Educating effective engineering designers: the role of reflective practice

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Educating effective engineering designers is an important goal. Exploring the extent to which this goal is being met hinges on our ability to characterise what contributes to effectiveness and to map students' performance against such standards. In previous work, we used verbal protocol analysis to analyse differences in the design processes of freshmen and seniors, the effects of interventions on student design processes, and process factors that contribute to product quality. In this paper, we utilise Schön's reflective practitioner theory to discuss our empirical results in the context of educating reflective practitioners. Such an approach may provide implications for enhancing engineering education.

Keywords: engineering design, design education, protocol analysis, reflective practice

Engineers, like other professionals, need to be able to handle the challenges imposed by design problems. Engineering education, therefore, needs to help engineering students develop the necessary skills to confidently and successfully handle design problems. While design education has always been a challenge of engineering education in the United States[1–4] new outcomes-based accreditation standards have placed even more emphasis on the design skills of graduating engineers[5].

We are interested in enhancing engineering design education. In particular, we are interested in research-based education, an approach that starts with developing an *understanding* of how engineering students approach design problems in order to *inform* engineering design education. Schön's[6] influential model of the reflective practitioner provides one framework for understanding design behaviour. From the perspective of our research-

1 Mann, C R A study of engineering education The Carnegie Foundation for the Advancement of Teaching (1918)
2 National Research Council Engineering education: designing an adaptive system National Academy Press, Washington, DC (1995)
3 National Science Foundation *Restructuring engineering education: a focus on change division of undergraduate education*, Directorate for Education and Human Resources, National Science Foundation, Washington, DC (1995)
4 National Society of Professional Engineers *Engineering education issues: Report on surveys of opinions by engineering deans and employers of engineering graduates on the first professional degree* NSPE, Alexandria, VA (1992)

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based approach, a focus on the reflective practitioner model leads to the following types of questions:

(1) How could we measure reflective practitioner behaviour in engineering students?
(2) To what extent do engineering students behave as reflective practitioners?
(3) In what ways are seniors more like reflective practitioners than freshmen?

We explore questions such as these in this paper. In particular, we explore these questions by using the reflective practitioner model as a lens through which we report and interpret results from our previous verbal protocol work on engineering student design behaviour. We will use these results to discuss the extent to which the engineering students in our studies are (or are learning to be) reflective practitioners, the utility of the reflective practice idea in this context, and the implications of these results for engineering education.

1 Reflective practice and engineering student design expertise

Donald Schön has been studying professional practitioners, particularly professional designers, for more than twenty years. In his work, Schön sought an account of the nature of professional activity based on the common elements of the practices he had observed. Schön rejected a theory of technical rationality that distinguishes professionals by the extent of their 'book knowledge' and developed an alternate theory of the professional as reflective practitioner[6].

A reflective practitioner is a practitioner whose knowing is not only rational and cognitive but also embodied in action and for whom reflection is critical to practice. Schön characterizes a reflective practitioner as one who emphasizes problem-setting (in addition to problem solving) activities, reasons about the problem and solution through experimentation, and fluidly engages in a variety of representations (both inscription representations and language representations) to experiment with the problem[6].

According to Schön, the reflective practitioner as designer interactively frames the problem and names the things she/he attends to within this frame, and generates 'moves' toward a solution and reflects on the outcomes of these moves. In this process, the designer functions as both a creator developing a solution and an experimenter trying to understand the

5 **Accreditation Board for Engineering and Technology (ABET)** *Engineering Criteria 2000: Criteria for accrediting programs in engineering in the United States (2nd edition ed.)* Engineering Accreditation Commission, Baltimore (1998)
6 **Schön, D A** The reflective practitioner: how professionals think in action Basic Books, New York (1993)

situation he is creating, hence the notion of the designer as having a 'reflective conversation' with the situation. Through this kind of interaction with the situation, the designer is shaping the situation. As such, Schön's model accounts for the dynamic, cyclic, and unfolding nature of design.

Important features of this model are the concepts of reflection, surprise, and unpredictability. For Schön, reflection is a critical element of professional activity and design. In particular, he differentiates among three types of reflection: reflection-in-action, reflection-on-action, and reflection-on-practice. For the purposes of this paper, we will focus on *reflection-in-action*. For Schön, the act of reflection-in-action is closely tied to the notion of surprise. Periods of reflection-in-action can be triggered by surprises that interrupt the flow of skilled, practised performance, and shift the designer's thinking to a more conscious mode of analysis. Surprises stem from the unpredictability of complex design situations, and the unpredictable nature of these situations encourages 'back-talk'. Back-talk is when a designer engages in a reflective conversation with the materials, a process that may aid in developing a deeper understanding of the design problem.

The reflective practitioner model is well suited for capturing professional activity in which practitioners must grapple with unique, value-laden, and uncertain situations and, from these situations, constructively shape problems that can be solved. As a result, Schön's work has been very influential in professional education. For example, the teacher education and human computer interaction communities have incorporated this theory of the reflective practitioner into their discourse. A search of the ACM digital library for "reflective practitioner" references located 47 references. A similar search of journal articles in the ERIC educational database located 50 references.

As of yet, the reflective practitioner model has not had a significant or broad influence on engineering design and engineering design education. For example, a search of journal articles in the INSPEC database (a database commonly used in engineering) identified only a single reference. We believe that now is the time to bring Schön's work more fully into the domain of engineering design education. In the next section we describe our verbal protocol work on engineering student design processes. In the subsequent section, we discuss mappings between the reflective practitioner model and our empirical results.

