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The Challenge of Developing Transferable Problem Formulation Design Behaviors in First-Year Students

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Introduction

A redesigned first-year engineering course more than doubled the number of students identifying the importance of problem formulation activities in a design process. 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 activities such as these are foundational to the learning objectives in engineering design courses and, hence, they are frequently required in reports and design reviews. *All teams of students* must typically include evidence of problem formulation activities (e.g., design requirements, needs, results from stakeholder interviews, the House of Quality, …) in required deliverables. Despite this requirement, prior work has shown *as little as 11% of said students retain the knowledge* that problem formulation is an important part of design[1].

The overall aim of this work is to further understand w*hat students learn about the role of problem formulation in engineering design classes*. Within this overall aim, the specific research question grows from prior work showing that few students learn about problem formulation in design classes: *What can be done to increase the percentage of students who demonstrate an understanding of the role of problem formulation after completing an engineering design course?*

Prior Literature

The results of prior work show that "doing design does not insure the learning of design"[2]. A foundational element of nearly all engineering design courses is *doing design*. Implicit in this pedagogy is the assumption that doing design is sufficient for learning design. Research into learning, in general, and learning design, in particular, counters this assumption.

In this work, "engineering design" refers to situations where an individual or team starts with a fairly vague notion of a need or set of needs that their design will address. For example, a team could be tasked with designing a system to detect the posture of a user 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 situation are all open-ended and would require non-trivial problem formulation. In contrast, none of the prior studies nor the current work presented in this paper use the word "engineering design" to refer to very constrained design optimization-type projects.

In an ethnographic study of a third year mechanical engineering design class at Georgia Tech, 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, her primary lesson learned is that "old ontologies die hard… doing design does not insure the learning of design"[2].

Her findings explore the reasons why this is the case. She witnessed an incredibly 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 was 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. Student interpretations will not necessarily map easily and unproblematically onto those of the teacher. This study suggests that, at least with post- secondary students, the tacit view is so resilient and resistant that it overrides and confounds the explicit view.[2]

That is, students' pre-existing views (of the role of a teacher, of the purpose of a team, of the reasons for assignments) were incredibly different than that of the instructor. These pre-existing views were so strong that the instructor's approach to changing the behavior of the students (to become better engineering designers) only led to surface-level changes. 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 form, but never saw the purpose.

These results are not surprising when viewed in the larger context of findings from educational research. The first learning principle from *How People Learn*[3] 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[4]:

- 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 paper were at odds with how the instructor wanted the students to learn. Further, lack of motivation 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 from the prior research.

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. The study was conducted at the University of Arizona in the fall 2005[1]. The first year class at the University of Arizona was divided into 13 sections, each taught be a different faculty member. Students in each section completed two projects. In project 1, they designed, built and tested a solar oven. In project 2, five sections worked on a project similar to the solar oven project, three worked on a product dissection project, three worked with actual clients on service learning projects, and one worked on a fourth project. Only the service learning projects had significant problem formulation activities.

The instrument used was the Design Process Knowledge (DPK) critique, in which students critique a proposed design process that has several deficiencies, including the lack of problem formulation activities. The results, seen in Table 1, are reported as the percentage of students who correctly identified that problem formulation activities were missing in the proposed process.

Table 1 Percentage of Students Who Correctly Identified that Problem Formulation Activities Were Missing from Proposed Process in 2005 Study

2005 study	Lower 95% CI	Average	Upper 95% CI
Prior to Class	7.1%	8.7%	10.4%
After the Class	9.0%	10.8%	12.7%

A Wilcoxon signed-rank test on the difference from after to prior to the class reveals no significant difference (W=714, n=286 p=0.463).

Further, there was no significant difference found between the students on the three types of projects run by multiple sections. Not shown in the prior paper, Wilcoxon signed-rank tests on the difference from after to prior to the class reveal no significant differences for any project type (tractor project W=114, n-114, p=0.223; dissection project W=52.5, n=86, p=1.00; service project W=72, n=82, p=0.514)

In part due to comparison with fourth year students who moved from 14 to 23% and also to experts who scored 45%, one suggestion by Bailey[1] is that first-year students may not be intellectually mature enough to learn problem formulation skills.

