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A qualitative investigation of design knowledge reuse in project-based mechanical design courses

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ABSTRACT
The interpretation and reuse of previous design solutions, or precedents, is central to design. This paper describes qualitative research conducted over three years at two institutions, aimed at investigating the role of design knowledge re-use in project-based mechanical design courses. Research data were collected through participant observation, student interviews, anonymous questionnaires, and website analytics. The paper identifies challenges that must be addressed in order to support novice engineers in rehearsing the types of knowledge required to successfully reason about and engage with design precedents. Two categories of design precedents are identified: concept precedents and detail precedents. Providing students with access to the latter is identified as a particular challenge, as is providing students with access to engineering communities of practice. Approaches to addressing these challenges are discussed.

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Introduction

Design is generally considered a central activity of engineering. In recent years, and in response to a perceived need for more emphasis on design activity in undergraduate programmes, engineering schools have introduced new project-based courses that seek to connect engineering theory and practice by giving students the opportunity to work on 'real-world' problems (Dym et al. 2005). However, there are a number of significant challenges to be overcome as part of this transformation of engineering education. The field of design 'lacks a coherent representation of design pedagogical content knowledge', that is, domain-specific knowledge associated with the teaching and learning of design (Crismond and Adams 2012). Thus, there is a need for research aimed at identifying pedagogical principles for engineering. This paper describes an attempt to address this need in one area of design teaching and learning: design knowledge reuse.

The interpretation and reuse of previous design solutions, or precedents, is central to design education and practice. Designers rely upon a 'repertoire' of previous problems and solutions to guide concept generation and evaluation (Lawson 2004). Among the characteristics of design expertise identified by Lawson 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, Wallace, and Blessing 2003). This reference to precedents supports a breadth-first problem-solving

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approach by allowing designers to conduct preliminary evaluations of design concepts to decide whether a solution is worth pursuing (Ball et al. 1997, 268).

Successful reuse of design knowledge can be difficult. On the one hand, referring to design precedents carries a risk of fixation, that is, attachment to a particular concept which may prevent designers from considering novel solutions (Jansson and Smith 1991). On the other hand, designers often fail to reuse existing solutions in situations where doing so may reduce cost and risk (Busby and Lloyd 1999). 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 engineering education, with its focus on abstraction and generality.

Thus, in order to become successful designers, students must rehearse and reflect upon the reuse of design knowledge. Learners should be provided with examples on which to draw, and encouraged to engage in reasoning with and about precedents. The use of precedents in design education is not a matter of simply increasing students' domain knowledge or improving 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. But how should this be achieved? How do students access, reuse, and learn from design precedents? What obstacles might prevent successful student use of precedents? The purpose of this paper is to answer these questions by examining the experiences of students in project-based mechanical engineering design courses.

Methods and materials

Research sites

The research took place over three years in two design courses at two institutions in the US and Ireland. Each of the courses involved teams of three to six students working with stakeholders to identify an unmet need, design a solution, and implement their design in a high-quality working prototype. A total of 32 teams composed of 148 students were studied. Both courses were extremely open-ended; student teams were expected to develop their own design briefs based on interactions with stakeholders, and were expected to define their own solutions to their brief rather than working towards a solution defined by the instructor. As a result, the project topics varied widely both within and between each year of a course. While both courses were focused on mechanical design, the open-ended nature of the projects meant that many student teams also engaged in electronic and software design activities.

Course A was a medical device design course at Harvard University. Each year, the class consisted of 16 undergraduate and graduate students working in four teams. Each team spent one semester collaborating with a medical practitioner to identify and address an unmet clinical need. Course B took place at Trinity College Dublin and focused on universal design. Each year, 10 teams of 4–6 students each identified their own stakeholder groups and worked with these stakeholders to design a device related to activities of daily living. Table 1 contains an overview of the courses studied. The courses did not run simultaneously; Course A took place in the second semester of each academic year, while Course B took place in the first semester.

Table 1. Overview of courses studied.

