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Assessing the design of a rapid product design cycle activity that develops student understanding of engineering design and professional practice

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Abstract

This paper analyzes the efficacy of a rapid, interdependent design sequence on student learning and engagement. The Rapid Product Design Cycle (RPDC) activity takes students through a three-part waterfall design sequence – problem formulation, conceptual design, and detailed design. Our objective was to give the students an appreciation of the challenges faced by interdependent teams across multiple different design stages within tight time constraints, and to encourage design work under the constraining pressures of time and stakeholder expectations.

This paper first details the design of the RPDC activity, and then examines the administration and logistics, assessment, student engagement and learning, and student response to this highly accelerated product design cycle. The examination of the activity pays specific attention to the challenges posed by a high frequency of cognitive disruptions (3 different design tasks in 5 weeks) compounded by the requirement of working in small teams.

1. Design Context – Introduction

A core premise of Praxis is that the perspectives, terminology, and tools of "engineering design" are transdisciplinary. In keeping with this premise, this engineering education paper has been structured as an engineering design report and uses engineering design terminology. Selected headings include both design-focused and education-focused terminology to assist the reader in navigating this structure.

Institutional and Program

The University of Toronto is a large, publicly funded, research-intensive Canadian university. The Faculty of Applied Science and Engineering offers undergraduate and graduate engineering programs, and admits approximately 1300 undergraduate students per year into one of 10 programs. All of these programs require that their students take a capstone engineering design course in their senior year, and a cornerstone engineering design and communication course in their freshman year.

Our program, the Division of Engineering Science, admits approximately 320 undergraduate students each year and is distinguished from the other programs pedagogically, structurally, and in the destination of its graduates. The Engineering Science pedagogy privileges foundational principles and breadth of application, and expects that students will engage in additional exploration beyond that presented in the classroom. The program is structured such that all students take a common two-year foundational curriculum, followed by a two-year specialization in an engineering discipline. Approximately 50% of the students pursue an advanced degree. The remaining students tend to seek employment in entrepreneurial or consulting organizations.

Nine years ago, we established a series of foundational design and communication courses known as Praxis. These courses were tasked with preparing students to practice engineering design in their other foundational courses, in any of the areas of specialization available to them, in their summer and internship experiences, and in their capstone design courses. The pair of cornerstone courses are in continuous (re)development and this paper reports on the design of a new assignment in the first course of the series.

Course

The Praxis courses are fully integrated engineering design and communication courses composed of lectures and design studios. The teaching team comprises two faculty member instructors and approximately 10 teaching assistants and sessional lecturers. Engineering design and communication are integrated in all elements of the course, with discipline-specific instructors present concurrently in lectures and studios. In partnership with a faculty organization focusing on engineering leadership education, the courses also encourage students to begin to develop their unique individual identities as engineers and designers.

The first Praxis course is composed of three activities: a two-week household product reverse engineering and improvement activity, a two-week bridge inspection and improvement activity, and a five week major design activity. Since the course was first designed, this final design activity been overhauled three times. This paper describes the design of the current, fourth iteration of the activity that was developed for the 2012-13 academic year.

2. Problem Statement – Developing a Meaningful Assignment

Our challenge can be understood as a straightforward educational design problem: design a five week design activity that provides freshman engineering students with a first university-level design experience in which they develop a foundation for their practice as engineering designers and communicators.

3. Design Requirements – Theoretical and pedagogical foundations

The Praxis course sequence, and constituent activities, have been based on a set of foundational theories and models based in research in the areas of teaching and learning, engineering design, engineering communication, and teamwork. These theories and models are analogous to the requirements in an engineering design project.

High Level Requirements – Course pedagogy and model of engineering design

Four major conceptual frameworks inform the Praxis courses: Vygotsky's Zone of Proximal Development, constructivism, design theory, and approaches to active learning. The overriding goal of Praxis is to support each student as they construct a unique, personalized approach to engineering design and communication.

Vygotsky's Zone of Proximal Development (ZPD) offers the foundational theory to guide the changes in requirements and expectations within and across each deliverable and activity. Core to the contemporary application of ZPD are the concepts of scaffolding and internalization.[6,7] Scaffolding refers to the support provided by an instructor as a student attempts a challenge that they cannot complete unaided (e.g. using only their internalized understanding). Students should be continually challenged to complete tasks that they cannot complete unaided, but that they should be capable of completing with support (in the form of scaffolding).[7] In a complete scaffolding learning exercise, the scaffold is removed as the students learn such that they work with increasing independence.

Internalization models learning as a continuous process of (re)constructing understanding based on new experiences and information. It is a precursor to the constructivist theories that we use to understand our students' learning experience. In both internalization and constructivism, students construct their own understanding of their experiences and of the materials they are presented.[1] Such construction asks students to refashion pre-existing beliefs about the topics covered in the course as they receive new ideas, deeper understanding, and novel approaches. To facilitate this, instruction focuses on providing students with opportunities to develop, apply, and reflect on their own conceptions of course materials, subject to ensuring compatibility with the wider engineering profession. Course instructors and instructional materials also avoid imposing particular perspectives, and instead focus on challenging the student's existing perspective and providing alternatives for the student's consideration and incorporation.