2 Previous verbal protocol studies

Because we are strongly interested in promoting a research-based approach to engineering education, we have expended considerable energy

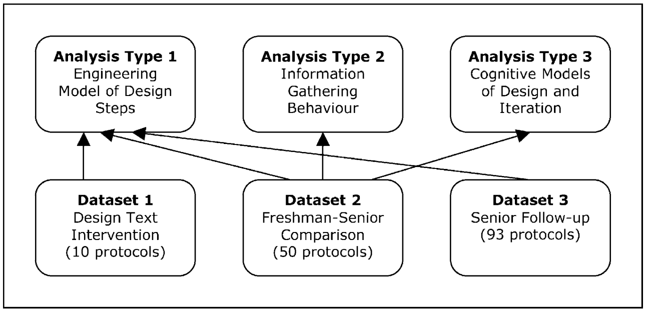

Figure 1 Overview of prior activity—mapping verbal protocol datasets to three different types of analyses regarding engineering student designing

researching engineering student design behaviour. In our previous work, we have used verbal protocol analysis to characterise the design processes of over 100 engineering students. In a verbal protocol experiment, subjects are asked to talk aloud while solving a problem. In our circumstances, the subjects have been undergraduate engineering students and the problems have been open-ended design problems[7].

2.1 Our datasets

Over the past ten years, we have collected three sets of verbal protocol data of engineering students engaged in design activity. These datasets are described below. The problems students were asked to solve ranged in complexity and students' level of familiarity with the problem context. Each set of data has been transcribed and segmented into smaller units[7].

Dataset 1—Design Text Intervention: This dataset consists of ten freshmen solving three short design problems, five of which read a textbook passage about design prior to the design session.

Dataset 2—Freshman–Senior Comparison: This dataset consists of freshmen (24) and seniors (26) solving a 'long' design problem—a fictitious playground.

Dataset 3—Senior Follow-up: This dataset consists of freshmen at the beginning (16) and at the end (16) of their first semester, and seniors (61) solving three 'short' design problems. This dataset also includes 18 sets of within-subject data (i.e., 18 of the 61 seniors were among the 32 initial freshmen).

2.2 General description of the analyses

Using these datasets, we have conducted five empirical studies of student design behaviour (and are currently working on completing a sixth). In each of these analyses, we have characterized the design processes of the engineering students, identified differences in design behaviours between groups of students and within individual students, and interpreted findings in a way that suggests pedagogical implications. As shown in Fig. 1, these

7 **Atman, C J and Turns, J** 'Studying engineering design learning: four verbal protocol analysis studies' in **M McCracken, W Newstetter and C Eastman** (eds) *Design learning and knowing*, Lawrence Erlbaum, Hillsdale, NJ (2001)

analyses having included studying the verbal protocols from the perspective of (a) models of engineering design activity (e.g., design step activities such as problem definition and feasibility analysis), (b) information gathering behaviours, and (c) cognitive models of design and iterative activity. A summary of each of these analyses is provided below.

2.3 Analysis Type 1: Engineering model of design steps

Three analyses (one for each of the three datasets) have focused on looking at student performance through a lens of engineering design models. For these analyses, each segment of the protocol was coded as representative of one of eight activities commonly indicated in models of engineering design: problem definition, information gathering, generating alternatives, modelling, feasibility checking, evaluation, decision, and communication[8]. In all instances, the protocols were double coded and all discrepancies were argued to consensus.

Together, these studies demonstrate that measurable differences exist in student design processes after three interventions: (1) after the first semester of a freshman year[9], (2) after a short term intervention of reading a text book[10], and (3) after completing an undergraduate engineering degree[11,12]. Example findings from these analyses are identified below. These analyses have been summarised in Atman and Turns[7].

- Number of transitions—significant for all datasets
- Time spent—significant for the Senior Follow-up and Design Text Intervention datasets
- Time spent in decision step—significant for Freshman–Senior Comparison and Senior Follow-up datasets
- Transitions rate—significant for Freshman–Senior Comparison dataset
- Number of design criteria considered—significant for the Senior Follow-up and Design Text Intervention datasets
- Progression to Later Stages of Design Process—significant for Freshman–Senior Comparison dataset

2.4 Analysis Type 2: Information gathering behaviour

For this analysis type, Dr Atman and her colleagues analysed how student designers in the Freshman–Senior Comparison dataset gathered and used information. Because the experiment was designed to encourage students to ask the administrator for additional information, it was possible to track the kinds of information explicitly brought into the design activity. Additionally, it was possible to identify and track implicit assumptions made in the verbal protocols. The findings illustrate that (1) seniors gathered more information covering more categories than freshman, (2) seniors

8 Moore P L, Atman C J, Bursic K M, Shuman L J and Gottfried B S Do freshman adequately define the engineering design process? *Proceedings of the Annual Conference of the American Society of Engineering Education* (1995)

9 Mullins, C A, Atman, C J and Shuman, L J 'Freshman engineer's performance when solving design problems' *IEEE Transactions on Education* Vol 42 No 4 (1999) 281–287

10 Atman, C J and Bursic, K M 'Teaching engineering design: can reading a textbook make a difference?' *Research in Engineering Design* Vol 8 No 4 (1996) 240–250

11 Atman, C J, Chimka, J R, Bursic, K M and Nachtmann, H N 'A comparison of freshman and senior engineering design processes' *Design Studies* Vol 20 No 2 (1999) 131–152

12 Atman C J, Turns J, Horn M and Adams R Engineering students solving design problems: cases from a within-subjects verbal protocol study *American Education Research Association National Conference*, Seattle, WA (2000)

made more assumptions than freshman, and (3) both groups failed to collect important types of information, such as legal and maintenance issues[13].