	Course A	Course B
Level	Mixed: undergraduate and graduate	Third-year undergraduate
Types of projects	Electromechanical	Mixed: mechanical, electronic, software
Duration of student project	15 weeks	15–21 weeks
Size of student cohort	13–16 students	46–61 students
Number of student teams	4 teams	10 teams

Methodology

The study employed a design-based research methodology, which seeks to increase the impact of education research on teaching practice (Anderson and Shattuck 2012; Brown 1992). 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 conducts a series of interventions in the learning 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. 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). Often, the data collection and analysis methods are adapted throughout the research, both during and between interventions (Collins, Joseph, and Bielaczyc 2004).

This paper describes the results from three cycles of intervention and observation in project-based design courses. Figure 1 is a graphical representation of the process followed. The first phase consisted of open-ended, exploratory research in both courses. The results from this phase were used to narrow the focus of the research and to redesign the learning environments. During the second phase, the emerging research themes were explored in more depth. This process was repeated during the third phase, with the research themes explored in even greater depth in just one course. The study presented here was part of a larger project aimed at exploring learning environments for engineering design. This paper focuses on themes related to design knowledge reuse that emerged from that project, rather than describing all interventions and results. A comprehensive description of the project can be found in Holland (2014).

Data collection

Participant observer field notes were the primary form of data collected throughout the three research phases. One of the authors participated in all courses as a teaching assistant, a role which involved mentoring student teams and organising learning activities. Field notes 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 the design teams' meetings as these provided opportunities to examine the participants' thought processes (Lloyd, McDonnell, and Cross 2007). To increase

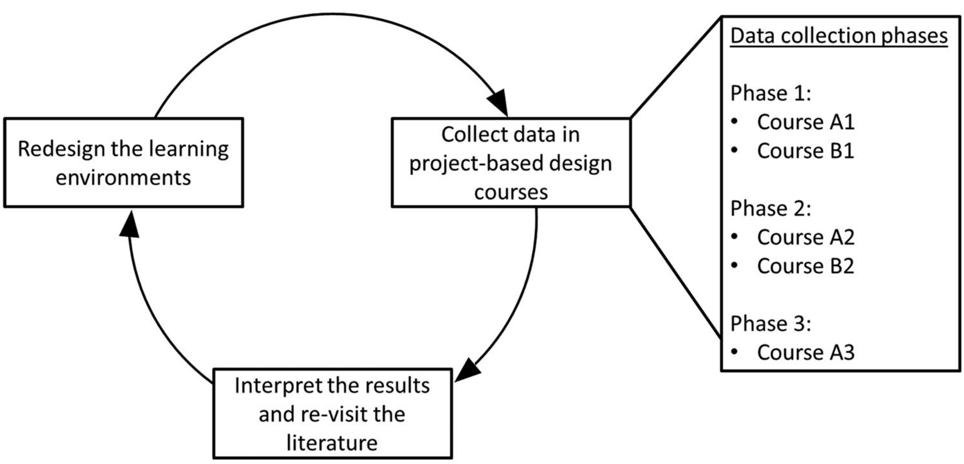

Figure 1. Schematic view of the iterative design-based research process followed in this study.

trustworthiness of results, a range of procedures recommended by Wallendorf and Belk (1989) were employed, including: prolonged engagement and persistent observation; triangulation of sources and methods; negative case analysis; debriefing by peers; member checks; and emergent research design.

Interviews with students were used as a method of data triangulation and as a means of conducting member checks, which involve seeking feedback from participants on emerging research themes (Wallendorf and Belk 1989). Two types of interviews were conducted: contextual interviews and exit interviews. Contextual interviews involved the researcher observing students engaged in classwork activities while asking questions about those activities (Beyer and Holtzblatt 1997). Exit interviews were conducted with students upon completion of the courses. 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. Questionnaires were used as a further source of data triangulation, and student responses were used to gain insights on themes emerging from the participant observation data. Finally, anonymous website analytics data was used to track students' engagement with a web-based collection of design precedent documentation.

Data analysis

Analysis of the resulting data was guided by van Manen's (1997) 'selective' approach, which involves searching the data for the episodes and statements that best encapsulate the meaning of the events described. Analysis began during data collection in order to identify emergent themes and guide further exploration. The data collected during each course was then revisited and analysed in more depth upon completion of the course. 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 student team was then considered in isolation. All field notes 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 the key episodes or quotes that were essential in explaining these experiences. The procedure was repeated for each team and the emergent themes were compared. This process resulted in a set of themes for each student cohort represented by illustrative events and quotes from students and instructors. The themes for each cohort were then compared to each other, to identify patterns of similarity and difference.

