

Connecting Design Doing to Design Learning

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Abstract

Prior work shows that doing design does not necessarily lead to learning design. This research paper explores how to strengthen the connection between the activities done by students in a design class and student learning.

In particular, we draw from prior studies focused on problem formulation knowledge of engineering students in first-year hands-on engineering design classes. In spite of the fact that students in these classes had been involved in problem formulation activities such as talking with and observing users, identifying needs, and/or writing requirements, the studies showed that there was no evidence that the students had learned the importance of including such activities in a design process. Several interventions were implemented in an effort to change this, with a prior study showing a statistically significant change: students were learning the importance of problem formulation activities after the interventions. What remained unclear, however, were the specific reasons for the improvements.

In this research paper, reasons for why student learning of problem formulation's role in design increased so dramatically are explored using interviews with students from the classes.

We interviewed six students who had taken one of the courses where improved learning was observed. These students had taken the course as a first year and were interviewed during spring of their junior or senior year. Questions were broad and open-ended, asking students, for example, to recall projects they had done during their first year and if any of those projects affected how they design now. Other questions focused specifically on the main takeaways from the first-year course and how they learned them.

Responses were iteratively open coded to identify emergent themes. All six subjects identified a one-week project done in the first week of class as 1) a key part of the class and 2) the place in the class where they learned that an engineer must engage in problem formulation activities. All subjects also discussed the term-long projects, but only one connected the term-long project to problem formulation. The one-week project is described along with key characteristics that led to its heavy influence on student learning about problem formulation.

Introduction

A one-week project drove the more than doubling of students identifying the importance of problem formulation activities in design. The study presented in this paper aims to close the gap between doing design in a class and learning effective design behaviors that are transferred to situations beyond the classroom. In particular, the focus is on problem formulation design behaviors such as engaging stakeholders, performing research, identifying needs, and writing requirements.

Problem formulation is called different names in different sources. In nearly any textbook on engineering design, however, problem formulation activities are included as part of design. Dym and Little state that “an essential part of an engineering design project is *clarifying* the client's objectives” [1, pg. 25]. Ulrich and Eppinger highlight activities such as collecting customer

needs, identifying lead users, and benchmarking competitive products [2, pg. 16]. Even the more technical and logical of engineering design texts, such as Pahl and Beitz's *Engineering Design*, speak to writing requirements and the need for close contact between the client and the design team [3, pg. 130].

Despite the fact that problem formulation activities are foundational to engineering design and included in nearly all engineering design classes, prior work from two studies has shown that as little as 11% of students recognize the importance of such activities in design [4], [5]. All teams of students must typically include evidence of problem formulation activities (e.g., design requirements, needs, results from stakeholder interviews, etc.) in required deliverables for design classes. Despite *doing* problem formulation activities to meet these requirements, prior work has shown scant *learning* that these activities are an important part of engineering design. Doing does not necessarily lead to learning.

Another prior study found that students did learn the importance of problem formulation after a set of interventions was implemented [6]. With the aim of improving engineering design process learning, several interventions were tried in a first engineering design course starting in 2012. Whereas just under 20% of the students recognized the role of problem formulation prior the course, over 55% recognized the role after the class. These results represent such a large (and positive) shift from all prior work that a follow-on study was conducted to explore the reasons for the change. The follow-on study is the focus of this paper.

The specific research question addressed in this paper is: *Why did the interventions improve learning of the role of problem formulation in design?*

Literature Review

“Doing design does not insure the learning of design” [7]. A foundational element of nearly all engineering design courses is *doing design*. Implicit in this pedagogy is the assumption that doing design is critical, if perhaps even sufficient, for learning design. Studies, however, show that “doing” is clearly not sufficient for learning to occur.

While design does not have one definition, the importance of understanding user needs is clear in most any definition. The Accreditation Board of Engineering and Technology currently defines design as “the process of devising a system, component, or process to meet desired needs,” [8]. This definition is currently being revised as part of a larger ABET update. Sheppard's succinct definition is that engineers “scope, generate, evaluate, and realize ideas” [9]. Dym, et al., define design as “Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints” while going on to add that a “designer has a client (or customer) who, in turn, has in mind a set of users (or customers) for whose benefit the designed artifact is being developed” [10].

In the work presented in this paper, “engineering design” refers to situations where an individual or team begins with a fairly vague notion of a problem or a set of needs that their design will address, as opposed to a situation where a very strict set of immutable requirements are handed to the team at the start. For example, a team could be tasked with designing a system to detect the posture of a user sitting in a chair and use that information to improve posture. Or, a student

could be tasked with designing a system to automatically detect bruised bananas as they speed by on a conveyor belt. Or, a team could be tasked to design a new activity for a spring carnival at a local school. These situations are all open-ended and would require non-trivial problem formulation.