The engineering design process model currently used in the courses is an amalgam of the models commonly used in introductory engineering design textbooks.[3-5] The model comprises four stages: Finding; Framing; Diverging; and, Converging. The model is presented as being fractal, in that those same process stages can be applied recursively (e.g. the full design process can be applied to the problem of diverging) and identically at multiple scales and across multiple types (e.g. designing the report that describes the design of the screw used in designing the landing gear...). Choosing a four-step process both reduces the cognitive load on the students, who have less to memorize, and invites them to expand or add additional steps based on their experiences and investigations. The four-stage model allows the "design" problem posed to the student to be both poorly-defined and open-ended.[2] This process provides sufficient detail that it can scaffold students as they grapple with their design problem, and is simple enough that it allows for multiple iterations during a single, 13-week teaching term.

The final set of theories that underlie the courses is an amalgam of cooperative, team-based, active, experiential, inquiry-based, and problem-based learning. There is significant overlap among these concepts, and contention among practitioners and researchers as to their exact definitions and differentiation.[8] However, the core premise is that students work together to socially construct their knowledge through the praxis of experience and reflection to create a deeper understanding than they could have developed individually. As such we have explicitly adopted only the Kolb Learning Cycle (comprising Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation)[9] and have implicitly adopted related elements from the related models of learning.

Mid-Level Requirements – Pedagogy for course activities

Having completed the first course, students in the second course in the series, as well as upper-year design instructors, and students returning from industrial internships, expressed concern that students did not appreciate the difficulties that arise when embodying a conceptual design. They also expressed concern that the students were neither familiar with, nor equally practiced in, the various roles that engineering designers may adopt. Within these courses, both their instructors and the students themselves noticed a common cause of many misunderstandings within design teams. Because students tended to describe their design verbally, in writing, or using simple sketches, rather than in high fidelity graphical or physical form, the potential for misunderstanding and reduced engagement increased. Given this feedback, the third activity in the course was required to embody constructionist (related to, but distinct from, constructivist) and practice-based pedagogy.

Constructionist pedagogy builds on constructionism and suggests that learning is further enhanced when students develop tangible deliverables.[10] Constructionism is traditionally associated with computer science learning, where the tangible deliverable is a working computer program.[10] In the context of engineering design, the tangible deliverables could include physical prototypes of varying fidelities, detailed solid models, detailed engineering drawings (as opposed to conceptual sketches), etc. Such tangible results enable more detailed and precise discussions and critique, both within a team and with instructors. Anecdotally, for some students producing a tangible result may increase motivation.

Practice-based pedagogy, and the related concepts of authentic or situated learning, all suggest that learning is enhanced when it mirrors “real world” practice.[11] This mirroring can include the tasks, resources, and supports provided to, and the deliverables expected of, students, but can also include the environment, both physical and social, in which the learning takes place. Two of the principles that guide the design of such environments, referred to as “practice fields”, were explicitly adopted as requirements for this activity: “Dilemmas are Ill-Structured” and “Support the Learner Rather than Simplify the Dilemma.”[1] The first principle was adopted given its congruence with the current course definition of engineering design; the second because of its congruence with ZPD. Further principles, including "Coaching and Modeling of Thinking Skills," were adopted implicitly.

Detailed Requirements - Learning objectives for the activity

The high level requirements on the design of the activity, in the form of pedagogical and learning theories, were refined into detailed requirements, in the form of specific learning objectives for the activity. These learning objectives were partitioned based on Bloom's Taxonomy of Learning Domains,[12] with an additional domain of "Reflective" added to emphasize the importance of reflection within course and experiential learning pedagogy.

Cognitive Learning Objectives

The cognitive learning objectives are divided more or less equally between design objectives and communication objectives. Those cognitive objectives that focus on engineering design processes are implicitly suffixed with "... using appropriate engineering tools and language." So, they can be expressed as: *Having completed the activity, each student will have*

- Identified and framed an engineering design problem.
- Gathered and structured engineering requirements that describe and codify an identified and framed engineering design problem.
- Generated a variety of design concepts in response to an identified and framed engineering design problem.
- Selected a subset of design concepts from a superset using engineering requirements.
- Identified key elements of a conceptual design and iterated the design of those elements in greater detail.

Those cognitive learning objectives that focus on engineering communication have an implied suffix of "... that are appropriate for engineering design activities." So, *having completed the activity, each student will have*

- Supported their results using both formal (e.g. sourced from textbooks, journal articles, etc.) and informal (e.g. ad-hoc experimentation, observation, etc.) research..
- Documented their design activities using textual representations.
- Documented their design activities using graphical representations.
- Documented their design activities using "physical" representations (e.g. in the form of physical prototypes, solid models, etc.).

The final cognitive learning objective explicitly links engineering design and communication:

- *Having completed the activity, each student will have* applied an engineering design approach to the design of their documentation.

Affective Learning Objectives

The Affective Learning Objectives focus on challenging the student’s assumptions regarding the nature, importance, and experience of engineering design and communication. Whereas the cognitive learning objectives are largely value-neutral, many of the affective objectives link to promoting specific values in the students. *Having completed the activity, each student will have grappled with*

- ambiguity and information that is ambiguous or poorly communicated
- whether to accept an existing result (e.g. framing, requirement, selection, etc.) or whether to “push back” against existing results (e.g. reframe, refine, redefine, etc.)
- the relative value of engineering communication when undertaking an engineering design activity
- the relative value of known design processes when undertaking an engineering design activity
- the complicated and complex nature of engineering design processes
- finding interest in and engaging with projects that are not intrinsically motivated
- applying an appropriate engineering design approach to a variety of traditional and nontraditional engineering activities
- working in a heterogeneous team where abilities and expectations vary

Psychomotor Learning Objectives

- *Having completed the activity, each student will have* assembled a low- to medium-fidelity prototype of a conceptual design

Reflective Learning Objectives

Having completed the activity, each student will have a preliminary answer to the questions:

- “What do I value within engineering?”
- “What aspects of engineering design and communication do I have to improve upon in future courses to ensure broad, baseline competence? ”
- “Of my engineering design and communication skills, which ones will I pursue in greater depth as I pursue further study?”