Theoretical frameworks

This study was informed by situated learning theory and cognitive flexibility theory. Situated learning theory highlights the importance of the context in which learning takes place (Lave 1988). In Lave and Wenger's (1991) model, learning is viewed as participation in a 'community of practice', a group who share a domain of interest and engage in and identify with a common practice. Learning occurs through interactions with the community, 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.

A related learning theory, which is particularly relevant for the study of knowledge reuse, is cognitive flexibility theory. Spiro et al. (1992) claim that solving problems in complex and ill-structured domains, such as engineering design, requires using the same knowledge in different ways depending on the particular details of a problem. Cognitive flexibility theory emphasises the 'reassembly of pre-existing knowledge to adaptively fit the needs of a new situation' (Spiro et al. 1992). From this perspective, rather than stripping problems and solutions of their context with the aim of making lessons more generally applicable, specific and rich contextual information should be provided (Jacobson and Spiro 1993). The objective is to expose students to the ways in which a given principle or procedure is enacted in real situations. 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).

Results and discussion

The study of 32 teams over three years produced a large amount of data covering multiple aspects of students' experiences in project-based design courses. Qualitative data is unsuited to producing universal, 'objective' rules related to design education. However, by comparing and contrasting the experiences of students across multiple years and in a variety of contexts, it has been possible to identify some emergent themes related to design knowledge reuse in these educational settings. The following sections present the main findings of the study, supported by example episodes observed by the researchers, and grouped under indicative headings.

Students need access to two types of design precedents

Students were observed to use two types of precedents. First, during the initial stages of 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 often also used to inspire certain principles of operation, or synthesised 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 a description from a company website was sufficient for students to understand the design and reason about its applicability to their problem.

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 realising a given concept. The information required about these precedents was much more detailed, and included specific mechanisms, morphologies, 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.

Access to concept precedents was sufficient

Previous studies of design knowledge reuse have typically focused on concept precedents. For example, studies on design fixation have investigated the influence of design precedents on concept generation activities (e.g. Jansson and Smith 1991; Purcell and Gero 1998; Viswanathan and Linsey 2013). Other studies have explored the effects that relevance of precedents, diversity of precedents, and the timing of precedents' delivery have on concept generation (e.g. Chan et al. 2011; Doboli et al. 2014; Siangliulue et al. 2015). Of particular relevance to design education, recent research has focused on the use of precedents by student design teams (e.g. Daly et al. 2012; Toh and Miller 2014). Thus, concept precedents have received significant attention in previous research.

In the courses observed during this study, concept precedents were typically identified by students as part of background research, prior art searches, or through interactions with stakeholders or teaching staff. Homework assignments were useful in encouraging students to identify these precedents. Early assignments in Course A1 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 any course actively sought information on concept precedents, the level of access to this information seemed sufficient.

Given the attention that concept precedents have received to date in the literature, and the fact that access to and use of concept precedents was not a challenge for the observed students, detail precedents were identified as the main topic of interest for further exploration. The following sections explore the use of detail precedents in design courses in more detail.

An example of detail precedent use

When undertaking tasks related to software or electronic circuit design, students made extensive use of detail precedents from documentary sources. An online culture of sharing source code and circuit diagrams exists, and students drew on these examples when prototyping their own designs. 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. Extracts from one such interview are presented here.

A student (S) 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 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.

Researcher: Is there any project that seems relevant?
S: Yes … 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: Are you following their diagram for the force sensor example?
S: Yes, 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 an example in the booklet that deals with another type of variable resistor ('the force sensor'). The booklet contains a wiring diagram for connecting these sensors 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 robotic actuators; such electronics 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 seemed to be based on her experience using similar approaches to software design; she had a 'procedure' for finding and using precedent knowledge and based design decisions such as the choice of programming language on the availability of documentation. Finally, she was capable of using precedents combined with trial and error to understand fundamental design principles; at the end of the episode she reasoned about the requirement for the second resistor and arrived at an understanding of the basic principle of operation of a voltage divider.