A seminal work in the body of literature showing that doing design does not insure learning design, is in an ethnographic study of a third year mechanical engineering design class at Georgia Tech. In this study, the researcher, Wendy Newstetter, embedded herself in a design team for a 10-week term. After observing students use all of the design tools and approaches taught in the class, **she came to a core finding that “old ontologies die hard... doing design does not insure the learning of design” [7].**

Her findings explore the reasons why this is the case. She witnessed a well-intended and thoughtfully designed series of assignments be approached as “tasks to be completed” by students. She saw students adopting practices that *looked like* design (i.e., they completed the assignments), but interpreting material and building knowledge that were very different than what the instructor intended (i.e., students learned that “design tools” got in the way of design and “cleverly faked” using them to pass the course).

Even if the teacher sets up an environment that values and promotes knowledge building and learning to learn, students will not necessarily assume the concomitant roles of knowledge builders and learners. [7]

Unlike experts, the students could not see the meaning and purpose in design tools and approaches; they only saw the form of the tools and approaches. **Students could mimic the patterns, but never saw the purpose.**

The Newstetter study further shows that adding “reflection” opportunities to the “doing” activities was not sufficient to promote learning in that case. The environment set up by the instructor “valued and promoted knowledge building” through explicit opportunities for reflection. Among other things, the instructor asked students to reflect in the middle of class, wrote those reflections on the board to encourage others to reflect, and assigned “learning essays” that focused on “moving students from an analytic or 'bits and pieces' understanding of the design process to a synthetic or conceptual understanding of the phases of informed decision-making” [7]. Regardless of these reflective activities, students did not build the intended knowledge about engineering design.

These results are not surprising when viewed in the larger context of findings from educational research: prior knowledge and its organization affects learning. The first learning principle from *How People Learn* [11] is that teachers must “draw out and work with the preexisting understandings that their students bring with them.” Expanding on this point, Ambrose includes the following three items in her list of seven research-based principles for teaching [12]:

- Prior knowledge affects learning
- Organization of knowledge (including prior mental models) affects learning
- Motivation affects learning

The prior knowledge and organizational schemes of students in the Newstetter study were at odds with how the instructor wanted the students to learn. Further, motivation centered on completing assignments led to surface learning of forms and procedures, not deep learning that would be transferred beyond the class. Specific to problem formulation and the methods used in this paper, two prior studies have further reinforced these points.

Prior Work

Prior Results

Prior work, replicated in different first-year engineering courses at different universities with different instructors, showed the percentage of students recognizing the importance of problem formulation activities in design was low (less than 20%) and did not improve after a class where they did many problem formulation activities during projects [4], [5]. In a prior study with a paired sample of 286 students in a first-year engineering design course, the percent of students that recognized the importance of problem formulation skills only changed from 8.7% prior to the course to 10.8% after the course [5]. Further, there was no significant difference found between the students on three types of projects (design from a kit of materials, product dissection, and a service project with community partners) [6]. These results were conducted at a large, public western university. The first-year engineering design course focused on design through three projects: the first two projects were designing a device for a design challenge using a kit of materials (e.g., designing a solar oven while using heat transfer and the physics of light to drive decision decisions) while the third project varied among the sections. Problem formulation was integrated by requiring teams to write requirements for the kit-based design challenges and by engaging them directly with users for the service design project.

Similar results were replicated at a different public university with a paired sample of 151 students in a first-year engineering design course where the percent of students that recognized the importance of problem formulation skills only changed from 10.6% prior to the course to 14.6% after the course [4], [6]. Integration of problem formulation activities varied among the different sections of this course, with several sections involving actual users with whom design teams engaged. No differences were found among the sections with respect to design learning.

The percentage of students recognizing the importance of problem formulation activities in design more than doubled after taking a class in which a set of interventions were implemented [6]. Based on three years of paired data from the courses with interventions, the percent of students that recognized the importance of problem formulation skills increased from 19.6% prior to the course to 55.4% after a first-year engineering design course (n=56) [6]. The interventions involved a short, one-week project conducted at the start of the term and changes to the term-long project.

Assessment of Design Learning in Prior Work

In this prior work, the goal of the assessment was to determine if subjects know to do certain design activities, not if they know how to do those activities well. For instance, do students know to generate many ideas instead of fixating on one idea early is measured, not if they are able to generate multiple ideas effectively. Of interest here is the assessment of if they know to engage in problem formulation activities early in a design process, not if they know how to execute these activities well. The reason we have focused on knowing to do an activity is related to the Newstetter article. In that study, students were doing design activities, but they were not seeing

the value of doing those activities. To have the ability to do something but lack the wisdom to know when to do it is of little value. This focus does not imply that knowing how to do something is not important; it is just not the focus here.