Similar results were replicated at a different 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. The study was conducted at the University of Virginia in the fall 2007[5]. The first year class at the University of Virginia was divided into 16 sections, each taught be a different faculty member. Faculty members could choose how to run their section; as a result, there were sections with client-based projects, others doing Lego Mindstorms challenges, others working on hypothetical projects, and others doing a series of small discipline-focused projects.

With the DPK also being used, the following results in Table 2 aligned closely with those in the IJEE study.

Table 2 Percentage of Students Who Correctly Identified that Problem Formulation Activities Were Missing from Proposed Process in 2007 Study

2007 study	Lower 95% CI	Average	Upper 95% CI
Prior to Class	8.1%	10.6%	13.1%
After the Class	11.7%	14.6%	17.4%

A Wilcoxon signed-rank test on the difference from after to prior to the class reveals no significant difference (W=313.5, n=151 p=0.360).

Methods and Experimental Design

Based on the lack of gains in problem formulation knowledge in first-year engineering design courses, two interventions for introductory engineering classes at the University of Virginia were implemented to help students better learn the role of problem formulation activities. Two interventions for the introduction to engineering course at the University of Virginia were introduced in 2009. They were focused on addressing the lack of learning about problem formulation, one through a) exposing students to the their prior knowledge and tacit views about design and the other through b) shifting the motivation away from the extrinsic "getting good grades" and towards the more intrinsically driven "impacting people".

Both interventions are about confronting the students directly: Intervention 1 confronts the students with their own behaviors. Intervention 2 viscerally connects the students with the impact of their work.

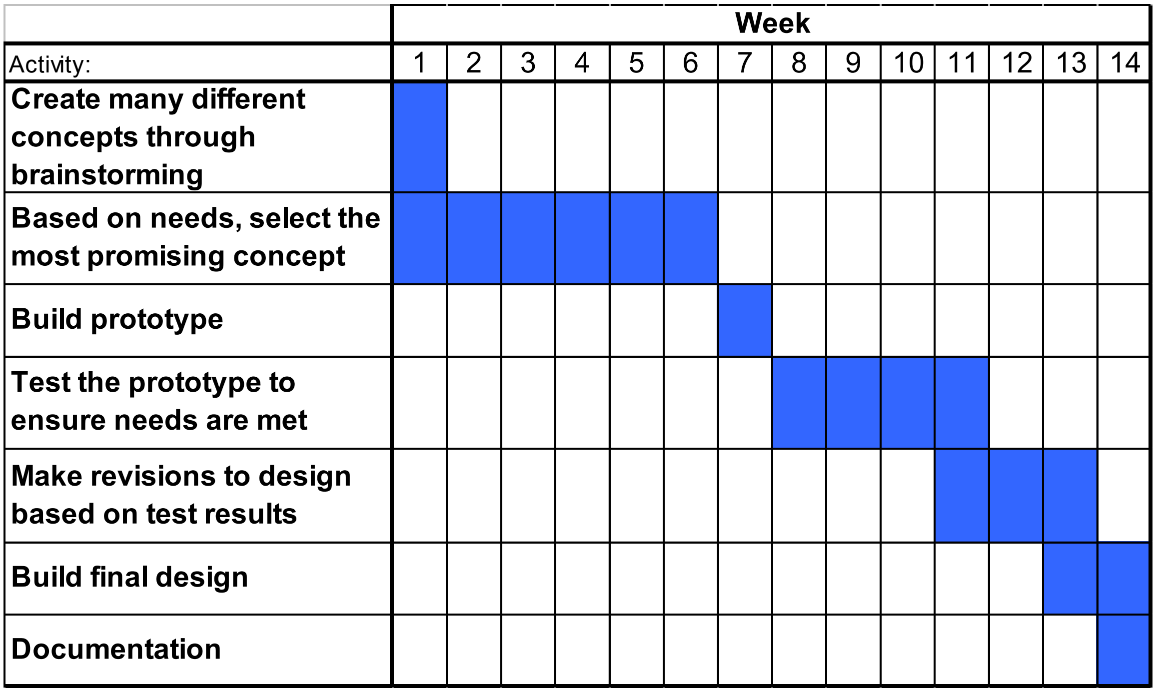
Intervention 1 is called the Chair of Scrap. With its name partially inspired by an activity in *Experiences in Visual Thinking*[6], students must design new seating for the professor's office with only recyclable materials. Given only one week, students work feverishly to design and build some sort of chair. Upon showing their designs proudly to the professor, they are surprised to hear that they have all made a crucial mistake. It is rare for *any of the students* to visit the professor's office or ask the professor any questions about what s/he wants in seating (i.e., they do not talk to any users or the client). It is even more rare for the students to generalize the problem and ask the professor why they think they need more seating (maybe they do not – maybe the best solution is a way to hold office hours online?) or to talk to students who have sat in the office to see what *they want* in a chair.

