCM)	Tasks • Create detailed solid model of most critical module (includes models of all custom machined and off-the-shelf component parts) • Create rough SW models of other modules Milestones • MCM engineering analysis and bench level experiments complete and documented • SW model of full assembly complete with all detail for MCM

10	Interfaces: Flexures, bearings Medical Devices 101: Real World Engineering in the Medical Field. *Guest Lecture*	• Lab to support MCM engineering analysis and creation of full SW model (tolerancing etc for MCM)	Tasks • Refine MCM SolidWorks model based on analysis and feedback from weekly meeting and lab feedback • ***Play*** with your prototype parts with your clinician and document the interaction/results • Begin detailed engineering of other modules Milestones • Document results of interaction with clinician • Detailed plan, and task list for remaining time and updated schedule to completion updated
11	Interfaces: KC/Bolts/Snap Medical Devices 101: *Guest Lecture*	• Lab to support preparation of final paper (come with draft and look for feedback)	Task • Begin working on final paper abstract, first paragraph & structure outline • Finalize detailed engineering of other modules • Complete detail SW models of all modules Milestones • Full SW model complete with all off the shelf parts and custom components with manufacturing plan for design review presentation
12	**Teams' Design Review Presentations**	• Lab to support preparation of final part drawing, interacting with vendors and placing all orders	Task • Show final detailed design and sketch model to clinician and document feedback • Refine full SW model based on feedback from design review in class and clinician feedback • Begin final manufacturing Milestones • Document feedback from clinician • Update plan, and task list for remaining time and updated schedule to completion • Parts out to external shops for manufacture and components ordered from vendors
13	Intellectual Property Next Steps *Guest Lecture* Medical Devices 101: *Guest Lecture*	• Help with development of testing plan	Tasks • Finalize manufacturing and assembly • Prepare testing plan Milestones • MCM complete and demonstrated • Testing plan documented • Machining complete • Full assembly competed
14	Medical Devices 101: Paths to commercializati on *Guest Lecture*	• Presentation dry run. Make sure you practice, its kind of a big deal!: • Help with final paper preparation	Tasks • Prepare final presentation • Prepare final paper • Test your completed prototype in a realistic clinical setting with your physician Milestones • Final presentation and final papers due to course staff for feedback • Final paper draft due • Testing complete and documented
15	Reading Period	Final Evening Presentations	Final Presentation: Data and time TBA Teams will present for 20 mins with 10 mins for Q&A.

Appendix F

Course B2 condensed syllabus document

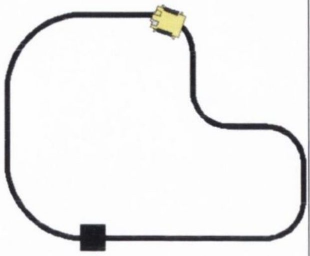
Week	Lecture & Design Loft Activity	Project Milestones (due Saturday)
1	Needfinding 1	Assignment 3 submitted: • Needfinding instruments and plan created • Users identified
2	Needfinding 2 Feedback on survey design, user recruitment, etc.	Assignment 4 submitted: • Results of needfinding • Problem area selected
3	Universal Design Feedback on problem area selection	
4	Bank Holiday: no lecture	
5	Reading Week: no lecture	Assignment 5 submitted: • Problem defined. • Mission statement created
6	Idea Selection Feedback on strategies	Assignment 6 submitted: • 3 strategies identified, best strategy selected
7	**Student presentations: Strategy** Brainstorming Feedback on strategies	Assignment 7 submitted: • 3 concepts selected and documented
8	Prototyping Feedback on strategy selection	Assignment 8 submitted: • 3 concepts developed and prototyped
9	Semester 2 Overview and Logistics Feedback on concepts	Assignment 9 submitted: • Best concept selected
10	**Student presentations: Concept** Feedback on concepts	Assignment A submitted Assignment 10 submitted: • Plan for detailed design and prototyping work until mini Showcase
WINTER BREAK – 4 WEEKS		