In the prior work, the instrument used to measure design knowledge is called the Design Process Knowledge (DPK) critique [13]. In this instrument, a proposed design process is shown to students for designing a hypothetical product. The proposed process can be represented many ways; in these studies, it was represented as a Gantt chart. The prompt to students is to report all of the good aspects and all of the bad aspects of the proposed process. Students are told to evaluate the process shown to them as if no work was done prior to it. In the process shown throughout the studies cited here, the team did not engage in problem formulation activities. No writing of requirements. No formulation of needs. No talking to or otherwise engaging users. No research.

Responses to the DPK critique can be scored using a detailed rubric which includes more than just problem formulation [13]. For the results reported in the prior studies, though, a simpler rubric focused only on problem formulation was used where any mention of the lack of problem formulation activities is scored as “identifying the importance” of problem formulation. For example, when “55.4%” of students recognized the importance of problem formulation skills, that means that 55.4% mentioned at least one problem formulation activity that the team should have done. Most but not all of the scoring was performed with multiple raters, with representative results showing Pearson and Spearman correlations from 0.7-1.0 [4], [14]. For the data reported most recently in [6], intrarater reliability was measured with a kappa score of 0.942.

Methods

Setting

The course where improved learning was observed is a first-year engineering design course at the same public university as the 151-student sample in prior work. The two sections of the course with improved learning centered around a 14-week project with local elementary and middle schools. The course starts with a short one-week project, called the Chair of Scrap, which is one of the two interventions.

With its name partially inspired by an activity from *Experiences in Visual Thinking* [15], the Chair of Scrap (see Appendix) asks the students to design a way to accommodate more students in the instructor’s office with only recyclable materials. Assigned on the first day of class and due in just one week, students work feverishly to design and build some sort of chair or stool. Upon showing their designs proudly to the instructor, they are surprised to hear that they have all made a crucial mistake. It is rare for *any of the students* to visit the instructor’s office or ask the instructor or any students questions about what s/he wants in seating (i.e., they do not talk to users or the client). While there are certainly barriers to a first-year student going to an instructor’s office (e.g., it can be intimidating, they not be familiar with campus buildings), there are no shortage of opportunities. Included among these is open class time during which students can work on the project.

The message that they overlooked a critical part of design is described to the students as an observation: when left to your own devices (i.e., your existing knowledge), you did not engage the stakeholders. The instructor’s job is to make the observation and to pose the question, “is not

engaging stakeholders good?” While it is true that just asking this question implies some judgment, the goal is for the students to recognize on their own that not engaging stakeholders is bad.

The second intervention was increasing the engagement with users in the term-long project. Compared to the classes in the prior studies, the term-long project in this class integrates more opportunities for engagement with stakeholders. The integrated opportunities for stakeholder engagement include

- Each team writing a strategy for how they will elicit stakeholder needs
- Each team executing this strategy, including *every individual student* submitting notes and drawings from observations of and/or interviews with stakeholders
- Each team writing a set of users’ needs and updating those throughout the term
- Each team showing two prototypes to users to get feedback
- Each team writing a set of requirements and updating those throughout the term
- Each team testing their final, functional design with users

While some of the projects in the prior studies were client-based, most were not (and, for those that were, there were fewer opportunities for engagement with stakeholders). Another intervention associated with the term-long project is that students gain more “making” skills to facilitate their ability to develop prototypes that could be used to engage stakeholders. Each student gained at least one making skill from the following: Arduino electronics, woodwork, 3d printing, and foamwork. It was not anticipated that the changes related to making skills would influence students’ learning about problem formulation. We did, on the other hand, hypothesize that the stronger focus on doing problem formulation through engaging stakeholders routinely in the term-long project could have increased learning about problem formulation.

Subjects

We interviewed six students who had taken one of the courses where improved learning was observed. All students from two years of the classes with improved learning were invited to participate in the study. We have complete data on six students who volunteered to be interviewed. Students were interviewed in the spring of their junior or senior year. They had taken the class in the fall of their first year. Of the six, half were juniors and half were seniors. Two were female. Four different majors were represented in the sample.

Interview Questions

Interview questions included open-ended question about design projects along with one question specifically asking about problem formulation skills. The interviews required roughly 45 minutes and participants received a \$10 gift card for their time. The Institutional Review Board approved the study. All of the results presented in this paper come from the subset of questions shown in Figure 1. The complete set of questions are in Appendix B. During the interview, there were some other questions between the four listed in Figure 1.