The bottom line is clear to the students: when left to your own devices (i.e., your existing knowledge), you did not engage the stakeholders for a design. And, we know that nearly all of the students would have said "yes" if asked, "should you talk to users of a design as part of a design process?" What they do does not match what they would say – which motivates them to be willing to change. This is huge in a situation where "old ontologies die hard."

Intervention 2 is testing the designs with users. As Newstetter finds, students' prior expectations for a class is that they need to please the teacher. By integrating the testing of the student designs by users, students shift to needing to please the user. In the interventions studied here, the users are groups of elementary-aged kids. Such a user group only amplifies the effect of shifting the focus away from the teacher: you cannot ignore the impact of engineers when you observe a bunch of elementary school children playing with your design, smiling, and laughing.

The Design Process Knowledge (DPK) critique, used throughout all of the studies in this paper, is an instrument previously used by multiple researchers in several studies to assess student recognition of the importance of specific design activities. The Design Process Knowledge (DPK) critique was designed to measure the types of activities and their relative arrangement over time that students think are important. It is process-focused (unlike design artifacts), at the individual level (unlike reports), time-efficient (unlike ethnography or video analysis), and can measure higher-levels from Bloom's Taxonomy (unlike close-ended questions)[7].

In the DPK, students are shown a Gantt chart of a proposed design process for a specific product and asked to critique the proposed process. Students are given 10 minutes to write their answers. The proposed design process used in this study does not include any problem formulation activities (See Figure 1).



	Week													
Activity:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Create many different concepts through brainstorming	🟦													
Based on needs, select the most promising concept	🟦	🟦	🟦	🟦	🟦	🟦								
Build prototype							🟦							
Test the prototype to ensure needs are met								🟦	🟦	🟦	🟦			
Make revisions to design based on test results											🟦	🟦	🟦	
Build final design													🟦	🟦
Documentation														🟦

Figure 1 Proposed Design Process in Design Process Knowledge Critique

A rubric developed to evaluate answers rates answers on seven design traits. In this paper, though, the only evaluation is a binary assessment of one design activity: is the lack of problem formulation activities in Figure 1 identified or not.

The details of the DPK and the rubric are described in other papers[1, 7, 8]. Researchers have used the DPK on first year students[1, 7, 9], capstone students[8], experts[1, 10], and elementary teachers[10].

Sample and Results

Based on three years of pre-post data of the courses with the two interventions, the percent of students that recognized the importance of problem formulation skills jumped from 19.6% prior to the course to 55.4% after the course. Data from five unique classes were collected in 2012, 2013, and 2014. Three of the five classes were taught by Professor A, one each year. Professor B taught the remaining two in 2013 and 2014. The exact dates of pre and posts tests are known for Professor A's students while the exact pre-test dates are not known for Professor B. Thus, the results only from Professor A's students are focused on here; that said, the conclusions do not change when Professor B's students were also included.

Fifty-six students from 2012-2014 completed both the pre and post test in Professor A's class. The results in Table 3 show the jump from pre to post-test scores.

Table 3 Percentage of Students Who Correctly Identified that Problem Formulation Activities Were Missing from Proposed Process in 2012-14 Study

2012-14 study	Lower 95% CI	Average	Upper 95% CI
Prior to Class	14.3%	19.6%	25.0%
After the Class	48.7%	55.4%	62.0%

A Wilcoxon signed-rank test on the difference from after to prior to the class reveals a significant difference (W=310.5, n=56 p=0.001). When data from both professors are included, the Wilcoxon signed-rank test on the difference from after to prior to the class also reveals a significant difference (W=748, n=93 p=0.001).

The results from the two prior studies and the 2012-14 data are presented on an interval chart in Figure 2.