4. Reference Designs – Existing introductory engineering design activities

Although not mandated by accreditation, many engineering programs in the Canadian and American context have a cornerstone engineering design course. A survey of such courses showed that many have a significant design activity, similar in scope to the one being designed. While each activity is distinct, certain archetypes were identified and considered as reference or candidate designs for this activity. The archetypes are:

- Design a Working Machine or Device That...
- Develop Engineering Design Solutions to this Design Brief
- Develop a Design Brief and Conceptual Solutions for this Client
- Assess and Improve this Engineering Design Case Study

The archetypes, and associated assessments against the activity learning objectives, are summarized in Appendix 1. Note that the assessments in Appendix 1 focus on the pedagogy of the activities but generally do not consider issues of scale (e.g. number of students, number of deliverables, etc.) and logistics (e.g. number of teams, team size, etc.).

Common across virtually all of the specific instances of these activities are detailed prescriptions by the course instructors on process and deliverables. Students are generally expected to follow a specific engineering design process, apply specific engineering design and communication tools, and to document their activities using provided templates. Such prescriptions, regardless if they are justified by reference to external authority or practices, violate the requirements for this activity. Those requirements based on constructivism and on the design of practice fields suggest that students should be given the flexibility to explore alternative processes and representations, so long as they meet the overall objective of being compatible with engineering practice.

5. Alternative Solutions – Previous activities

A description of the previous iteration of this activity can be found in "Modeling an abbreviated product design cycle in a first-year engineering design course." [15]

6. Selected Design – The Rapid Product Design Cycle (RPDC)

A Rapid Product Design Cycle (RPDC) was selected as the design project that best met the objectives of the course and the desired learning outcomes. The RPDC was designed with the primary aims of: (a) pushing students beyond the conceptual design phase of the design process, and (b) simulating a real-world work environment by: (i) increasing the interdependence between student teams and (ii) increasing the students' perceived value of engineering communication.

The RPDC took place in the last five weeks of the course and was divided into three distinct phases: problem formulation, conceptual design, and detail design comprising 11, 12, and 8 days respectively. Each phase was completed in rapid succession by a different team, on a different type of product, Figure 1. No communication was allowed between teams working on different stages of the same project to ensure students invested time in developing quality written communication.

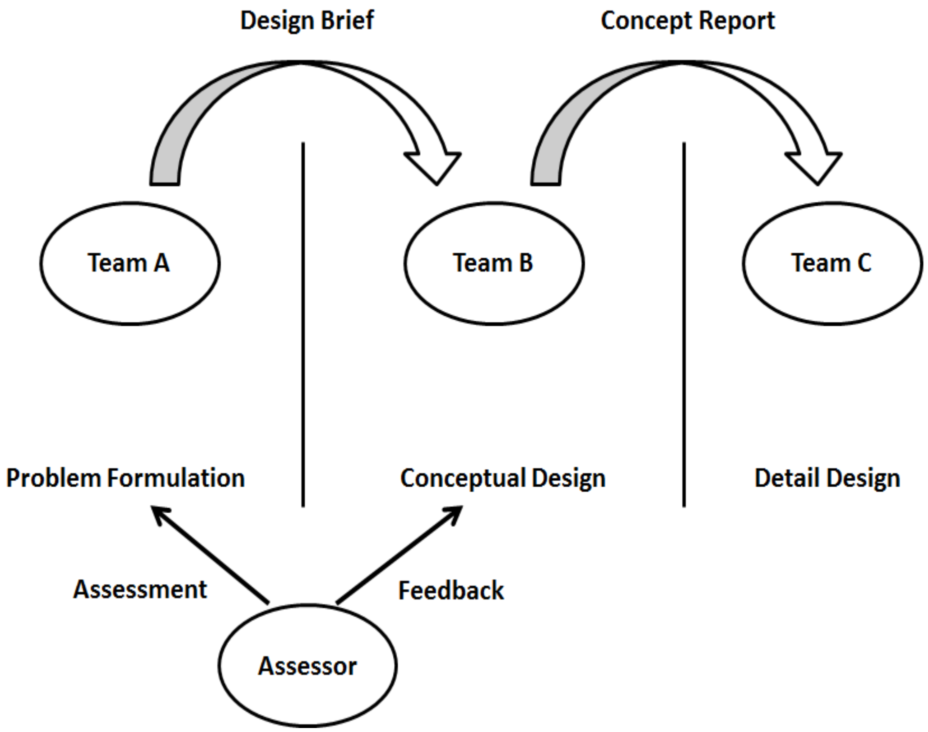

Figure 1. Flow of a product's deliverables during the RPDC. Each written deliverable was "passed over the wall" to the team that would work on the product during the next phase.