11	Shaft Analysis Feedback on detailed design work	
12	Failure Mode and Effects Analysis Feedback on prototyping	Assignment B submitted
13	Limits and Fits Feedback on prototyping	Assignment 11 submitted: • Prototype built • Design documented • Presentation prepared • 1-page glossy – features and benefits
14	**Student presentations: Detailed Design and Prototypes** Mini-Showcase	
15	Finite Element Analysis	Assignment 12 submitted: • Plan for redesign • Tasks delegated
16	Finite Element Analysis Feedback on refinement plan	• Assignment C submitted
17	Reading Week – no lecture	
18	Finite Element Analysis Prototyping session	
19	Finite Element Analysis Prototyping session	
20	Bank Holiday – no lecture	
21	Finite Element Analysis Prototyping session	Assignment 13 complete: • Final prototypes completed • Final presentation prepared • Poster prepared Assignment 14 submitted: • FEA analysis conducted and documented in report
22	**Final presentations** Showcase	

Appendix G

Concept Questions and Rubrics for Pilot Test

You have been asked to design an autonomous robot which can follow a black line drawn on a white surface. Describe the main subsystems that will need to be designed, and give a brief description of the tasks that will have to be undertaken for each subsystem.

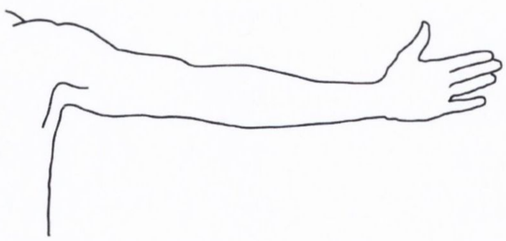


Code	Rubric	0	1
1A	Mentioned all major subsystems, e.g. structural, actuation, sensing, software		

Estimate the quantity of oil imported to the USA annually. Show your calculations or provide a rationale for your answer.

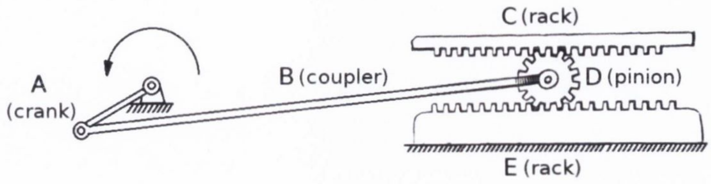
Code	Rubric	0	1
1A	Attempted to break problem into subproblems		
1B	Modelled the problem in some way		
1C	Guessed quantities		

You are designing a wearable device to assist with lifting tasks. Create a mathematical model of the arm in the position shown below, and use it to estimate the torque that must be applied at the shoulder to hold the arm in this position.



Code	Rubric	0	1
1B	Provided a mathematical model		
1C	Guessed quantities		

Describe what will happen when the crank (A) rotates. What do you think is the purpose of this setup?



Code	Rubric	0	1
2A	Rack amplifies motion		
3B	Angular to linear motion		

Sketch a mechanism that converts continuous circular motion into intermittent circular motion.

Code	Rubric	0	1
2B	Produces a legible sketch		
3B	Depicts anything that would conceivably produce the required motion		

Sketch a mechanism that converts continuous circular motion into reciprocating linear motion.

Code	Rubric	0	1
2B	Produces a legible sketch		
3B	Depicts anything that would conceivably produce the required motion		

You have been asked to judge four proposed solutions to a design challenge. The designers were asked to identify ways for social enterprises to improve the health of low-income communities in the developing world. Specific health concerns identified in the brief included: infant health and mortality; malnutrition; reproductive and sexual health; and unhealthy living conditions. Please choose the best concept from the list below and give a brief explanation for your choice.

Concept 1: Unmanned Arial Vehicles (UAVs) to deliver medical supplies to remote areas. The UAVs would carry supplies from clinics to remote areas, over difficult terrain. This would provide previously inaccessible areas with medicine. Local businesses could build, operate and service the UAVs.

Concept 2: Importing affordable medical devices. This concept is for a local business that would import low-cost medical devices, or purchase patents in order to manufacture devices locally. The aim is to create jobs while providing access to safe and appropriate medical devices.

Concept 3: Health-care vending machines. The proposed enterprise would place vending machines stocked with medical supplies in remote villages, and would employ trained distributors to stock the machines. The aim is to reduce the need for travel to clinics or pharmacies to obtain basic supplies.