- 7) *Did you participate in any projects in your engineering classes in your first semester? If so, tell me about the projects. What kinds of activities did you do to complete the project?*
- 8) *Is there anything (in or out of class) from the first semester that affects how you approach design now?*
- 12a) *What were your main takeaways from the class? How did you learn this through the coursework of class?*
- Asked only if problem formulation had not been mentioned previously in the survey (asked of 2 out of 6 students):
- 12c) *Many engineering curricula teach that things like identifying the problem, talking to the client/user, writing requirements, etc. are good things to do in engineering design. I noticed you didn't mention any of these... tell me more about that.*

Figure 1 Core Questions in the Interview

Interviews were audio-recorded and then transcribed. The interviews were conducted by two undergraduate research assistants. Transcriptions were open-coded to identify emergent themes.

Coding

The focus of the primary coding was to identify any answers that might explain why learning about problem formulation's role increased. The author of this article, who is also one of the two instructors of the course where the interventions were implemented, conducted the coding. After the audio files were transcribed verbatim by the undergraduate research assistants, the process for coding was

- Perform a first pass coding for each question, This coding is most similar to “initial coding” as defined by Saldaña [16], with in vivo coding [16] used to identify quotes that had particularly rich content or emotion.
 - For all questions, identify any answer where problem formulation was involved.
 - For some questions such as “what were your main takeaways from the class?”, identify any codes that emerged.
- Perform a second pass coding for each question.
 - The second pass was as much a screening as it was refinement of codes. For all of the questions, any first pass code related to problem formulation activities was identified. The section from the original transcription where those codes originated was then re-read and codes were refined as appropriate.
- Perform a third pass to aggregate.
 - Codes resulting from the second pass were read and summarized, re-reading original transcriptions as necessary. This third pass resulted in a summary of codes related to their responses related to problem formulation. One summary was created for each subject.
- The aggregated data was read and re-read across participants to look for commonalities and differences. This is most akin to the second cycle coding method of “focused coding” defined by Saldaña [16].

As an example of this procedure, consider the following direct transcription to the question about main takeaways from the class.

I guess 1620 introduced me to the idea of systems thinking and the process of design. Then also the importance of taking your user's needs into account and that engineering can impact people or social aspects of everyday life as opposed to just building something or doing a technical job.

The first pass coding for this was:

- *systems thinking and the process of design*
- *importance of taking user's needs into account*
- *"engineers can impact people or social aspects of everyday life... [not] just building something or doing a technical job"*

The second pass coding eliminated the first bullet (as it was not explicitly problem formulation related) and refined the next two bullets:

- *users' needs,*
- *engineers do more than technical work, they impact people*

The third pass aggregated the codes for each subject so that they could be easily read through multiple times. The aggregated coding was reviewed across subjects. The major themes presented in the Results section resulted from this cross-participant coding.

After completing this coding, it became clear that secondary coding was necessary to explore implications of the findings. In particular, the Chair of Scrap was cited in everyone's answer. I reviewed every time the Chair of Scrap was mentioned to identify any characteristics about this project. In particular, this secondary coding investigated references to the project for:

- Did students feel tricked by the assignment?
- Did students feel that the Chair of Scrap was a safe place to fail?
- Did students feel they could learn how to do problem formulation well even though most of them did not do it well on the Chair of Scrap?

No a priori coding scheme was used for any of the coding; themes related to answering questions emerged during the coding process. In vivo coding [16] was used frequently in the secondary coding.

Results

All respondents cited the one-week "Chair of Scrap" project as a critical event that shaped their understanding of problem formulation activities in design. All six respondents cited – often emphatically – remembering the Chair of Scrap project and that the point of it was to not overlook engaging with users. Five of the six respondents mentioned the project prior to Question 12c in Figure 1, which is the only question specifically about problem formulation. Four of the respondents identified the Chair of Scrap as something that affects how they design today and/or is a main takeaway from the class (which they completed more than two years prior to the interview). A set of quotes about the Chair of Scrap from actual responses is shown in Table 1.

Chris¹, a senior about to graduate, speaks to “vividly” remembering the Chair of Scrap from the first week of her college career. Pat speaks to the assignment “hammering home” through a “shock and awe” approach the need to focus on users and solving the right problem. Five of the six refer to how almost no students talk to the users as part of the Chair of Scrap and that that was the main point. All six directly connect the Chair of Scrap project to learning about the importance of engaging users.