2.5 Analysis Type 3: Cognitive models of design and iteration

For this analysis type, two kinds of cognitive models of design activity were explored. In the first study, Dr Adams developed a cognitive model to empirically explore and identify iterative processes in design activity[14–16]. Although iteration is considered to be an integral part of design activity and a natural attribute of design competency, there is little research that explicitly operationalises iterative activity. To explore iteration in design, Dr Adams analysed 32 protocols from the Freshman–Senior Comparison dataset (a subset of 16 freshmen and 16 seniors) for the playground design problem. From this analysis, it was found that iteration represents a significant portion of design activity, iterative activity occurs throughout the process, and seniors engaged in more effective iterative behaviours. In particular, seniors were significantly more likely to (1) spend time iterating, (2) have more iterations, (3) transition through more design steps in an iteration, (4) spend more time in transformative iterative processes, (5) spend more time in iterations triggered by self-monitoring and examining activities, and in iterations that resulted in revisions coupling problem and solution elements, (6) spend more time in iterative design cycles that coupled problem scoping and solution development activities, and (7) be aware of iterative strategies and their own processes for monitoring, detecting, and resolving design failures.

In the second study, a subset of three protocols from the Freshmen–Senior Comparison dataset was analysed to characterise how subjects talked about their evolving solution[17]. In particular, Dr Turns examined students' use of structural, functional and behavioural descriptions of their evolving design solutions (guided by the work of McNeill et al.[18], Gero et al.[19], and Rosenman and Gero[20]). One hypothesis in the literature is that expert designers will use functional descriptions early in the design process to keep themselves from committing to a particular solution instantiation. In this pilot study, we explored this issue by analysing the design protocols of three subjects, one each of high, medium and low quality final solutions. We observed that (1) references to structure are pervasive, (2) references to structure seem to increase during later periods in the design process, (3) the two subjects who had lower quality solutions had periods of sustained reference to structure, (4) references to behaviour are infrequent for all three cases although some clustering of references exist, and (5) subjects who had high quality scores talk about function early in the design process,

13 **Bursic, K M and Atman, C J** 'Information gathering: a critical step for quality in the design process' *Quality Management Journal* Vol 4 No 1 (1997) 60–75
14 **Adams R S and Atman C J** Cognitive processes in iterative design behavior *Proceedings of the Annual Frontiers in Education Conference*, November, San Juan (1999)
15 **Adams R S and Atman C J** Characterizing engineering student design processes: an illustration of iteration *Proceedings of the Annual Conference for the American Society of Engineering Education*, Charlotte, NC (2000)
16 **Adams R S** *Cognitive Processes in Iterative Design Behavior* Dissertation: University of Washington (2001)
17 **Turns J, Atman C J and Sidiadinoto I** Students use of functional, behavioral and structural terms to describe artifacts during design *American Society of Engineering Education National Conference*, Charlotte, NC (1999)
18 **McNeill, T J, Gero, J S and Warren, J** 'Understanding conceptual electronic design using protocol analysis' *Research in Engineering Design* Vol 10 No 3 (1998) 129–140
19 **Gero, J S, Tham, K W and Lee, H S** 'Behaviour: a link between function and structure in design' in **D C Brown, M Waldron and H Yoshikawa** (eds) *Intelligent computer aided design*, Elsevier Science Publishers, North Holland (1992)
20 **Rosenman, M A and Gero, J S** 'The what, the how, and the why in design' *Applied Artificial Intelligence* Vol 8 No 2 (1994) 199–218

whereas subjects who had low quality scores talk about function intermittently.

3 *Engineering students as reflective practitioners?*

The premise of this paper is that Schön's model of the reflective practitioner can provide a lens through which we may interpret the results of our prior analyses, identify possible measures of reflective practice behaviour, and determine new types of analyses for our existing datasets (see Fig. 1).

Schön's work suggests two important descriptors of a reflective practitioner: recognising the importance of problem setting and listening to a situation's back-talk. In this section, we describe these two descriptors and discuss mappings between our data, our existing analyses, and these descriptors.

3.1 *Recognising problem setting as an important challenge*

Schön makes the point that when engaged in design activity, a reflective practitioner behaves as if problem setting is as important as problem solving. This is particularly true in complex and ambiguous situations.

How can we operationalise a definition of problem setting? One aspect of problem setting is how a problem solver defines the problem—specifically, how broadly does the problem solver perceive the problem? In our data we have captured the 'broadness' of problem perception by analysing (1) design factors subjects list as important, and (2) information that problem solvers gather as they engage in solving a design problem. A related aspect of problem setting is the distribution of time spent in problem setting activities during design problem solving. In the following three sections we present empirical data to describe each of these problem setting attributes.

3.1.1 *Listing design factors*

In one of the three problems in the Senior Follow-up Study (dataset 1) we posed the following problem to the subjects:

Over the summer, the Midwest experienced massive flooding of the Mississippi River. What factors would you take into account in designing a retaining wall system for the Mississippi?

Each of the factors that students generated was categorised with respect to two codes: 'Parts of the System' and 'Types of Knowledge'. Elements of these codes were generated so they could display the breadth with which