Concept 4: Food subscription and insurance. People in low-income communities tend to buy food on a daily basis, which is more expensive in the long run than buying in bulk and often results in an unhealthy diet. The proposed business would allow families to pay a fixed daily fee and receive a box of healthy food. The business would buy food in bulk, and the savings made would be placed in an insurance fund that the family could use when they can't afford their daily box of food.

☐ **Concept 1** ☐ **Concept 2** ☐ **Concept 3** ☐ **Concept 4**

Code	Rubric	0	1
1D	Related choice to brief		
3A	Selected 3 or 4, or gave good reason for other choice		

You have been given the design brief below, and asked to think of as many analogies as possible that could be used as inspiration for the design. Please list any useful analogies you can think of (e.g. from nature, from other industries, from existing devices, etc.)

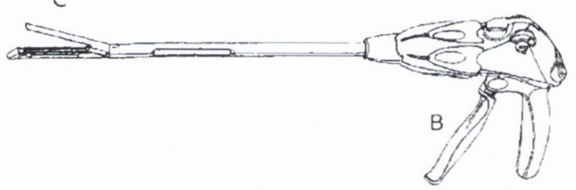
Design brief: Chain wear indicator. Chain hoists are used for listing and lowering movable loads. The lifting is done by an electric motor. Over time the chain wears, and the chain must be replaced if any of the following conditions are observed: cracks, visible distortion, severe corrosion, or a 2% increase in length. Currently chain wear is measured by hand with a caliper. The aim of this task is to design a better method for monitoring chain wear.

Code	Rubric	0	1
3C	Gave at least one analogy		

You are designing the column of an office chair. What do you think is the most likely failure mode that you will have to consider in your design?

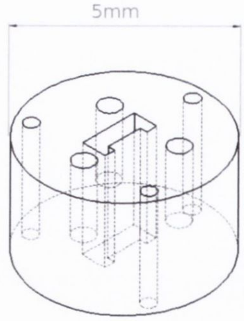
Code	Rubric	0	1
3E	Makes some mention of buckling or bending		

You are working with a team designing the surgical stapler shown below. Your task is to design the handle (A). When the surgeon pulls the trigger (B) the jaws (C) close and the staples are deployed. You have created initial designs for the handle casing and the internal mechanisms (which consist of pulleys and cables attaching the trigger to the jaws), and are now at the stage of prototyping and testing the handle. Briefly describe the tests you would carry out to validate or refine your design.



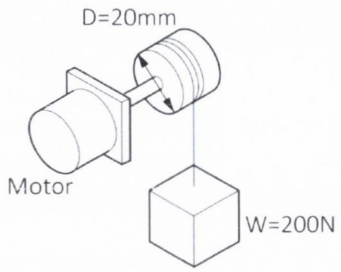
Code	Rubric	0	1
3D	Describes at least one useful test mentioning force		

You are designing a device which includes the part shown, which will be made from stainless steel. What manufacturing process would you use to produce a prototype of this part to scale?



Code	Rubric	0	1
4C	Mentions a viable manufacturing method taking account of the feature shapes (e.g. wire electrical discharge machining)		

You are designing a device containing a motor which must lift a load of 200N at a speed of 0.001m/s. Which of the motors from the catalog below would you choose for your device?

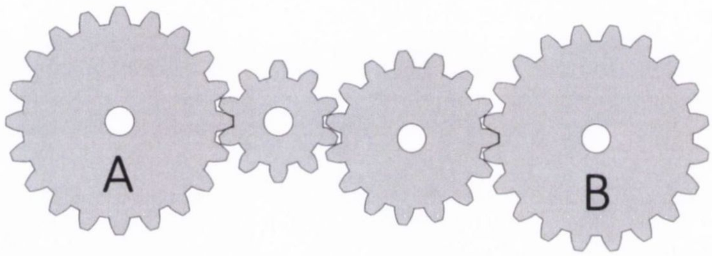


	Motor A	Motor B	Motor C	Motor D
Rated power (W)	0.3	3.2	20	250
Weight (g)	2	38	240	2100
Price ($)	91.25	146.5	218.25	1006.00
Values at nominal voltage:				
Supply Voltage (V)	3	3	6	70
No load speed (rpm)	18600	6890	4850	2610
No load current (mA)	21.3	23	123	120
Nominal speed (rpm)	5670	5820	3090	2410
Nominal torque (max. continuous torque) (mNm)	0.324	2.89	39.7	865
Nominal current (max. continuous current) (A)	0.242	0.72	3.55	3.54
Stall torque (mNm)	0.485	17.3	120	12600
Starting current (A)	0.336	4.19	10.4	49.7
Max. efficiency	56%	86%	75%	89%