Table 1 Responses Citing the One-Week Chair of Scrap project

Subject	Q#	Response (<i>actual quotes in italics</i>)
Chris	7, 8, 12a	<i>I vividly remember the chair project that he assigned at the very beginning, and that probably had the biggest impact on me; I still talk about it med[ical] school interviews. Like when I was interviewing for med[ical] school I would always bring that up describing the engineering design process.</i> <i>It basically scared the s*** out of me. well, it didn't scare the s*** out of me – it made me remember to always question what I'm doing, what the user needs, and thinking outside the box. So, I'll always remember that. Then the actual project itself – stepping through each stage of the design process was helpful, and it's something that I mentally view nowadays whenever I'm designing something.</i>
Pat	7 & 12c	<i>[He] really kind of hammered it home with the [Chair of Scrap] project... [he] comes in and rips all of our projects to shreds because no one ... thought, “well, is what [the instructor] needs actually a bench.” Right? So, that was a shock and awe type way of getting everyone's attention”</i>
Alex	12a	<i>I learned that users needs were important through Chair of Scrap.</i> <i>[I learned this through] an assignment for the first week of class and it was to design a bench for his office, and then he basically failed everyone ... because no one actually went to his office about what he actually needed.</i>
Drew	8	<i>And one thing I remember [about the Chair of Scrap] was that only one group actually went to him and talked to him about what he wanted for design and everyone else just designed it. That really stuck with me to remember to ask a future employer, or whatever, what they want.</i>
Sam	7, 8, 12a	<i>After citing the Chair of Scrap when asked about projects from that term, Sam goes on to say:</i> <i>information gathering is an important step that is necessary for a good design and is often skipped ... so that's a big takeaway.</i>
Jesse	12c	<i>almost no group ever talks to him because the chair is for his office. And he does that on purpose, and then he tells us that that's like a very big part of engineering-that you should focus on the client. And then after that, I don't think that it's so much reemphasized, but I think that's a fair amount of like-emphasis on it. On the [term-long] project, [since none of us have a car and the users are 2 miles away] there wasn't really much we could do [to directly focus on the client].</i>

¹ Pseudonyms are being used for each subject.

Interestingly, the one-week project (where most students did not engage users) was cited more frequently than the 14-week project where all students had to engage users at multiple points as part of the project requirements. The term long project required deliverables throughout the term, several of which were client/user focused. In spite of this continual focus on the users in the activities being done for the class, Jesse (in Table 1) says that the focus on users was not as strong in the term-long project as it was in the one-week Chair of Scrap. This point is made explicitly only by Jesse. Through omission, however, it was implicit in the responses of four other subjects that the term-long project was not connected to learning about engaging users or problem formulation.

Only one of the six respondents, Chris, commented on learning about the importance of engaging users through the term-long project. After Chris identified “user stuff” as one of her main takeaways from the class, we asked her “how did you learn about that?”; to which she stated “[The instructor] made us go talk to the kids at [the] elementary [school]. He made us turn in assignments all the way through....” As seen in Table 1, Chris also indicated the central role of the Chair of Scrap. In short, only Chris said that one way she learned about problem formulation was through both the Chair of Scrap *and* the term-long project.

This juxtaposition bears repeating:

- All six subjects said they learned the importance of problem formulation through NOT doing problem formulation richly (in the Chair of Scrap) and later realizing their omission.
- Only one said she also learned the importance of problem formulation through doing problem formulation on the term-long project.

As can be seen in Table 1, references to the Chair of Scrap emerged as responses to different questions. Three students cited problem formulation as a main takeaway. This made problem formulation the most cited takeaway, with other themes including:

- Prototyping, teamwork, and design process (each mentioned by 2 subjects)
- Ideation, “making” skills, systems thinking, communication, and iteration (each mentioned by 1 subject)

Discussion

The results indicate that the one-week Chair of Scrap project is the driver of increased learning about problem formulation. The increased focus on user engagement in the term-long project was not as important for learning the importance of problem formulation. **The fundamental question explored in this section is: what makes the one-week project so impactful?**

Our leading explanation is rooted in exposing students to their own preconceptions, providing a secure environment where they feel safe identifying problems with their own preconceptions, and ensuring they understand that they are capable of fixing these problems.

Feeling Tricked?

The results of the ethnographic study by Newstetter and the principles from *How People Learn* [11] provide a basis for this explanation. Not only do “old ontologies die hard,” they will never die if a student’s preexisting knowledge is ignored.