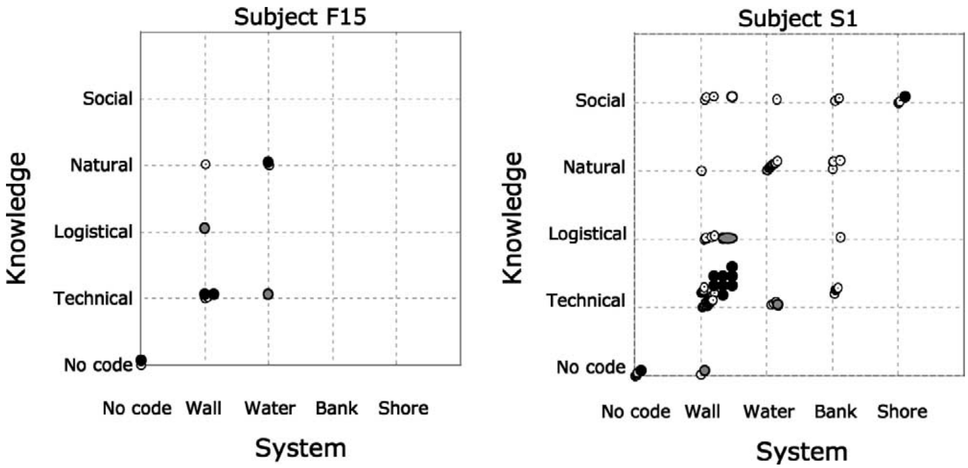

Figure 2 Breadth of design factors listed by a freshman (F15) and a senior (S1) subject solving the Midwest floods problem

a subject has characterised the design factors. In the System code, the factor is coded as to whether it refers to the wall, water, bank or shore. In the Knowledge code, the factor is coded as to whether it refers to a technical, logistical, natural or social element of the problem. To illustrate, the statement "I have to take into account how many times a year it's going to overflow" is assigned the codes 'water' and 'logistical'. The two-dimensional intersection of the coded factors (as demonstrated in Fig. 2) represents a *problem definition space*.

The results of the analysis indicate that graduating seniors both list more factors ($p<0.0001$) and cover a larger portion of the problem definition space ($p<0.0001$)[21,22]. These results are portrayed graphically for two subjects in Fig. 2—a senior who was very broad in the factors listed and a freshman whose data is representative of the freshmen subjects. In this figure each dot represents a factor stated by the subject.

The senior student data in Fig. 2 represents a student who comes close to a "goal state" for graduating students. This student lists many factors, and these factors cover a large portion of the possible problem definition space. In contrast, the freshman student data that is presented shows a student who does not list many factors, and is much more limited in the coverage of the problem definition space. These data are informative, however they represent a listing of factors that a student thinks are important instead of actual observations of what factors are included in the solution of a design problem. The next aspect we consider addresses this potential problem.

21 **Bogusch L, Turns J and Atman C J** Engineering design factors: how broadly do students define problems? *Frontiers in Education Conference Proceedings* (2000)

22 **Rhone E, Turns J, Atman C J, Adams R, Chen Y and Bogusch L** Analysis of senior follow-up data: The midwest floods problem—addressing redundancies in coding *Center for Engineering Learning and Teaching (CELT) Technical Report #01-05*, University of Washington, Seattle (2001)

3.1.2 Gathering information

Another measure of the breadth with which a problem solver approaches a problem is the amount of information that is gathered while a problem is being solved. In the Freshman–Senior Comparison (dataset 3) we asked subjects to design a playground for a fictitious neighbourhood. Subjects took between 2 to 3 hours to solve the problem. They were able to request information that they needed as they developed their design solution. The number and type of information requests were compared between the freshmen and senior subjects[13].

We found that the seniors gathered significantly more pieces of information (p=0.014) and covered more categories (p=0.006) than did freshmen. The percent of subjects in each group requesting information in each information category coded is presented in Fig. 3. While these plots show that the seniors do collect more information and cover more categories, they also show that a large fraction of the graduating seniors do not consider some important elements of the problem such as maintenance and liability issues.

3.1.3 Time spent in problem setting activities during designing

The previous two aspects illustrate the breadth with which engineering students define the problem they are solving. Another important element to the process of design problem solving is the distribution of these kinds

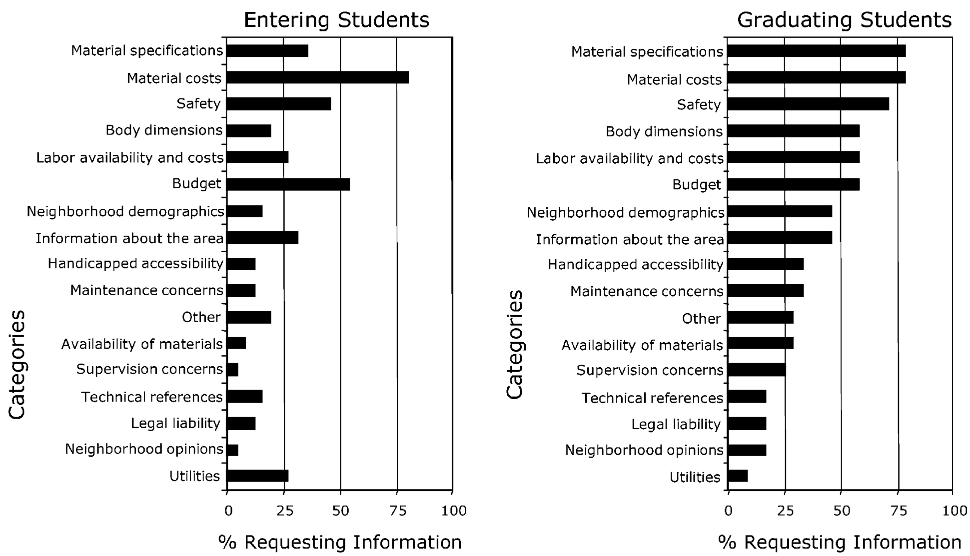

Figure 3 Information requested by freshmen and senior subjects designing a playground

of problem setting activities throughout the process. Our data suggests that problem setting is actually a dynamic activity that occurs throughout the task. The way problem setting is distributed among other aspects of design problem solving can differ dramatically across engineering students. This can be illustrated with data from the Freshman–Senior Comparison (dataset 3) that was described in the previous section on information gathering.