☐ **Motor A** ☐ **Motor B** ☐ **Motor C** ☐ **Motor D** ☐ **None of these (explain)**

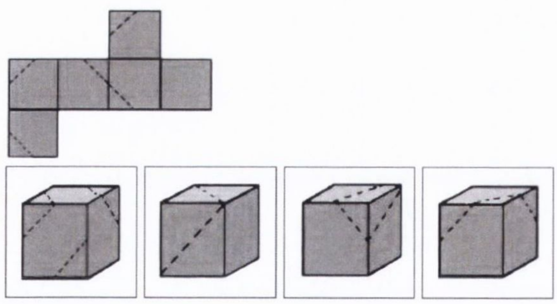
Code	Rubric	0	1
4B	Selected C or provided good rationale for another choice		

If gear A turns clockwise at a constant speed of 10 rpm, how fast and in what direction does gear B turn?



Code	Rubric	0	1
2A	10 RPM counterclockwise		

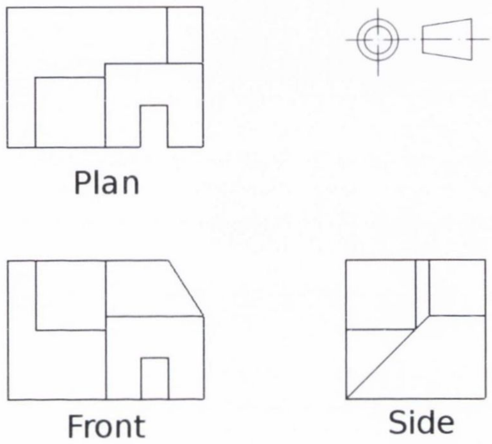
When the cut-out shape is folded along the solid lines, what is the resulting shape?



A ☐ **B** ☐ **C** ☐ **D** ☐

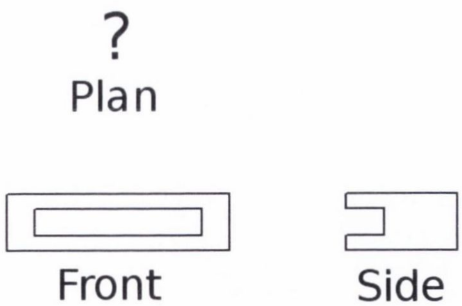
Code	Rubric	0	1
2A	Selected D		

Sketch an isometric view of the object shown in third-angle orthographic projection below.



Code	Rubric	0	1
2A	Drawing corresponds to projection		
2B	Produces a legible sketch		

Sketch the plan view of the object shown in front and side views below.



Code	Rubric	0	1
2A	Sketches any feasible shape		

Appendix H

Course A3 Pre- and Post-Test Instrument and Associated Rubric

Engineering Design Quiz

This is quiz is part of a research study focused on evaluating and improving engineering design courses. Please do not spend more than 30 minutes to complete the quiz, so work as quickly as you can. Your responses will be collected and stored by a researcher who is not a member of the teaching staff. After the course has concluded and grades have been assigned the responses will be analyzed. The quiz data will not include any personal identifiers, but will include project group identifiers. During analysis and reporting all identifiable information will be removed; only the researcher will have access to the link between identifiable and de-identified information and only for the duration of the data analysis. When research results are reported, no identifiable information will be included and responses will be aggregated and described in summary.

Your participation in this study is greatly appreciated.

BACKGROUND INFORMATION

Age: ____________________

Gender: ____________________

Project Group: ____________________

Choose the category that describes you best:

- ◯ Engineering Student (Undergraduate)
- ◯ Engineering Student (Graduate)
- ◯ Non-Engineer with a Science Concentration (Undergraduate)
- ◯ Non-Engineer with a Science Background (Graduate)
- ◯ Non-Engineer without a Science Background

DIRECTIONS: *Please answer Q1 by selecting the answers that best represent your beliefs and judgment of your current abilities. Answer each question in terms of what you know today about the given tasks.*

Q1. Rate your degree of **confidence** (i.e. belief in your current ability) to perform the following tasks by recording a number from 0 to 100.
(0 = cannot do at all; 50 = moderately can do; 100 = highly certain can do).