Even if the teacher sets up an environment that values and promotes knowledge building and learning to learn, students will not necessarily assume the concomitant roles of knowledge builders and learners. Student interpretations will not necessarily map easily and unproblematically onto those of the teacher. [7]

Having students do design does not challenge old ontologies... as they can simply complete tasks while relying on the instructor to frame the nature of design. The Chair of Scrap allows students to use their own approach, not the instructor’s. Perhaps the most important moment occurs when the instructor observes that the students’ own approach did not engage users and, through asking if this is good, encourages students to recognize their mistake.

It is at this point that the activity could go one of (at least) two ways.

1. *Down the first path, the students could feel tricked.*
A student might think “The instructor told me to do X and then chastised me for doing X.” Or, “I would have engaged the instructor or former students if I thought I needed to.... The instructor purposefully framed the assignment to discourage me from doing so... s/he is the reason I didn’t.” This path would only seem to reinforce existing ways of thinking.
2. *Down the second path, the students would also see the problem with their own approach.*
A student might think “I thought I knew what I was doing... but, in hindsight, I definitely messed up.” Such self-recognition could potentially rattle even the “resilient and resistant ... tacit views” [7] of post-secondary students.

The data can be used to figure out which of these two paths was experienced by the students. More than halfway through the interview, students are asked if any projects in the introduction to engineering class were not useful. None of the six students cited the Chair Scrap as not useful – and all of them had talked about the Chair of Scrap prior to that question. While this is a good sign that students did not feel tricked, more detailed coding did reveal that two students recognized that the instructor set them up, on purpose, to fail. Jesse said “almost no group ever talks to him because the chair is for his office. And he does that on purpose...” Later in the interview, however, Jesse goes on to say:

I liked both of [the projects]. The chair was a nice like, introduction to like Introduction to Engineering. It was a very like, small first project that you could like easily understand, and think about and prototype, and build. And then that definitely helped Segway into the final project, where we built something on a larger scale for children.

For his part, Sam said, “it was kind of fun, but the intention is that we would fail ultimately. Which was a good experience.” Both Jesse and Sam realized that the assignment was designed for students to fail yet, at the same time, expressed that they liked the project. Neither of them

expressed anything to imply that the experience was a “gotcha” moment or made them feel tricked. None of the other four students expressed such sentiments, either, Pat said “I don’t remember having a negative reaction per se to any of the projects” and Chris asked the interviewer to thank the instructor for the Chair of Scrap in her response to “Did any of the class projects stand out as particularly useful?”

In summary, all of the data indicates that the Chair of Scrap did not make the students feel tricked.

Elements of the Intervention that Encouraged Change

Students bring preconceptions of what design is when they arrive to a class. Many of these preconceptions go against what engineering design educators aim for their students to learn; i.e., they are “pre-misconceptions.” The results from this study indicate that, if we want to change these pre-misconceptions, exposing students to their own pre-misconceptions appears to be helpful. The Chair of Scrap assignment accomplishes this as follows.

Step 1: Enough Autonomy to Commit

Students are put in the position to do the project on their own. In this case, students do this prior to any teaching about design. By making students commit to action, their pre-existing views are exposed – to themselves and to the instructor. Exposing students to their own views is critical to this approach, as students’ self-reported views may differ from what they actually do [17].

Step 2: A Safe Space to Recognize Failure (after self-assessed success, if possible)

The results show that students cite learning more about the role of problem formulation from failure (the Chair of Scrap) than from success (the term-long projects). The aim is to achieve failure along the lines of “I thought I did it well, but it is so clear to me now that I did not,” not “I thought I did it well, but the instructor doesn’t. I guess we’ll have to disagree.” While an instructor might need to help the students see it at first, a critical feature of this approach is that the student must recognize their mistake. It could be this self-recognition... where a student quickly moves from “I thought I did it well” to “it is so clear now that I did not”... that causes the “hammering” home of the message and the “vivid” memories.

Further, a goal is to not create failure in the form of “I thought I did it well, but now I am in trouble for not doing it well.” The class needs to be a safe place for failing and the Chair of Scrap can be used, early in the term, to establish that security. While part of this security is based on how an instructor tells the students that they skipped a major part of design, another part is based on not letting such failure negatively affect grades.

The data shows mixed success at accomplishing all of Step 2, as some of the students state that the instructor “rips all of our projects to shreds” (Pat) and “scared the s*** out of me” (Chris) – indicating that failure did not make them feel safe. On the other hand, many responses show security in and ownership of failing, such as “I remember ... that only one group actually went to him and talked to him about what he wanted for design ... [and] that really stuck with me.” The student who said that it “scared the s*** out of me,” immediately corrected her wording by saying “well, it didn’t scare the s*** out of me – it made me remember to always question what I’m doing, what the user needs, and thinking outside the box. So, I’ll always remember that.” Pat, who said the part about the instructor ripping projects to shreds, also later said (as reported earlier in the paper, “I don’t remember having a negative reaction per se to any of the projects.”