The prompt provided to the students to frame the types of problems they were to define was "Design a product that enhances personal efficiency suitable for submission to Kickstarter." In the problem formulation phase students were required to personally define the terms of the prompt and develop a design brief that reframed the problem to their chosen area of interest, identified stakeholders, and presented preliminary design requirements for a type of product to be designed. Design briefs were then swapped between student teams–through a process that ensured the anonymity of the delivering team–to create the starting point for the conceptual design phase. In this phase, students were required to provide any necessary reframing to make the problem workable, complete both ideation and selection activities, and produce a conceptual design, alternative designs and low-fidelity prototype(s). These designs were then swapped between teams as in the previous iteration so that each team had a new type of product to work on for the detailed design phase. Teams were required to select, ideate, and justify three detailed design decisions in support of the conceptual design, and provide a higher-fidelity prototype, solid model(s) and basic engineering drawings of their product. The option to have their solid-model 3D-printed at a small scale was offered to the teams, provided they completed their solid model at least 72 hours in advance of the phase deadline.

The project culminated in a detailed design critique where each student team had the opportunity to see how their design brief had evolved throughout the project. Each team was required to present their detail design work to the team that authored the original design brief and the team that developed the conceptual design for it along with assessors.

Student teams were held constant throughout the cycle so as to minimize any additional cognitive disruptions and to allow students to develop improved team processes by cycling multiple times through re(storming) and (re)norming.[13] In advance of the cycle, students were instructed on the fundamentals of effective teamwork, and provided with tools and techniques for building trust, negotiating conflict productively, and for understanding themselves and others. Students completed the Bolton and Bolton Work Styles Inventory[14] as a starting point for being able to identify what they bring to a team, and what they need from teammates. Students then participated in a 2-hour workshop on team-building and designing that introduced team members to each other, had them develop norms of behaviour for the project, and had them engage in a rapid design activity in response to given model design briefs.

Assignment requirements for each phase provided an additional model for design reports as all assignment information was presented as a design report. As a result, each assignment presented background and stakeholders, as well as the requirements of the deliverable in terms of the objectives, constraints and criteria against which the deliverable would be assessed.

Logistics: Swapping design products amongst teams

Projects were swapped amongst teams so that each team saw a different type of product at each of the three stages, Figure 2. Teams were grouped into clusters of three teams based on the design briefs, that they submitted. Each cluster had three unique types of products to design, e.g. an alarm clock, an umbrella, and a backpack. The goal was to ensure that the students had sufficient variation in the types of products they saw, and that no team had a similar product at two stages of the cycle. Each team worked on one product for one stage of the cycle and then handed off their work to another team to complete the next stage of the design cycle in that product’s development. Student teams were not allowed to communicate amongst each other to ensure that there was a focus on students creating high quality communications. All student submissions were passed between teams without any filtering of exceptionally poor submissions; student grades were adjusted based on the relative improvement of their work over the work that was handed to them. Each student team submitted the following materials: at the problem formulation stage, a design brief; at the concept stage, a report and low-fidelity prototype; and at the detailed stage, a solid model (3D printed where possible) and an oral presentation in the form of a design critique.

To facilitate the movement of deliverables amongst teams, and assessment, each team was given a unique identifier, which was the only identifying information that was used in this cycle. To maintain anonymity no identifying information, including the team's unique identifier, was permitted on any deliverable. To ensure deliverables were routed appropriately one member of the team would submit a digital copy of the deliverable through an online submission system that would track their university login and route the deliverable to the appropriate folder on the server for their team. As a result, the teaching team could simply rename the deliverable and move it to the download site for pickup by the next team in the cycle. Students would then log in to the download site and see only the documents that their team submitted, or were to receive. This allowed for a seamless transition of documents in manner that required minimal resources or manual intervention from the teaching team.