	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Conduct engineering design	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Identify a design need	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Research a design need	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Develop design solutions	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Select the best possible design	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Construct a prototype	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Evaluate and test a design	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Communicate a design	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Redesign	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

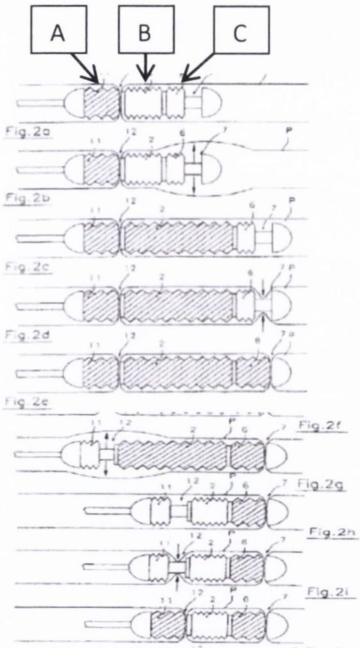
DIRECTIONS: *Please answer all of the following questions related to the design of soft robotic actuators and medical devices.*

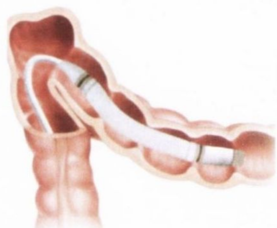
Q2. Please list as many uses for this soft bending actuator as you can think of in five minutes.

Q3. You have been asked to evaluate two concepts for the design of an endoscope. Endoscopes are used to examine the interior of an organ or cavity of the body. A major challenge in endoscopy is effectively and safely maneuvering the endoscope inside the patient. As the endoscope is pushed/pulled inside the patient, the forces that are applied on the cavity walls can cause patient discomfort, pain, and potential tissue damage. This is especially of concern when navigating sharp turns or places where the cavity is collapsed/folded in on itself. Two concepts for an endoscope navigation system that addresses these problems are described below. Give your opinion of each concept. What do you think are the important issues to consider when deciding between the concepts?

CONCEPT A

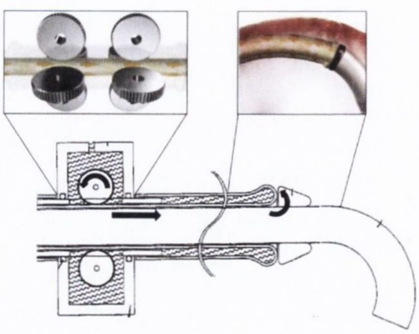
This device semi-autonomously advances through tubular cavities using an "inchworm"- like method. The body of the device consists of three bellows (A, B, C); the bellows expand longitudinally when inflated and contract when deflated. Each end of the device consists of an anchoring mechanism. As shown in Fig. 2d and Fig. 2e, the anchoring mechanism works by applying a vacuum to collapse the surrounding cavity walls, and then inflating the relevant bellows (in this case C) to grasp the collapsed tissue. The central bellows (B) alternately expands and contracts to advance the device.

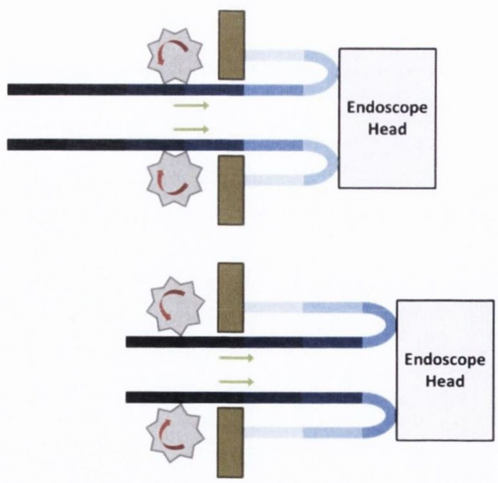




CONCEPT B

Instead of being pushed or pulled, this endoscope is driven in and out of the colon. The driving mechanism is the eversion of a flexible tube (see figure on right), in which a set of gears pushes the tubing forward and it turns inside-out while pushing the endoscope head forward. As a result, there is no motion of the tubing relative to the cavity wall.