The verbal protocols that the students gave as they designed a playground were coded with respect to time spent in design process activities. The codes were developed by surveying freshmen engineering design textbooks to identify design activities taught to engineers[8]. These activities were synthesised into the following set: problem definition (PD), gather information (GATH), generate ideas (GEN), model (MOD), feasibility analysis (FEAS), evaluation (EVAL), decision (DEC), and communication (COMM).

The data can be presented in a timeline to display how a subject allocates time across the coded design activities. Timelines for two subjects are displayed in Fig. 4. A tick mark on a line indicates that the subject spent time in that design activity. These timelines represent a successful senior who designed a high quality playground and an average freshman who did not design a high quality playground. These particular timelines illustrate one of the findings—that seniors transition more frequently among design activities than do freshman (p=0.002)[11].

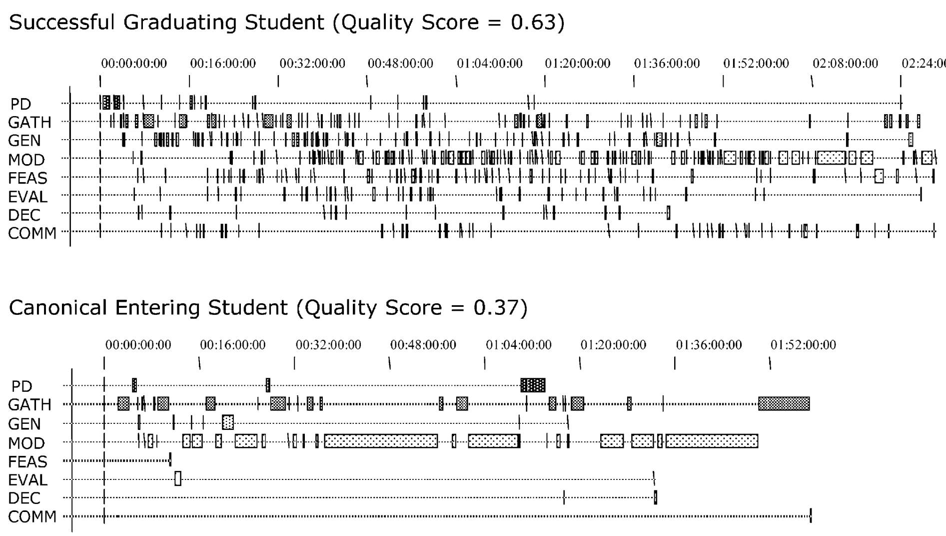

Figure 4 Design activity timelines for a freshman and a senior subject designing a playground

The timelines also show processes that are qualitatively quite different. The senior transitions frequently, returning often throughout the design process to the problem setting activities of problem definition and gathering information. This is in contrast to the freshman who spends large chunks of time in each of the activities that are visited, displaying far fewer transitions among the design activities. The transitions displayed by the senior data is suggestive of a kind of conversation between problem setting and problem solving activities—perhaps suggesting a *structure* for successful reflection-in-action.

3.1.4 Relating our data to problem setting

Schön[6] states that problem setting is a "recognised professional activity" (pp. 18). In our data we have found that students who have more experience (seniors) display more problem setting behaviours, and therefore are potentially acting more like professionals. Second, effective problem setting *matters*. In the Freshman–Senior Comparison Study (dataset 3), each of the elements of effective problem setting we discussed (number of information requests, number of categories of information requests and number of transitions) is correlated with high quality solutions. These measures of breadth of problem perception (list of factors to consider and amount and type of information gathered) are one way to indirectly capture problem setting in empirical data.

3.2 Effectively listening to the 'back-talk' of the situation

Another important characteristic of the reflective practitioner is that she/he listens to the 'back-talk' of the design situation and reacts accordingly. From a process perspective, Schön talks about how the designer conducts experiments that push the solution forward but then is open to discover irregularities in the situation that suggest further clarification of the problem. As seen in the previous section, transition activity is suggestive of the structure of this process: more advanced students and those who produced higher quality designs were more likely to 'move' to different design activities frequently throughout the task. In this section, we probe deeper into this behaviour by exploring the mechanisms and outcomes of iteration in design activity. We begin by first identifying characteristics of reflective practice and then demonstrating how these characteristics may map to measures of iterative activity.

To begin, Schön describes reflection-in-action as a shift that happens when a surprise interrupts the flow of skilled, practised performance, and the designer shifts to a more conscious mode of analysis. This differs from knowing-in-action because it is closely tied to an element of surprise that stimulates reflection in such a way as to influence action. Key characteristics of this activity include[6]:

(1) it is triggered by an unexpected event;
(2) it produces a shift in a mode of analysis that stimulates the practitioner to engage in a reflective conversation with the situation's back-talk;
(3) it results in a process of spiralling through stages of "appreciation, action, and re-appreciation" (p. 132) that may prompt a change in understanding or yield new discoveries; and
(4) it is marked by a willingness to experience an unexpected event: "a practitioner allows himself to experience surprise, puzzlement, or confusion in a situation which he finds uncertain or unique" (p. 68).

In comparison, design may be described as an iterative process in which the designer incrementally and simultaneously advances upon both a representation of the problem and a final solution. In design, iterations may mark an awareness that neither the problem nor the goals are well-defined, and are the result of attempts to reconcile ambiguities and contradictions. Each time an adjustment is made, the designer must analyse not only the effects of the change, but re-evaluate the design task. In one of our studies we sought to empirically explore iteration in design[16]. A subset of students was drawn from the Freshman–Senior Comparison dataset (16 freshmen and 16 seniors) in which subjects designed a fictitious playground. For our purposes, iteration was modelled as a goal-directed activity in terms of underlying cognitive mechanisms that identify how iterations begin and end[15]. Here, goal-directed refers to a purposeful progression through stages of the design process to revisit and address design issues.