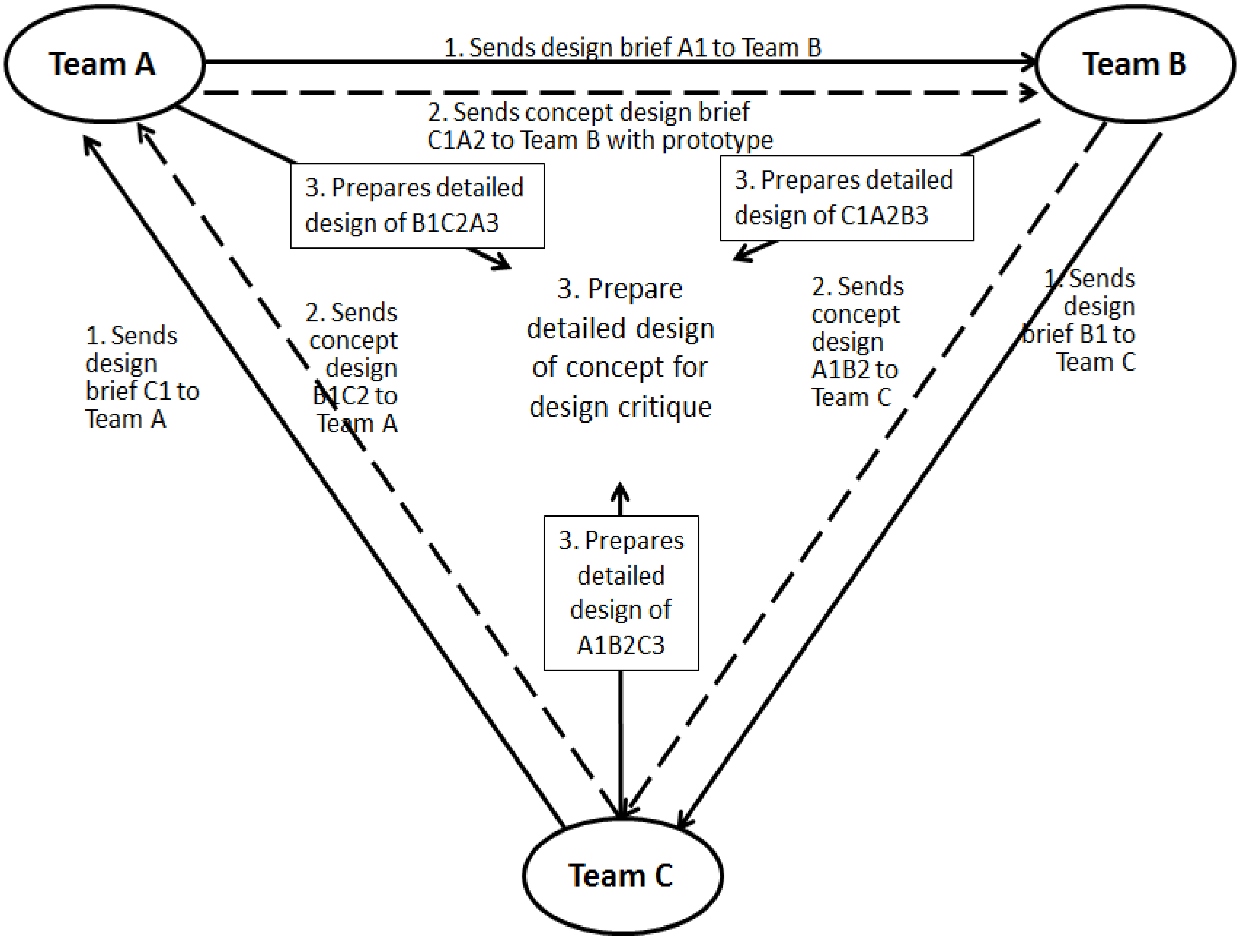

Figure 2. Organization of swaps between project teams. Each deliverable was passed sequentially about the cluster of three teams such that each team worked on a different type of product at each design stage.

For the submission components that were required to be physical, such as prototypes, one member of the teaching team moved them amongst the teams in the cluster, maintaining anonymity across groups. Students submitted these deliverables in their studios with a sticky note denoting the team that the deliverable came from. All deliverables were then grouped together, and sticky notes moved about the deliverables such that they then represented the team that the deliverable was to go to. Once all deliverables' sticky notes were swapped, deliverables were returned to the studios for students to collect. Having the identifying information on a medium that was not permanent and transferable amongst deliverables allowed for physical deliverable swapping to take no more than 30-45 minutes per 100 students.

Student Assessment and Evaluation

Student evaluation had a similar rapid turn-around to the timelines in which students were completing each phases' deliverables, however feedback and assessment on deliverables were approached as separate components of evaluation. Figure 1 demonstrates the directionality of assessor feedback and assessment. Feedback was seen as information that would be useful to the team receiving the deliverable to move it to the next stage of the design cycle, whereas assessment was seen as the evaluation of performance on meeting the requirements of a deliverable submitted; feedback was verbal, formative and for the receiving team whereas assessment was documented, summative and for the submitting team. Feedback was seen as a necessary component of the cycle's functionality as no student submissions were removed for poor performance and the teams receiving those documents were in need of teaching team support to move them forward successfully. The same member of the teaching team would provide both the feedback to the team receiving the deliverable and the assessment to the team that created the deliverable so that evaluation of the document only needed to be completed once while presented differently to the two teams.

The teaching team was required to have read and be able to provide feedback at each transition between phases. This sometimes meant that the teaching team would have 60-72 hours to read and provide feedback on 5-6 deliverables. Feedback comprised being able to identify the strengths and problem areas within the document, identify areas in which reframing would be necessary, and provide assistance with preliminary steps to begin moving the product to the next stage of the design cycle. All feedback was provided verbally to the team receiving the deliverable upon their receipt of it, with no documented feedback provided to them.

Assessment of written deliverables had a longer turnaround time, with the teaching team each assessing approximately 10-12 deliverables over a 10-15 day timeframe. Assessment was provided in a documented manner on rubrics to the authoring team. With a 12 member teaching team, marking was highly distributed requiring comprehensive rubrics with clear descriptions of each performance level. Criteria from assignment deliverables formed the foundation of these rubrics, which were provided to students as "independent assessment tools" to compare their deliverables against prior to submission. Assessors provided both criteria-specific evaluations of the work as well as a holistic evaluation of the work as a whole.

Assessment of the final design critique presentation was performed by two assessors who each heard the presentation independent of the other. Both assessors each developed feedback and a performance evaluation of the presentation; however, whichever assessor attended the presentation of the team first had the opportunity to provide formative feedback to the team in advance of their second presentation. Students who improved between the first and second round of presentations were rewarded when the assessors combined their evaluations to determine a final grade for the presentations.

7. Design Assessment – Assessing the RPDC

The RPDC was designed to "provide freshman engineering students with a first university-level design experience in which they develop a foundation for their practice as engineering designers and communicators. " Broadly speaking the RPDC can be assessed in the following ways:

1. Is it composed of activities, scaffolds, and assessments that are known to or suspected to result in the desired outcomes? (e.g. Does it have "face validity"?)
2. To what extent did the students meet the learning objectives?
3. Is there transference of skills and attitudes to later courses? (e.g. Does it have "external validity"?)
4. What were the experiences of those engaged in the course?

Assessing external validity is not yet possible, as the students have not completed a subsequent design course. The case for face validity has already been made through the previous discussion of requirements and reference designs. We are in the process of analyzing the assessed activity deliverables to determine first whether the associated assessment rubrics are a valid reflection of the learning objectives, and second whether the student performance indicates that the objectives were met. At this point in time our assessment of the RPDC is necessarily limited to a qualitative discussion of the experiences of those engaged in the course, in particular the teaching team and their perceptions of student learning.