Another student directly noted that lack of impact on grading that a low grade on the Chair of Scrap had on students, “but it was only worth a tenth of a percent of your grade. In summary, the data did show two students expressing lack of security during the Chair of Scrap; on the other hand, both of these students and some of the others also made statements that show that the Chair of Scrap was a safe place to fail.

These two steps in the Chair of Scrap project – commitment to an approach and security to recognize failure of that approach – could have been the reasons that students were willing to review preexisting understandings and to change.

Step 3: You Have the Competency to Learn

Another additional component of the Chair of Scrap is ensuring that the students feel like they can learn how to design better through this class. They may have struggled in the Chair of Scrap, but they need to be assured that they have the ability to learn how to design more competently through this class.

Despite not asking any questions specifically about the Chair of Scrap, Sam’s comments directly addressed this third step. None of the responses from the other subjects did. Sam said:

Both of [the projects], together, are important. Um, one- engineers need to- to fail um, and it’s best to fail early, than it is to fail a week before your deadline. Um, and especially when you’re learning how to engineer- like it’s- it’s good to s- to realize: oh yeah, I’m- I’m not that good at this. But then to have another chance at it, um to make something that’s really cool and- and uh useful, is, um, is good. So I think the two of those together, in that class, um, is a great way of doing that.

The class material, like the progression from like- here you’re going to fail at this project and then we’re going to teach you some stuff and then we’re going to like- let you practice it, like that was cool.

Taken together, having the autonomy to commit to a certain approach, the security to recognize the failure of that approach, and the sense that you can learn from that failure form the basis of my explanation for how the Chair of Scrap increases learning about the importance of problem formulation in design.

Limitations and Future Work

The results presented here address internal validity concerns related to linking the one-week Chair of Scrap project to improved learning. Without the results from these interviews, history and maturation prevent us from connecting the improvements in learning seen in prior studies to the engineering design course [6]. That is, without the interview results, the cause of the improvements could have been from an intervention or from any number of other external factors such as changes made to other classes that all of the students take or changes in high schools that had primed the students to learn more quickly. With the survey results, however, we are able to identify the central role of the one-week Chair of Scrap assignment in impacting students’ learning about the importance of problem formulation in design. We are also able to

see the more limited role that doing problem formulation in the term-long project plays in the conscious mind of the students.

Selection bias is an issue with the interview data. The interview study does bring with it a threat to the validity of the findings: selection bias. The six subjects in the interview study were solicited from a group of over one hundred students who had taken the class as first-year students. Instead of being randomly drawn from this larger sample, they volunteered to participate. The concern is that only those students that had positive experiences with the class volunteered to be in the study. This could prevent the data from showing any negative effects of activities such as the Chair of Scrap. It would also reduce the chance that any subject had completely forgotten the class, as those students who did not remember the class well would be less likely to participate in the study.

Future work directions could minimize selection bias and expand scope. To reduce selection bias, all students could be surveyed at the end of the class (not 2-3 years later). While an interview during the term would introduce its own problems (i.e., students could be influenced by feeling like the interview could affect their grades), adding questions to the anonymous end-of-course evaluation could be a viable mechanism to get responses from everyone in the class. Expanding the scope of the work beyond exploring why learning improved in the class, following students to their capstone projects to investigate their problem formulation behaviors would also be interesting future work. We have some limited data from one of the survey questions about this, but it is not sufficient to make any definitive findings. Many threats to validity would exist in such an experiment, including both history and maturation, but these could be partially controlled by including students from other sections of the first-year engineering class to serve as a control group.

Conclusions

The results show that a one-week project that exposed students to the fallacies of their preexisting knowledge contributed to improvements in students' knowledge about the role of problem formulation in design. Learning about problem formulation's importance in engineering design had not been seen in two prior studies of first-year engineering design classes [4], [5]. In a third prior study, statistically significant changes were seen [6]. In this study, six students from the first-year engineering design classes where improvements in learning about problem formulation had been seen were interviewed. Results from the interviews showed all six students linking the one-week "Chair of Scrap" project to learning about the importance of engaging users in a design process. A key component of this project cited by most subjects is that students "fail" at engaging users well in the project. That failure – and the resulting exposure it gives to the problems with students' preexisting understanding of problem formulation – appear to be the critical feature of the Chair of Scrap that drives learning

Acknowledgements

I would like to thank Becca Towler and Derek Boylan for their work on this project. Not only did they conduct the interviews, but conversations with them shaped the direction of this work. I would also like to thank the Hereford Scholars Program for their support.