The following examples provide some insight into how measures of iterative activity may be characteristic of listening and responding to a situation's back-talk. In particular, we focus on describing the underlying processes of iteration and where they occur in relation to design process activities.

3.2.1 What is the underlying process of iteration?

From our analysis, the central cognitive activities triggering an iteration included self-monitoring, clarifying, and examining activities. Observations of self-monitoring activities include reviewing and evaluating progress, self-monitoring understanding, and searching for or being open to finding potential solution failures. Examples of clarifying activities were efforts to interpret the meaning of ambiguous problem requirements or identify other important criteria. Examples of examining activities were efforts to determine solution behaviour and feasibility. In addition, iterations were most likely to result in redefining problem elements and coupling revisions across problem and solution elements. Redefining problem elements involved providing greater detail or introducing new criteria into the design task. In comparison, coupled iterations involved revising an understanding of the problem in the context of developing or revising solution elements—or, from the perspective of Schön, engaging in a conversation across problem and solution spaces.

Characteristics of these coupled iterations include (1) gathering information on a just-in-time basis, (2) qualifying or quantifying problem requirements by justifying or describing how a solution functions or behaves, and (3) evaluating solutions while clarifying evaluation commitments from multiple perspectives. An example of adopting a just-in-time strategy of gathering information is gathering technical information such as material specifications or the average weight of children (aged 1 to 10 years old) to select a chain for hanging swings that can withstand a maximum expected load. Observations of justifying design decisions while interpreting attributes of the problem requirements suggest that students who had higher quality scores were more likely to evaluate the appropriateness of their decision. For example, a student may rationalise that a modification to a slide design, such as a handrail, may reduce the level of accidents related to children falling over the side but stop short of evaluating whether or not this is an appropriate or useful modification. In comparison, another student may rationalise the layout of their playground equipment in terms of how each placement encourages opportunities for parents to have an unobstructed view of their children. This, in turn, may prompt the designer to clarify an aspect of the safety requirement stated in the problem and then evaluate the location of each playground activity from the perspective of parents.

Iterations related to continually evaluating solution elements in multiple contexts and levels of abstraction were often triggered by self-monitoring activities. An example is when a student purposely reviews the problem requirements to search for any design issues not previously addressed and determines that they have not addressed the requirement that the playground equipment must "remain outside". This prompts an effort to interpret the requirement and modify the solution to include skid-resistant materials and other related safety components. Another example is a student evaluating their solution to determine if it meets the handicapped accessibility requirements and in the process defining the evaluation commitment as facilitating movement between different activities for people in wheelchairs or using crutches. This new definition then becomes an objective rule that aids the student in evaluating and improving the quality of their overall solution.

As seen in these examples, coupled iterations may be the result of a dialectical interaction between representing the problem and specifying the solution. In these circumstances, problem and solution elements are mapped through levels of abstraction. As illustrated above, the predominant mapping mechanisms consist of self-monitoring understanding and progress, clarifying the nature of the task within the context of developing solutions, and continually evaluating solutions while clarifying evaluation commitments. These processes were more likely to be classified as transformative processes in which new understandings were generated and synthesised into the design task. Overall, subjects spent more than two-thirds of their total iteration time in transformative processes rather than introducing small (diagnostic) revisions. These transformative processes represent a conceptual shift in thinking and as such may facilitate and mark design learning.

Synthesising across these findings, it appears that these transformative processes are indicative of what Schön refers to as engaging in a situation's back-talk. As Schön[6] notes:

> [if] they are good designers, they will reflect in action on the situation's back-talk, shifting stance as they do from 'what if?' to recognition of implications, from involvement in the unit to consideration of the total, and from exploration to commitment (p. 103).

These moves prompt the designer to become aware of a whole new idea that "sets criteria for further designing"[6].

As shown in Fig. 5, seniors were more likely to engage in iterations trig-

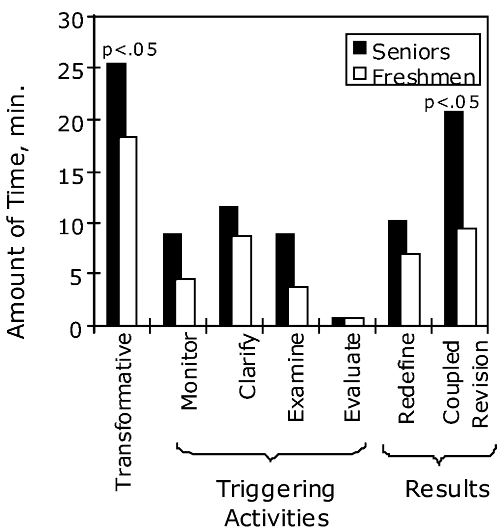

Figure 5 Differences in time spent in cognitive activities and processes in iterative activity for freshmen and seniors designing a playground

gered by self-monitoring, clarifying, and examining activities; and were more likely to have iterations that resulted in coupling revisions across problem and solution elements ($p<0.05$) (see Fig. 5). Seniors were also more likely to spend time in transformative iterative processes ($p<0.05$). In addition, each of these activities positively correlated with measures of quality and information gathering behaviour. In particular, the amount of time in transformative processes significantly correlated with the amount of information gathered ($p<0.05$) and with the number of transitions ($p<0.05$). This data suggests that not only are seniors more likely to engage in iterative activities that may be indicative of reflective practice, but that these activities are associated with indirect measures of effective practice.