Students lack access to detail precedents for mechanical design

While many of the student teams were observed to make use of detail precedents for electronic or software design tasks, all teams encountered significant difficulties in retrieving and using detail precedents when working on mechanical design tasks. In some 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 for mechanical design 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 secret. In other types of engineering 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 was not feasible for teaching staff to provide all of the required detail precedent information, regardless of their experience or expertise.

The result is that much of students' time in these courses was dedicated to seeking basic information about mechanical design, 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 a lack of access to detail precedent knowledge was identified as the primary issue to be addressed during subsequent research phases. Prior research suggests that designers need access to detail precedent information via two channels: documentary and social sources. Studies of knowledge sharing in industry have found that when answering factual questions or clarifying tasks, designers refer to documentary knowledge sources. However, during later design phases the use of both social and documentary sources is required (Ellis and Haugan 1997; Milewski 2007). This seems to indicate that designers access problem definition information and concept precedents primarily through documentary sources, while they access detail precedents through both informal social interactions with peers and reference to documentary sources. 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 (Deken et al. 2012; Demian and Fruchter 2006). Thus, addressing the observed issues requires attending to both of these sources of design precedents. The following three sections discuss the social aspect of design knowledge reuse; documentary sources are explored in subsequent sections.

Students require access to engineering 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 project-based design courses is to support students in rehearsing 'designerly ways of knowing' (Cross 1982), access to such communities would seem to be essential. However, during the first phase of research both courses were characterised by obstacles to participation in engineering communities of practice.

In particular, students faced difficulties in accessing solution domain expertise. Students had direct access to experts: in Course A1, each team worked with an experienced clinician; while in Course B1, students consulted with design advisors from a stakeholder advocacy group. 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 invaluable for the definition of problems and the framing of potential solutions, they did not provide the engineering knowledge required by students engaged in detail design, prototyping, and testing.

Problems of access to communities of practice were not due to ignorance or neglect of this issue by teaching staff. As noted above, it is not feasible for teaching staff to provide the variety of domain knowledge required across the multiple student projects. 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 given 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 particular 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 largely irrelevant. Thus, there is a need for approaches to course planning that allow the provision of access to engineering communities of practice in a timely manner, while maintaining the open-ended nature of the design projects.

An approach to providing access to engineering communities of practice

A variety of possible approaches exist for providing students with access to design precedents through engineering communities of practice. Many engineering design courses adopt a relatively 'closed-ended' approach, in which the product to be designed is known in advance, thereby allowing teaching staff to assemble relevant examples and experts for use by the students. Some engineering programmes combine this with deliberate attempts to create a community of practice amongst student engineers. For example, in the aircraft design programme described by Thompson (2002), students participate in a single project throughout the four years of their undergraduate degree. This is an elegant means of creating a community of practice; new entrants to the programme have access to the knowledge of more experienced students, and the senior students obtain experience mentoring other engineers.

However, these approaches are less suitable for the courses studied in this paper. As discussed previously, these courses emphasise user-centred design and are deliberately extremely open-ended, with each student team tackling a different design problem and free to explore any possible solution. Thus, a different approach was required to address problems of access to design precedents and engineering communities of practice.

During the second phase of research, both courses were re-designed to incorporate project themes, with the aim of predefining some aspects of the student projects so that access could be planned in advance, while maintaining the freedom for students to define their own particular problems or solutions. By establishing a shared theme across the different student projects, this approach also aimed to create a community of practice within the classroom, thereby allowing students working on very different projects to learn from each other. In each course, a different approach was taken. In Course A2, the theme related to the type of technology likely to be used in most projects. 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 materials and compliant structures in the design of electromechanical devices. 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 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, staff engineers, and graduate students. These experts 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, a variety of clinical stakeholders who were likely to require soft robotics solutions were invited to work with the student teams. However, the projects remained open-ended, with students free to develop their own design brief and to employ any technology they chose for their solution.