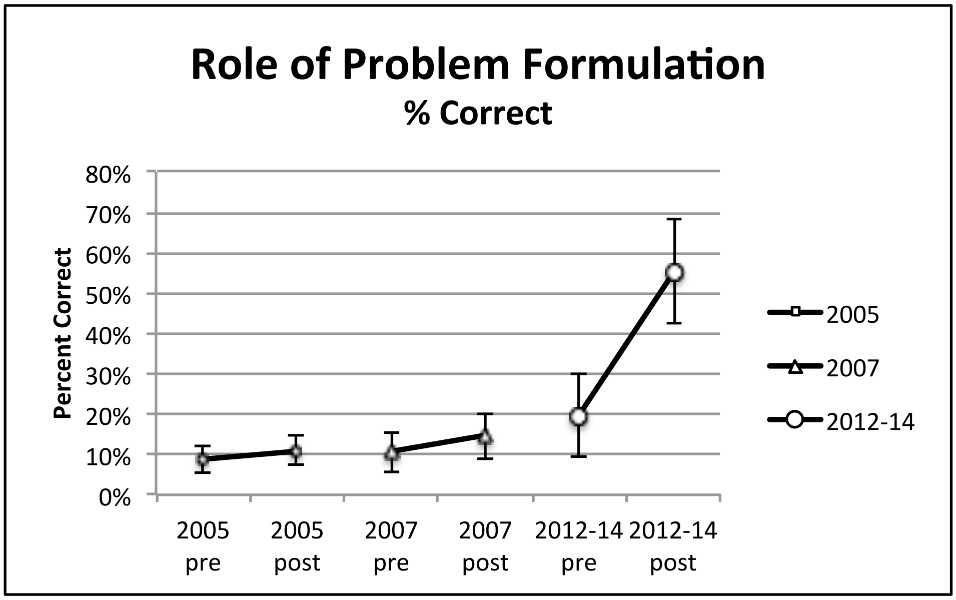


Figure 2 Percent of Respondents Who Correctly Identified Lack of Problem Formulation Skills

Discussion

While these results do not causally link the introductory assignment and user testing with improved learning about problem formulation, the large pre-post change suggests a link. Based on random assignment of students to the sections of the course at University of Virginia, the difference in performance of the 2012-14 group compared to the 2007 group cannot be attributed to a selection bias. This random assignment is supported empirically by the percentages of students who identify the lack of problem formulation activities in the DPK prior to the class in 2007 not being statistically different than those in 2012-14 (two sample test of proportions: z=-1.54, p=0.123). Further, the pre-class scores between 2005 at University of Arizona and those in 2007 at University of Virginia provide evidence of the generalizability of these results beyond one institution (two sample test of proportions: z=-0.62, p=0.538).

That said, without data from a true control group in 2012-14, threats to validity such as history and maturation persist. These threats prevent our making a causal connection between the two interventions and the large improvements seen in 2012-14.

Further, while the addition of the chair of scrap assignment and the integration of user testing were the two major changes to the courses between 2007 and 2012-14, the reality of any engineering course is that it evolves over time. To assert that the only change to the design classes in 2012-14 compared to the ones in 2007 were these two would be to ignore reality. Specific projects changed. The students were given better training in "making" skills in 2012-14. The professors matured and adapted their view of engineering design. Notwithstanding, the only two changes with direct connections to problem formulation are the chair of scrap assignment and the integration of user testing.

Returning to the quote “doing design does not insure the learning of design,” the findings suggest that exposing existing mental models (via the chair of scrap) and a powerful experience where the impact of learning can be directly seen (through the integration of user testing) can improve learning.

Further Work

To further identify the cause of the improved learning, next steps include interviews with students. Interviews with students will be used to probe more about the rationale for their responses. For instance, students who did identify the lack of problem formulation in the DPK will be asked 1) why did you include that in your answer? and 2) do you remember any experiences in class where this point was made particularly clear? Trends in such answers would be indicative of more causality between elements of the course and learning about the importance of problem formulation.

Conclusion

The results of prior work show that “doing design does not insure the learning of design”[2], with specific studies focusing on students “doing” problem formulation in class but not “learning” to do problem formulation outside of class. This study focused on a course where two interventions – an introductory assignment and the incorporation of user testing in the project – were made to improve the learning and retention of problem formulation design behaviors. Based on three years of pre-post data of the courses with the two interventions, the percent of students that recognized the importance of problem formulation skills jumped from 19.6% prior to the course to 55.4% after the course. While these results do not causally link the introductory assignment and user testing with improved learning about problem formulation, the large pre-post change suggests a link. Future work includes conducting interviews with students in the classes to explore reasons for this large change.

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