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Appendix A

Chair of Scrap

Learning Objectives:

learn about design and teaming through both doing and reflecting

Due:

get practice presenting in front of class

Format:

To be completed by teams of 5-7 students

Don't have enough seating in my office for students.

And I want you to design something to help me. I want to be able to have seating for 8-10 students total. I want something that is durable, looks good, and can be out of the way when I don't have such a large group of students to meet with. I'd like a solution that is adaptable to my needs as they might change over the next few years. A rough layout of my office is shown below.

For materials, you can only use items that can be recycled or used by the City of Charlottesville. In addition, you can use tape or other bonding agents if needed, but I'm not interested in seeing a chair that looks like giant pieces of duct tape.

In class:

Today, you will spend time forming teams and getting started on this project.

Advice:

Be smart with your time! Don't sink into hours into something that can be done more simply. Split up work among the team when possible. This assignment could take forever if you let it.

Presentation Team:

Each team will have 5 minutes to present their design to the client (me). You should use Powerpoint and the projector for your presentation. Due to the 5 minute time limit, no more than 3 slides should be used per team. Each group needs to develop team names and make your team name clear during the presentation as well as the names of each of your team members (put your names on the title slide).

Design Process: Individual work on this alone:

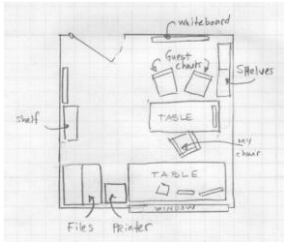
Each individual is to describe, on one page, the process that their team used to design a solution (i.e., what did you do first, second, etc.). Your description must be graphical (as in, visual) representation of the process. On this page, point out 2 things that you think are good things about your team's design process and 2 things you think could have been done better.

To Turn In:

Powerpoint presentation: one student on each team uploads it to Collab by 9:00 am on due date; use the file naming convention listed in the class policies.

Your chair: One per team... bring it to class on the due date. It should be a "working prototype", meaning that it can be used during class/could be put in my office.

Design Process: Each individual brings a hard copy to class on the due date.



Rough Office Layout

Figure A-1 Chair of Scrap Assignment

Appendix B

1. Could you please tell me your name?
2. What is your age? What year are you?
3. What is your sex?
4. How do you describe yourself racially/ethnically?
5. Where were you living first year?
6. What kinds of activities were you involved with in first year?
7. Did you participate in any projects in your engineering classes that semester?
 - a. Tell me about the projects. What kinds of activities did you do to complete the project?
8. Is there anything (in or out of class) from that semester that affects how you approach design now?
 - a. What do you feel was the most effective way you learned engineering design your first semester?
9. What professor did you have for Introduction to Engineering (from here on, this class will be referred to as 1620)?
10. Did you like 1620?
 - a. Was it too much/little work? Was the grading fair?
11. What was your favorite part of 1620?
12. What were your main takeaways from 1620?
 - a. How did you learn this through the coursework of 1620?
 - b. Was there a specific part of engineering design you felt was stressed or emphasized in 1620?
 - c. Many engineering curricula teach that things like identifying the problem, talking to the client/user, writing requirements, etc. are good things to do in engineering design. I noticed you didn't mention any of these... tell me more about that.
 - i. If so, how were they taught? Were they effectively taught?
13. Did you learn or practice engineering design in any activity (other than 1620) during your first semester?
 - a. What was it? What did you learn from that? Was that activity aligned with what you were learning in 1620?
14. What projects do you remember from 1620?
 - a. Did any of them stand out as particularly useful?
 - b. Did any stand out as particularly not useful?
 - c. What did you learn from the useful projects?
15. Before taking 1620, did you ever have any experience with engineering design via a class or through your own studies?
16. Is there anything else about your experiences in your engineering classes that semester you would like to add?
17. Do any of your current classes' material overlap with what you were doing in 1620?
 - a. What topics specifically overlap?
18. Have you done design since 1620?
 - a. Tell me about it. What did you do?
 - b. During planning, did you meet with anyone the product was being designed for?
19. Do you have any questions for me at this time?
20. (*GIVE PARTICIPANT The Design Process Knowledge (DPK) Critique*) Please read this. After you've finished, please comment aloud what you believe is good about the proposed process and what you believe should change. Take as much time as you need.
21. (*GIVE PARTICIPANT THEIR The Design Process Knowledge (DPK) Critique FROM THEIR FIRST YEAR*) Here is your response to this same critique from your first year. Please comment aloud as you read your previous response.
 - a. Why do you believe your original response is different from your current response?
 - b. How are they the same?
 - c. Do you remember what most influenced your response during your first year?