3.2.2 *Where do iterations occur?*

From the perspective of an engineering design model, our findings illustrate that the bulk of iterative activity begins in conceptual design activities (e.g., modelling, feasibility, evaluation) and are directed towards problem scoping activities (e.g., information gathering). Again, this suggests that the predominant characteristic of iteration is a dialectic process across representational spaces. Further analysis clarifies that these kinds of iterations are associated with revisions across problem and solution elements (e.g., coupled revisions) and are likely to be transformative in nature.

Examples of where in a model of the design process iterations occur are provided in Fig. 6 for a senior with a high quality score and a high level of iterative activity (Fig. 6(a)) and a canonical freshman with a low quality score and a low level of iterative activity (Fig. 6(b)). These diagrams represent activities in a model of the design process[8]. The diagrams start with Problem Definition and move clockwise towards Information Gathering,

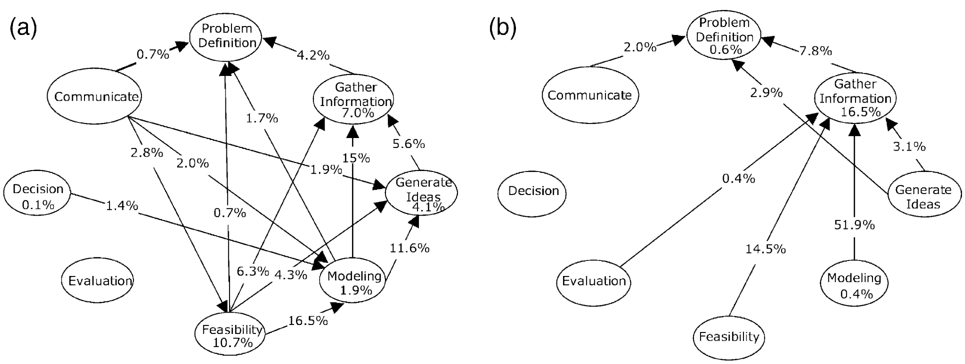

Figure 6 Iterative transition diagrams for a senior (a) high level of iteration (45.1%) and high quality score (0.708), and a freshman (b) low level of iteration (19.5%) and low quality score (0.375), designing a playground—transitions represent moves among design step activities

Generate Ideas, Modelling, Feasibility, Evaluation, Decision, and Communication. Because the subjects in this study were provided with the problem need and the design task concluded in a paper design, Problem Need and Implementation activities are not included in these diagrams. The arrows in the diagram signify an iterative move as triggered during one design step activity and directed towards another design step activity. For each type of iterative move the percent of time spent in that activity as a portion of the total iteration time is provided.

As shown in Fig. 6(a), this senior exhibited a high level of iterative moves. In particular, this student spent a considerable amount of time iterating from conceptual design to problem setting activities. In comparison, the canonical freshman (see Fig. 6(b)) had considerably fewer iterative moves across design step activities and overall spent less time in iterations coupling conceptual design and problem setting activities. An interesting trend is that the senior in Fig. 6(a) also iterated from the Communication design step to conceptual design steps (e.g., modelling, feasibility). The amount of time spent in this kind of activity was found to positively correlate with a quality score for meeting the required elements stated in the problem, and for the transition from Communication to Generate Ideas this was significant at $p<0.05$. Observations of these iterative cycles suggest a process of clarifying the nature of the problem and identifying possible design failures while writing down or sketching elements of a design solution.

Overall, seniors were more likely to spend time iterating from conceptual design to problem setting activities or from communication to conceptual design activities, however these differences were only weakly significant ($p<0.1$). In addition, these iterative moves tended to correlate positively with design success. Seniors were also significantly more likely to engage in more kinds of iterative moves, and the number of iterative moves correlated positively with design success ($p<0.05$).

The iteration diagrams in Fig. 6 illustrate that information about the problem is assimilated throughout the design process. This suggests that the subjects, particularly the seniors, are continuously monitoring their activity and may be more willing to revisit earlier design decisions. At the conclusion of the design task subjects were provided with a description of the design process and asked to comment. Seniors, in particular those with higher quality scores and higher levels of iterative activity, were more aware of iteration in design and described their own iterative processes as adopting a flexible strategy for monitoring, detecting, and reconciling failures. Seniors were also more willing to express a belief that failures could exist. For example, one student commented, “the problem can always change no matter how far you are into the process. It can definitely change . . . might even change your goals". Similarly, another student commented that ". . . when you're solving something you find something else . . . maybe I gotta go back and get information on that . . .", and another that "your problem definition isn't written in stone, as you go on definitely you might have to go back and modify it as you find out more information".

3.2.3 Effectively listening to a situation's 'back-talk'

Overall, this model of iterative activity appears to map well to Schön's theory of reflective practice. Schön[6] describes the process of reflection-in-action as beginning with an unexpected event that triggers a shift in a mode of analysis that stimulates a reflective and transformative conversation with a situation's back talk. As such, the reflective practitioner:

> ". . . does not keep means and ends separate, but defines them interactively as he frames a problematic situation . . .. Because his experimenting is a kind of action, implementation is built into his inquiry" (p. 68).

In our data, we found that central features of iterative activity map well to elements of this process. More specifically, the bulk of iterative activity resulted in coupled revisions across problem and solution elements, and these events were predominantly triggered by self-monitoring, clarifying, and examining cognitive activities. Coupled revisions were most likely to be classified as transformative processes and may be described as dialectic processes across representational spaces that aid mapping of solution elements to problem requirements. As such, these processes may be indicative of effectively listening to and responding to a situation's back-talk, and are believed to facilitate and mark design learning[16]. In addition, we found that seniors spent more time engaged in these behaviours and that many of these behaviours correlated with measures of design success. Therefore, these measures of iterative activity may be one way of directly capturing the underlying mechanisms and outcomes of reflection-in-action in empirical data. This, in turn, may help explain why iterative activity constitutes effective design practice.