In Course B2, the project theme related to the types of problems to be solved. Student teams were required to design solutions to support successful ageing. Due to the phenomenon of population ageing in Europe and elsewhere, 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. The focus on projects related to successful ageing was intended to facilitate students in interacting with a wide variety of domain experts. Thus, the teams in Course B2 shared a common problem domain, while the teams in Course A2 shared a common solution domain. The remainder of this section compares these two 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, 8 of the 10 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 10 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 city to visit a research group and tour their facility. However, while these interactions provided students with insight into the practice of engineering research, the consulted experts 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. 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 synthesise elements of previous designs and combine these elements with their own original work. The student interactions with experts 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 typically 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 also been observed in interactions between design experts and novices in the aerospace industry (Ahmed and Wallace 2004; Deken et al. 2012).

An example of student-expert interaction

This section contains excerpts from a conversation between a student in Course A2 and a domain expert, that provide some insights on how these types of interactions provide students with access to knowledge about design precedents. A student (S) is meeting with an expert (E) who has extensive experience in the medical device industry. The student's team has decided on their solution concept, and is working on the mechanism details and a prototyping plan. The course instructor 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 tools, and has shared solid model files that the 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 yes 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 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.

In this brief excerpt the discussion covers topics including medical procedures, materials, fabrication methods, potential mechanism designs, related commercially-available devices, and previous design experiments conducted by the expert. 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 semester some teams had begun contributing knowledge back to the research groups by sharing their own fabrication methods or design variations.

However, students' appropriation and modification of design precedents was not always successful. One week after the meeting described above, 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 members 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, 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 which the experts 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. The following sections discuss an attempt to provide students with documentary sources of precedent knowledge, with the aim of reducing the time required for experts to share background information with students.

Documentary sources can supplement access to communities of practice

During the third phase of research, the study focused solely on Course A3 in order to explore in more depth the use of a technological theme and, in particular, the use of a documentary source of design precedent information related to that theme. Again, the focus of the course was medical applications of soft robotics, and student teams were again connected with both clinical stakeholders and engineering communities of practice. The primary difference in the teaching approach, compared to Course A2, was the use of a web-based collection of documentation sets describing the design, fabrication, characterisation, and modelling of soft robotic components. Each documentation set contained detailed tutorials and multimedia protocols, as well as case studies and design files such as CAD solid models that could be downloaded and modified. This resource was developed specifically for use in Course A3, and the content of the documentation was based in large part on recordings of student-expert interactions during Course A2. For more details about the development and use of the resource, see Holland et al. (2014).

The web-based resource was used to support a new series of introductory laboratory sessions intended to introduce the students to some of the basic concepts about soft robotics. Most of these hands-on activities related to the design and fabrication of soft components. Typically, these activities take multiple days due to the sequences of casting and curing required. The detailed step-by-step instructions contained in the web-based resource enabled students to complete these activities outside of scheduled class time; without this resource, it would not have been possible to complete as many laboratory assignments during the semester.

Students' use of the resource was explored through participant observation, as well as anonymous website analytics data. Only students in Course A3 had access to the website, and class instructors used a browser plug-in to prevent their website visits from being recorded in the analytics data, so it was possible to track students' use of the resource while preserving their anonymity.

From participant observation data, it was clear that student teams' use of the resource varied widely. Some teams relied heavily on the resource, modifying the designs described on the website to suit the particular requirements of their projects. These teams' interactions with experts tended to be regular brief discussions of specialised topics rather than longer meetings discussing background information. For other teams, their projects were less directly related to the designs documented on the website; these teams tended to spend more time interacting with more experienced engineers. However, all student teams used information from the web-based resource, even if their designs had very little in common with the precedents documented on the website. In particular, information about fabrication processes was relevant to all projects in the course.

For all student teams, providing a documentary source of detail precedents enabled independent work on design and fabrication tasks. The website analytics data plotted in Figure 2 reveal patterns in how the resource was used. At the beginning of the course students made a large number of brief visits to the website 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 already learned 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 observed was that the documentary source 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 resource was then used as a source of detail precedents 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 documentary source was useful in supporting the interactions between novices and experts, which was the primary objective of introducing it to the course.