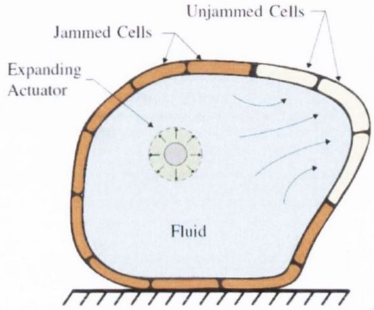


Your evaluation of Concept A:

Your evaluation of concept B:

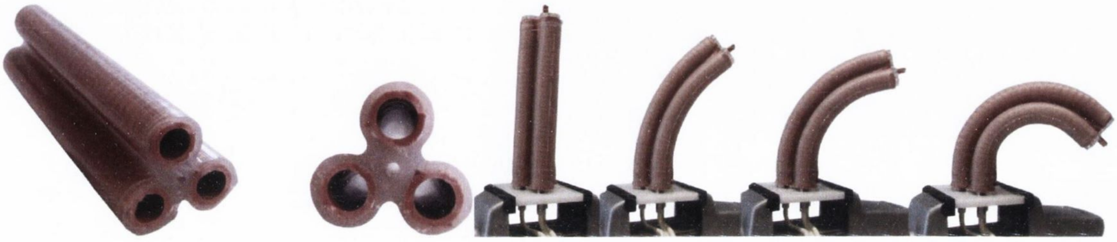
If you were working on this project which concept would you select to pursue?

Q4. The soft robot shown below consists of a central fluid-filled chamber that can be pressurized by expanding an inner actuator, and an outer skin consisting of "cells" filled with jammable slurry. Unjamming selected cells while pressurizing the central chamber causes specific areas to bulge, achieving controlled locomotion. See this video for more details: http://goo.gl/1ch3d3



How would you fabricate this robot? Please provide a detailed plan, describing the steps you would take, the materials and equipment you would use, the design of the molds (if any) you would require, and so on. Be as specific as possible. Use sketches to help describe your plan.

Q5. The actuator shown below consists of three cylindrical elastomer tubes, each radially constrained by Kevlar thread wrapping and held together by an outer skin. A central Bowden cable acts as the strain limiting layer. By pressurizing the cylinders individually or in combination, a range of motions can be achieved. Imagine that you are part of a team designing **a pick and place robotic arm.** One of your team members has made this actuator as a prototype for the arm. How would you evaluate the load carrying capabilities of the design? Describe the tests you would carry out and the equipment you would use.



Question 3 Rubric

	0 – N/A	1 – Poor	2 – Acceptable	3 – Good	4 – Excellent
Describes criteria used to evaluate concepts	Impossible to tell what criteria were used to evaluate concepts.	Criteria for evaluation provided, but they are incorrect or miss the most important criteria.	Some important criteria for evaluation are implicitly clear.	Mentions at least one important criterion for evaluation.	Explicitly lists multiple important criteria for evaluation.
Choice relates to evaluation	No evaluations, or no choice.	Choice seems to contradict the written evaluations.	No clear contradiction but it is difficult to understand why the concept was chosen.	Choice seems to follow logically from evaluations.	Written evaluation clearly argues for the concept selected.
Demonstrates understanding of medical context	Evaluation in no way mentions issues related to a medical context	Contains only vague reference to medical context.	Refers to medical context but contains errors.	Refers to medical context with no significant errors.	Makes extremely clear and insightful reference to medical context
Identifies strengths of concept A	Makes no mention of strengths of the concept	Identifies weakness as strength with no good explanation of why	Identifies aspects of concept as strengths without any indication of why.	Explicitly describes and explains one strength of the concept	Explicitly describes and explains more than one strength of the concept
Identifies weaknesses of concept A	Makes no mention of weaknesses of the concept	Identifies strength as weakness with no good explanation of why	Identifies aspects of concept as weaknesses without any indication of why.	Explicitly describes and explains one weakness of the concept	Explicitly describes and explains more than one weakness of the concept
Identifies strengths of concept B	Makes no mention of strengths of the concept	Identifies weakness as strength with no good explanation of why	Identifies aspects of concept as strengths without any indication of why.	Explicitly describes and explains one strength of the concept	Explicitly describes and explains more than one strength of the concept
Identifies weaknesses of concept B	Makes no mention of weaknesses of the concept	Identifies strength as weakness with no good explanation of why	Identifies aspects of concept as weaknesses without any indication of why.	Explicitly describes and explains one weakness of the concept	Explicitly describes and explains more than one weakness of the concept
Provides reason for choice of concept	Provides no reason for choice	Provides poor reason that seems to contradict points from evaluation	Provides poor reason that repeats point from evaluation	Provides good reason that repeats point from evaluation	Provides good reason that goes beyond the written evaluation