Overall, students indicated to instructors in studios that the project helped them understand both the nature of design in the engineering profession as well as the different roles played by design engineers. As there was no communication allowed between teams in the different phases, coupled with the pace of the deliverables, a greater appreciation for the importance of engineering communication was seen, as students had to quickly assimilate the previous teams' work. Students were more capable to critically assess the deliverables that formed the starting points of their phase than they were of other engineering communication artifacts presented to them earlier in the term. Whether this was due to the higher stakes and pace of this project, or because students had developed these skills over the course of the term is unknown.

Framing the prompt around enhancing personal efficiency was an excellent decision as it encouraged students to leverage their personal experience and apply personal judgment during the design process. In previous design activities, students were hesitant to utilize their judgment as they perceived that the outcomes of the design decision-making tools had to be correct, whether it made sense or not. By allowing the students to define problems that they had experience with provided them a basis with which to critically assess the results provided to them by the decision making tools, as well as the confidence to challenge their validity.

The hardest part of the assignment for the student, as perceived by the teaching team, was developing the design briefs during the problem formulation stage. Students found it very challenging to think of a product to design in response to the prompt. When encouraged to think of things that annoyed or inconvenienced them, students found it easier to generate ideas. Overall, there was a good breadth of topics that students identified, allowing for there to be a decent amount of differentiation in the types of products students addressed. A sample of some types of products identified by students is provided below, note that each cluster of teams had no more than one product from a category.

- increasing the utility of sleep time (alarm clocks, pillows, etc.)
- multi-tasking devices (new umbrellas, portable work surfaces, better load carrying devices, etc.)
- outdoor maintenance devices (lawn mowing, leaf raking, snow shovelling, etc.)
- rain-protection
- organizational devices (for workspaces, bags, etc.)
- kitchen tools (food slicers, spice dispensers, etc.)
- money sorting and dispensing devices
- article locating equipment
- new auditorium/classroom seating/desks

Throughout the cycle there were impressively low levels of team dysfunction as compared to the previous exercises in the course. Team-effectiveness and cohesion between team-members grew as students moved from the problem identification to conceptual design phases, but was hampered in the detail design phase. This was a result of the solid modeling component of the deliverable. To address all sections of the detail design deliverables in the short time span, student teams typically delegated a student on the team to address the solid modeling and engineering drawings components while the rest of the team addressed specifying the product. While the division of roles was successful within the teams, as measured by team performance, it was clear in the critique that teams were less cohesive as compared to previous stages as the teams functioned more as working groups rather than teams.

Incorporating the solid modeling and engineering drawings in the detail design deliverable was greatly appreciated by students as a valuable skill to learn, and one that should help them greatly in the subsequent design course. Teaching assistants and students both found it helpful in communicating the designs, and also that it added an extra "cool" factor that made students interested in investing the time to develop a high quality model. Students were provided instruction in both OpenScad a free-ware parametric modeling tool as well as SolidWorks, with additional support provided for SolidWorks in the computer lab due to its ability to generate engineering drawings. The explicit instruction in the computer lab was essential to help students learn how to use and troubleshoot the software. However, more time with the students in the computer lab would have been beneficial had there been sufficient teaching team support and time. Printing students' solid models was an additional "cool" factor that incentivized students to engage in developing better models. The models developed this year, as compared to years in which there was no printing, were significantly more detailed and precise. Students used the printed models effectively during the design critique to demonstrate the scale, functionality, and component interfaces for their products. However, given the number of models that needed to be printed in a 72-hour turnaround, the timeline was too tight for printing and resulted in the member of the teaching team who did the printing doing almost nothing else for the 72 hours in advance of the critiques.

The feedback sessions that transitioned the deliverables between phases with the teaching team facilitated an open line of communication between students and instructors. Students appeared to find the sessions highly beneficial as it demonstrated to them that the teaching team acknowledged the quality of the deliverable they were receiving and the resultant amount of work that was required to bring it to a high quality level in the next phase. While reframing was encouraged throughout the course as a means of demonstrating engineering judgment and pushing back against overly or ill-defined problems, students in all previous exercises were reluctant to reframe. These sessions in effect gave students "permission" to reframe or rescope the deliverable they were given to make it workable with their knowledge level and the timeframe for the phase. Additionally, these sessions facilitated a more open line of communication between the teams and the teaching team that resulted in more students discussing issues, either team or project related, with the teaching team in a timeframe that provided the teaching team sufficient time to help the students remedy the situation. Running the cycle without these sessions would have resulted in significantly poorer quality work.

As students were always building on the work of other teams of varying abilities, "improvement" had to be factored into assessment. Students who received a poor brief or concept but produced a quality follow-up deliverable needed to be rewarded for the relative improvement in design quality, and vice versa for those who reduced design quality. Assessors were kept constant across phases for a particular product so that they could assess the relative improvement of the product's formulation or design as compared to the team that completed the previous phase.

Based on the relative difference between a received report's grade and the produced report's grade, an adjustment factor of 10% was applied to teams which increased the quality of work by greater than 15%. It was decided that teams which produced a deliverable that was worse than their received report would not have their grade lowered, as this poor quality was considered no different than performing poorly on an instructor defined problem.