Cognitive flexibility theory can guide the development of documentary sources

The development of the documentary source was guided by cognitive flexibility theory, of which a fundamental principle is that concepts, principles, and theories should be presented from multiple

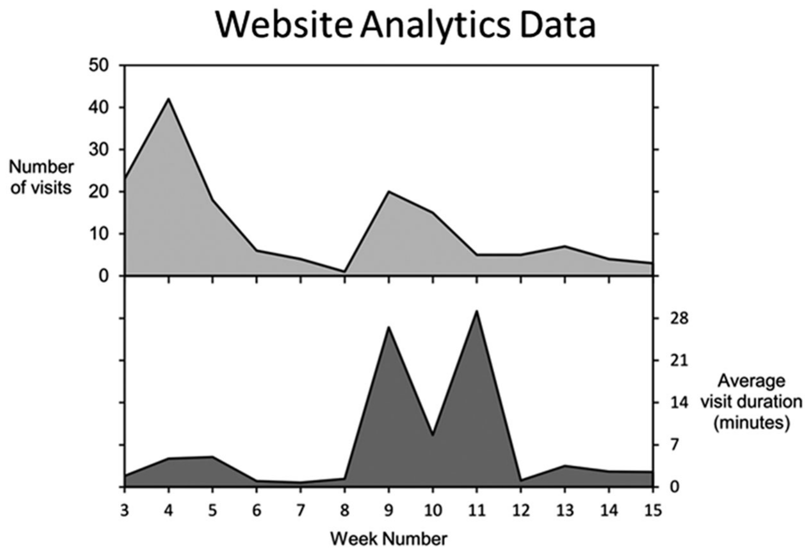

Figure 2. Website analytics data showing number of student visits per week and average duration of student visit per week.

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. This principle aligns with Variation Theory, which posits that learners must experience multiple examples of an 'object of learning' in order to discern its 'critical features' (Mun Ling and Marton 2011). An assumption in the design of the Course A3 resource was that each type of component technology was a particular representation of the fundamental soft robotics concept of 'morphological computation', or the attainment of complex behaviour through mechanical design rather than through sophisticated software or electronic control systems. 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 documentary source were so dissimilar, that it was difficult for students to transfer design knowledge from one context to another. For example, one team in Course A3 based much of their design on a modified version of an actuator documented in the web-based resource. When making their 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 all similar actuators. 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 more fine-grained 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. The team documented their own design experiments as a contribution to the resource. The implication is that, rather than thinking of the entire documentation set 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.

Conclusions

This paper has presented the findings of qualitative research conducted over three years in two project-based mechanical design courses. The research has yielded insights on the role of design knowledge reuse in design education, and in particular has identified challenges that must be addressed in order to allow novice engineers to rehearse the types of knowledge required to successfully reason about and engage with design precedents. The paper has identified two categories of design precedents: concept precedents and detail precedents. While students seem to be capable of accessing information about concept precedents with minimal support, providing students with the required access to detail precedents for mechanical design has been identified as a particular challenge. It has been found that students require information about detail precedents in two ways: from detailed documentation that describes methods of designing and fabricating mechanical parts; and from interactions with communities of practice composed of engineers with varying levels of expertise. Providing access to engineering communities of practice has been identified as an additional challenge.

It is hoped that the findings presented here can provide guidance to instructors in similar project-based design courses. In attempting to apply these findings to other courses, the following points should be noted. First, during this study the use of a technological theme proved successful in exposing students to engineering communities of practice; however, the choice of theme must be carefully considered. In the case presented here, soft robotics represented a multidisciplinary area that was receiving substantial attention from a large number of local research groups. In addition, it is a topic that is extremely broad and could be applied to a wide range of design problems and mechanical devices. It is expected that a more specific, closed-ended theme, or a theme tied to the activities of a small number of research groups, would not have been as successful. Second, it is expected that there are multiple possible approaches for connecting students with engineering communities of practice; the field would benefit from similar studies investigating alternative approaches to those presented here. Third, while the use of a documentary source of detailed precedent information has been found to support student design activity in one course studied here, it should be noted that the authors do not propose such a resource as an alternative to interactions with engineering communities of practice; prior research suggests that both documentary and social sources are essential. Finally, the development of course-specific documentary sources of detail design precedents is a substantial undertaking; ideally researchers and educators would pool their resources to accelerate the development of learning materials. The web-based resource presented here has since been made freely available to the public, has been visited by over 200,000 people in 175 countries, and now hosts design precedent documentation from multiple universities (Holland et al. 2017). It is suggested that taking a similar approach in other technology domains would represent a significant contribution to engineering education.

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