Question 4 Rubric

	0 – N/A	1 – Poor	2 – Acceptable	3 – Good	4 – Excellent
What materials and equipment will be needed?	No materials or equipment listed.	Vague mention of unspecified materials or equipment.	Mentions either molds or material but not both	Mentions both molds and material	Mentions molds, elastomer, and other specific materials.
How will the jammable cells be made?	No description of molds or fabrication process for the cells.	Fabrication process (and/or related molds) mentioned but not described in any detail.	Describes molds in some detail but does not describe fabrication process (or vice versa).	Describes molds and process but reader would have to figure out many of the details to implement procedure.	Feasible procedure & mold description which could be followed by a student with limited experience.
How will the cells be filled with slurry & sealed?	No mention of the slurry in the cells.	Slurry in cells is mentioned but no description of how the cells will be filled or sealed	Vague description of how the cells will be filled and sealed.	Detailed description of how the cells will be filled and sealed.	Detailed and feasible description of how the cells will be filled and sealed.
How will the central chamber be made and filled?	No description of fabrication process for the central chamber.	Chamber and/or fluid mentioned but process not described.	Vague description of process.	Describes process but reader would have to figure out many of the details to implement procedure.	Feasible procedure description which could be followed by a student with limited experience.
How will the expanding actuator be made?	No mention of inner actuator	Actuator mentioned but process not described.	Vague description of fabrication process.	Describes process but reader would have to figure out many of the details to implement procedure.	Feasible procedure description which could be followed by a student with limited experience.
How will tubing be connected?	No mention of tubing.	Tubing briefly mentioned but no description of how it will be embedded or routed.	Vague description of how tubing will be embedded or routed.	Detailed description of how tubing will be embedded or routed.	Detailed and feasible description how tubing will be embedded or routed.

Question 5 Rubric

	0 – N/A	1 – Poor	2 – Acceptable	3 – Good	4 – Excellent
How much detail is provided?	No test, equipment, etc. described.	Very vague mention of either the equipment or the procedure but not both.	Vague mention of both equipment and procedure	Main equipment and procedure described but not much detail	Most details are described but reader would have to figure out some parts of the setup.
What will be measured?	Impossible to tell.	Quantities mentioned do not include force.	Only force will be measured.	Force and a second quantity (e.g. pressure, time, range of motion, etc.) will be measured.	Force and two other quantities will be measured.
How feasible is the test(s) described?	Impossible to tell.	The test would probably not work.	The test might work but there are problems not considered in the answer.	The test would probably work.	The test would probably work and the answer mentions potential problems.
How accurate would the test(s) be?	Impossible to tell.	The test would probably not provide a measurement of the intended quantity.	The test might measure the intended quantity but leaves a lot of room for human error or other noise.	The test would probably measure the intended quantity.	The test would probably measure the intended quantity and issues of accuracy are discussed.
How repeatable would the test(s) be?	Impossible to tell.	The test involves a setup that would be almost impossible to replicate multiple times.	The test involves a setup that would be difficult to replicate multiple times.	The test would probably give similar results over multiple attempts of the same design.	A similar approach could be used to evaluate other designs.
Does the answer demonstrate an understanding of the relevant fundamental physics principles?	Impossible to tell.	Answer displays fundamental misunderstanding of basic physics.	Makes passing reference to fundamental principles with some minor errors.	Makes reference to fundamental principles with no obvious errors.	Discusses fundamental principles in some detail with no obvious errors.