However, completing such relative assessments was difficult in the last phase as the final deliverable was a design critique presentation and as such comparing it to the conceptual design report was not as intuitive as the relative assessment across the design brief to conceptual design report phase. As a result, design critique grades were held as their own with no adjustments based on previous performance as no comprehensive or fair manner to do so could be decided amongst the teaching team. It was found, however, that students did not apply the same rigour to the detail design phase (barring the solid model) as the other phase deliverables as there was only a presentation. During these presentations, students could not provide the same level of justification and evidence of decision-making practices as in previous stages. When asked, some students commented that they did not feel the same burden of proof was needed for an oral presentation.

Both students and the teaching team reported that the timeline for the entire cycle was too short for students to truly gain traction and both learn and apply design concepts. The frequency of cognitive disruptions was jarring for the teaching team and students as they were required to be switching products every two weeks, resulting in the teaching team feeling that it was difficult to develop enough background knowledge in each area to support the students as effectively as they wanted. Student morale in general dropped between phase transitions as students assimilated their new products; however, within a few days morale typically recovered. One significant concern expressed by the teaching team was that there was not sufficient time around prototyping at the conceptual design stage and as a result students were not leveraging their prototypes. Instead of building prototypes for the testing and refinement of ideas, students were building them quickly once reports were written to meet assignment requirements.

After the project was complete, all of the stakeholders reported appreciating both the experience as a whole and the value of participating in each phase of an integrated engineering design project. While many of the student designs were not developed in depth, introducing students to a complete design experience early on in their design curriculum allowed the students to better understand the need for a clear problem definition, quality requirements, rigorous decision making, and clear communication. As student buy-in at various stages was highly affected by the type of product they were working on, changing the product types at each stage ensured that no student was forced to work in an area they did not enjoy for the entirety of the project. Student performance at all stages of the activity was not hindered by the timeline. Average student grades were on par with other design activities in the course.

8. Refinements – Changes to the RPDC for 2013-14

Based on the assessment of the design cycle presented above, as well as recommendations from the teaching team, the following refinements are proposed for the next iteration of the design activity. If an institution is interested in implementing this activity, we recommend that it be implemented with the following refinements:

1. Ensure there is a written deliverable at the completion of all phases of the cycle. The amount of research and judgment that is required for decision making is too great to be communicated effectively in solely a design critique. When dealing with students in upper years, this refinement may not be necessary.

2. Spend more time instructing students on how to develop solid modeling and ensure that all students engage in this learning. Much frustration was voiced by students who felt they had a significant amount of learning to do on their own. While our students rose to this challenge, if support and resources are available it is recommended to spend more time than 2-3 hours instructing students on these tools/processes.

3. Make sure that if there is a solid modeling component that students are able to see something tangible from it. Much of the learning students invested time in was so that they could touch and see their product once it was 3D printed. This level of engagement and accomplishment could not have been attained by a lesser form of prototyping.

4. Remove substandard student deliverables. Allowing all student work to move through to the next phase was not a good decision. While it increased many student's investment in the communication they produced, some design briefs in particular were so poor that students receiving them had to complete two phases in the timespan of one. Several ways to address this issue have been proposed by the teaching team:

- provide students a template for the design brief that has to be completed in its entirety - could possibly affect the ability to appropriately scope a type of product
- remove exceptionally poor briefs from circulation and duplicate others
- make the prompt less ambiguous so as to allow students to develop an idea for the problem quickly, giving them more time to write the design brief
- more instruction on how to identify and find problems, as well as providing students with tools and techniques to do so.

5. The design critique did not work at the end of the detailed design phase due to the nature of detail design work. This type of assessment would be much better if provided at the conceptual design phase as a means of formatively evaluating student ideas and concepts before the final selection that is codified in their report. This would ensure that no poor designs are passed on to

the detail design phase, and that the intuitive assessor questions as to the relevance of a particular type of product being {practical, functional, marketable} would be more appropriate.

9. Future Work

The RPDC activity itself, subject to the refinements outlined in section 8, is now approaching stability. As discussed in section 7, we are currently only able to complete one of the four assessments of the RPDC, in part due to the changes made to the activity and in part due to missing the infrastructure necessary to validate the activity. Future work on the RPDC will focus less on the activity itself and more on developing this infrastructure. Specifically:

- validating that the assessment rubrics for the RPDC deliverables capture student performance against the RPDC Learning Objectives
- assessing transference by identifying and partnering with design courses situated later in the curriculum, and mapping the rubrics used in those later courses to the RPDC rubrics
- assessing changes to the RPDC activity through methodologically rigorous, year-over-year comparisons of student performance and both student and teaching team perceptions.

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Appendix 1. Assessment of Archetypal Freshman Engineering Design Activities

Design a Working Machine or Device That...

Activities that fall under this archetype challenge students to conceive of, assemble, and test a working machine or device that accomplishes a task. Examples range from autonomous robots through to Rube Goldberg Machines. The activity is usually presented as a set of requirements where performance criteria are specified in detail and a small set of design constraints are mandated. In some cases the activity is framed as a scaled-down simulation of a “real world” engineering challenge. In many cases students are provided with a “kit” of parts (e.g. a Lego Mindstorms™ NXT, a standard set of components sources from a hardware store, etc.) and may be permitted to acquire additional components as necessary. To justify their designs, students may be required to apply skills and knowledge from their other courses (e.g. computer programming, statics and dynamics, etc.)