4 Discussion

We began this analysis with three questions in mind:

(1) How do we measure reflective practitioner behaviour in engineering students?
(2) To what extent do engineering students behave as reflective practitioners?
(3) In what ways are seniors more like reflective practitioners than freshmen?

We explored these questions by revisiting our empirical studies through an interpretive lens of Schön's theory of reflective practice. Our overarching goal has been to use this theory to greater understand engineering students' emerging design abilities.

Across the empirical studies discussed in this paper two trends emerge: problem setting and engaging in a reflective conversation across problem setting and problem solving activities are important features of effective design practice. Underlying these trends is a predicament typical of complex and ambiguous design tasks—information cannot be gathered meaningfully unless the problem is understood but you can't understand the problem without gathering information about it. As Schön notes, a process of reflecting in action provides one means for filling this gap. It allows new requirements to emerge (and be synthesised) during solution development that cannot be adequately identified or pursued until portions of the system have been designed.

Secondly, this analysis provides insight into both indirect and direct measures of problem setting and effectively engaging in a conversation with a situation's back-talk. As such, Schön's theory of reflective practice helps explain why these measures are indicative of effective design practice. Indirect measures of problem setting include measures of the breadth of a students' perception of a design problem such as the number and kinds of design criteria considered and the number and kinds of information gathered for solving a design task. For both of these measures, senior engineering students were significantly more likely to consider more issues. For the case of information gathering, the breadth of information gathered positively correlated with design success for students designing a fictitious playground. Our data also suggests that transition activity and how time is distributed across design activities may be an indirect measure of the structure for successful reflection-in-action. Again, for this measure there were significant differences between senior and freshmen engineering students, and the number of transitions correlated with design success.

Measures of coupled iterative activity may be one way of directly capturing the underlying processes of effectively engaging in reflective practice. More specifically, measures of coupled iterative activity and transformative iterative processes map well to characteristics of conversing with a situation's back-talk. In addition, seniors were more likely to spend time in these activities and time spent in these activities generally correlated with design success. From the perspective of iteration, these activities were described as a dialectical interaction across problem and solution spaces and may be a marker of design learning.

Overall, this exercise provided a wealth of insights into characterising reflective practice and gave us a new way to analyse our empirical data. Many of the results discussed in this paper have provided another theoretical framework that supports our earlier findings, as well as why certain behaviours may be characteristic of effective practice or design expertise.

Acknowledgements

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Discussion

(Discussant: Peter Lloyd, School of Industrial Design Engineering, TU Delft, Netherlands)

PL The amount of data that you have collected here is impressive. I liked the way you focused on very specific issues by operationalising concepts and doing statistical analyses. You are interpreting your results through a Donald Schön lens, but I thought you carried out your studies in a way more fitting to Herbert Simon—analytical and focused. Why did you choose this approach?

RA I would definitely say there was a lot of Herbert Simon embedded in the way we organised the research, he's just not in the way we tried to stand outside the results. One of the things we struggled with was finding ways to translate our research findings into something useful for engineering educators, and we resonated with Schön in finding a way to do that. He provides a very nice umbrella under which we can talk about these things. It's a little more accessible. Also, a goal of this particular paper was to identify measures of reflective practice that could be useful for informing education practice.

PL Schön often mentions what he feels good designing to be: the 'conversation with the situation' should be reflective, he also mentions the idea of 'repertoire' a lot: good designers have a large repertoire and a large range of 'tools' at their disposal. Now in some sense Schön's theory guarantees your results. Graduate students will obviously have a bigger repertoire than freshmen and will therefore, according to Schön be better designers.

RA Having so much data meant that we could aggregate it somewhat, and talk about it a little bit further away than the individual. On the one hand that's good, on the other not so good. In the transition diagrams (Fig. 6) there were certainly a number of freshman who in the larger group displayed the kinds of behaviours that looked like that, but not in the aggregate. The other thing is that in terms of what happens to these students as they're freshmen and as they're seniors we can't necessarily say that they have a lot more design experience, we can't necessarily say that they were good design experiences that helped them. What we can say is that they did a lot of coursework. A lot of students take control of what they do, in cooperative education experiences and internships, so it's a difficult decision to say let's look at individual students and look at things very deeply and say for students that have these kinds of experiences we can see these kinds of behaviours.

PL I like your comparative approach: the seniors with the freshmen, the novices with the experts—I think Fig. 4 is striking—what I was interested in was within the subject groups what were the good designers doing and what were the bad designers doing? If you average out the good design and the bad design to be mediocre design for the two groups would it not have been better to say OK these are similar people, we accept that they have this knowledge and repertoire but there are still these differences and the good designers seem to do this and the bad designers seem to do this . . .?

RA We didn't say as much about good and bad designs. What I will say is that the quality score that we used is an aggregate: did they address the problem that was stated? Did they identify what would be considered as more expert issues? The answer might be easier to find in the iteration data where you can break it down. One of the things that comes out of the iteration data is that it's not necessarily good or bad solutions, it's more like good or bad revisions, so what you see is the coupled activity supports better revisions, the students are sitting there, making a change to their solution and in that process they are justifying how it relates back to the problem. Justifying it, evaluating it, and clarifying what that means. They may say: 'Oh yes, maybe that's not such a good modification, it really should be this way'. If it's less coupled activity the students are more likely to say: 'I'm just going to change x, I'm going to add 6 tyres and 12 sliders'. It probably doesn't take much to realise that in a small playground area there could be a better decision. There was also some evidence of good revisions that were just re-conceptualising, thinking about the problem, and those tended to be associated with the students who had more technical knowledge.