This archetype is explicitly constructionist, and provides students with exposure to the “back half” of an engineering design process. By mandating a “working” result, students are required to go beyond a conceptual design, and even beyond representational prototypes, such that they will likely encounter the difference between “in theory” and “in practice”. Providing students with an “I made this!” experience, possibly usually with a competition, promotes a concrete sense of achievement and may promote engagement. This archetype mirrors the work environment of a mechanical or electro-mechanical design firm.

According to the course definition, this archetype does not construe an engineering design activity. While the results may be “open-ended”, depending in large part on the constraints and the provided “kit”, the problem being addressed is well-defined; students engage in neither the problem finding nor the problem framing aspects of engineering design. By providing students with a single type of challenge to address, namely specifying and constructing a physical design, students are not exposed to the variety of contexts to which engineering design can be applied.

Students who are less interested in machines, devices, or the “back half” of engineering design may find it difficult to engage with or succeed in these activities. Finally, by having the students address only a single challenge they are not required to reframe, reorient (“pivot”), or otherwise take ownership of an incomplete activity.

Develop Engineering Design Solutions to this Design Brief

Activities that fall under this archetype provide students with a design brief and challenge them to develop appropriate engineering design solutions. The design brief is usually relatively short, in the order one or two pages, and may be accompanied by supplementary information. In many cases the brief is based on a “real world” design project, usually simplified so as not to overwhelm the students. The entire class may be tasked with solving a single brief, or multiple briefs may be worked on by subsets of the class. Students may be required to (re)frame the brief into an engineering requirements document; they are required to develop divergent design solutions and to converge on a preferred design. Depending on the time available and the skills of the students, they may be required to refine their preferred design into a more detailed form, or to embody it in a solid model or prototype.

This archetype provides students with exposure to three of the four stages of an engineering design process, although the extent of the (re)framing stage varies. Because construction is not required, students are usually required to apply a wider variety of formal engineering design tools, and to produce a wider variety of engineering (communication) deliverables than they would otherwise. This archetype mirrors the work environment of a product design firm.

By not exposing students to the finding stage of an engineering design process, this archetype removes one of the most challenging aspects of engineering design. By not requiring either detailed design refinements or a tangible product, students are neither exposed to the full complexity of an engineering design activity nor to the challenges of transitioning from concept to implementation. As with the Working Machine archetype, students who are not interested in the problem posed by the brief may find it difficult to engage with the activity. Similarly, having the students address only a single challenge removes the experiences of reframing, reorienting, or otherwise taking ownership of incomplete activities.

Develop a Design Brief and Conceptual Solutions for this Client

Activities that fall under this archetype provide students with the contact information for a client, either internal or external to the university or course, and challenge them to complete a full engineering design activity. Students usually work with one client; a single client may work with multiple students. The client may have a documented problem statement, usually in a pre- design brief stage and likely not framed as an engineering design problem, or may have only a vague, undocumented need that they wish addressed. Students are expected to work with the client to find an appropriate problem, frame it as an engineering design problem complete with requirements, develop divergent solutions, and select a preferred alternative. Unless the activity spans a complete academic term, the students are usually not expected to produce a detailed design or a tangible result. Access to the client may be moderated through instructors or may be limited in form (e.g. email, telephone, interviews, etc.) and frequency.

This archetype provides students with exposure to a complete engineering design process, although the extent of the finding stage usually varies depending on the client. As when they respond to a provided design brief, because construction is usually not required, more formal written and graphical deliverables are mandated. Assuming that they have sufficient access to the client, the tangible presence said client can provide students with additional incentives to perform that may not be present with the project is presented in the form of a design brief. This archetype mirrors the work environment of a comprehensive engineering design consultancy, although the extent of the mirroring may depend on the clients' needs.

Solving a single problem for a single client has the same issues as the previous two archetypes: lack of variety, potential lack of engagement, and the potential to avoid taking control of an incomplete or poorly defined project. Depending on the client this last issue may be mitigated, as some clients will embody "ill-defined problems". Of greater concern is that students are unlikely to assert their own opinions, values, and beliefs when confronted with an external client. Engineers, distinct from technicians and technologist, are expected to "push back" against nonsensical, unsafe, or otherwise suspect requirements; in our experience few students are willing to "push back" on their instructors, and even fewer on an external client.

Assess and Improve this Engineering Design Case Study

Activities that fall under this less frequently encountered archetype provide students with an existing artefact, in tangible form or through engineering documentation, and task them to analyze and improve the design. "Reverse Engineering" activities would fall under this archetype, and would "Analyze and Improve" activities. The amount of supporting or supplementary material varies, as does whether the students are tasked with understanding only the artefact or also the engineering design process that led to its production. In many cases the criteria, in whole or in part, and the tools that are used in the analysis are prescribed by the instructors. Students are usually required to refine their improved design to the detailed design level, and to produce a tangible prototype. Depending on the activity students may be given a common artefact or may be permitted to select one of their choosing.

This extent to which this archetype provides students with exposure to a complete engineering design process depends significantly on how the assignment is framed. If students are required to "reverse engineer" back to the finding stage of design, and then work forward through to selection and refinement, then they will encounter a complete process; if they are required to pick a small number of elements and improve on those within the framing of the original design, then the breadth of their exposure will be reduced. Depending on the source of the artefact, students may or may not find the project engaging and fulfilling as a prescribed artefact may not be of interest, but a self-selected artefact may not be tractably improvable given the time, resources, and skills available to the students.

This archetype has the same issue of working on a single issue as the previous archetypes. As a case study it also tends to choose relevant information for the student, rather than challenging the student to locate and prioritizing information. As such activities that fall under this archetype are likely to violate the requirements related to practice fields.