A Skills-focused Approach to Teaching Design Fundamentals to Large Numbers of Students and Its Effect on Engineering Design Self-efficacy

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Design courses are often tasked with teaching all the steps of the engineering design process in the span of a single semester. Project-based curricula are particularly useful in this regard, providing end-to-end exposure all the steps of the engineering design process, including fabrication, testing, and (sometimes) iteration. Examples of this include the approach (often replicated) to teaching design popularized by Ulrich and Eppinger [1]. Excellent reviews of the applications of end-to-end approaches, particularly in early college-level engineering design courses, can be found in the works of Wood and coworkers [2], [3].

It is evident, however, that the coverage of the design process is biased in many realizations of this approach; problem identification, research, and brainstorming are easily taught in a traditional classroom, whereas fabrication, testing, and iteration are often emphasized less, presumably because they are demanding of faculty time, and require greater physical resources. Indeed, some texts (e.g. [4]) and courses on design (e.g. [5]) have been organized to emphasize stages of the design process that do not involve fabrication or iteration.

Further, there can be great variability between the skills acquired by individual student teams, and between individual students on a given team. For example, a typical “divide and conquer” approach to a problem naturally gives rise to specialists on student teams; some team members may, for example, focus on documentation, while others focus on fabrication. Moreover, a design approach favored by one team may involve a diversity of prototyping skills, while another team may require only one (e.g. 3D printing). Indeed, we found this to be the case in our own implementation of the Ulrich and Eppinger model curriculum.

To partially overcome these limitations, we instituted three changes to a second-year design course. First, the course was delivered in two sections, partially online, to reduce the student-to-instructor ratio [6]. Second, rather than an open-ended project, the students were instead trained *individually* in a variety of useful engineering skills, ranging from embedded controllers and CAD, to power tools and welding. Finally, rather than a forward engineering approach to teaching design within the context of an open-ended project, design was instead learned through the reverse engineering approach [3], [7] of product archaeology [8], [9].

We assessed these changes relative to a previous project-based year via anonymous course evaluations, including textual analysis. We found that course evaluations were improved, that students better connect learning to skills, and that students appreciated the opportunity to develop a uniform skill set by the end of the semester. This is in contrast to a project-based class where skills development was not uniform between or within teams, and students did not connect learning to skills development. We further assessed this pedagogical approach by measuring the psychological construct *engineering design self-efficacy* at the beginning and end of the semester, since there are prior reports of gains in the confidence of students in their fabrication skills as a result of immersive design-build projects [10], [11]. We found that students’ belief in their abilities improved significantly over the course of the semester in every step of the engineering design process. We hypothesize that developing early student competencies in design fundamentals will lead to improvements in design projects in the later years of engineering students’ education, and at a level greater than project-based learning.

Intervention (non-immersive, skills-focused format)

To partially overcome these limitations, we instituted three changes to a second-year design course "BME Design and Discovery" in Biomedical Engineering at the University of Virginia.

First, "replacement" blended learning [6] was used to reduce the class size and lend flexibility to the class schedule. While the class is scheduled into an ordinary twice-a-week slot (i.e. Tuesday and Thursday), half of the class attends in person one of those two days (Tuesday), and the other half of the class attends on the other (Thursday). The entire class is responsible for a ~1.25-hour video lecture each week. Lectures were recorded using Camtasia (*www.techsmith.com*), while graded questions were embedded in the video lectures using an online tool (*www.zaption.com*). The embedded questions were meant not only to ensure completion and attention, but also to invoke the testing effect [12]. Using this seat-replacement blended learning approach, students received approximately the same amount of instructional time as in face-to-face approaches but with half the class size of a traditional class, and with the same demand on the faculty time (that is, after the video lectures have been created).

Second, rather than an open-ended project, the students were instead trained individually in a variety of skills and fabrication techniques that we judged to be valuable to the engineering design process as it pertains to devices. These included:

1. Embedded controllers and basic electronics
2. CAD, mechanical drawings, and FE simulation
3. Reference management software
4. Underused word processing features
5. 3D printing
6. Soldering and desoldering of circuits
7. Reducing soft stock material (table saws, circular saws)
8. Forming and shaping soft materials (band saws, jig saws, drill presses, sanders)
9. Forming and shaping metals (horizontal band saws, drill presses, grinders, tap and die)
10. Laser cutters and solvent welding
11. MIG welding

The fabrication skills in the above list (numbers 5-10) were taught to competency; that is, students were given a task and a tolerance (or other minimal goal), and were required to repeat the task until it was completed to specification. Provided that they committed no safety violations in the process, a perfect score was awarded once competency was demonstrated. Reports are difficult to find of *curricular* efforts to train students in fabrication [13], [14].

Finally, rather than a forward engineering approach to teaching design within the context of an open-ended project, design was instead learned through the reverse engineering approach of product archaeology [8], [9]. This enabled us to move some of the learning that previously took place in time-intensive projects to a more traditional classroom setting. Two product archaeology reports were generated by each student team. The first was due mid-term and was completed out of class. The artifact on which this mid-term report was written was the "Oral-B® 3D White™ battery powered toothbrush" (Walmart product number 553890159). The second product archaeology report was generated in real time during the 3-hour final exam period, with the artifact being the “CVS® Offset Grip Cane with push button height adjustment” (CVS product number 41731). The written style of the reports were as though students formed the product design and market analysis teams that were deciding whether to produce and sell this medical device.

Each report consisted of:

1. Value proposition (1-2 paragraphs)
    a. Value to the customer
    b. Market analysis
        i. The target market and its size (1 paragraph)
        ii. Competitive analysis (length as needed)
        iii. Regulatory landscape (1 paragraph)
        iv. The market potential, including a consumer-side forecast of sales (around ½ page, plus any descriptive text)
2. Design constraints (about 1/3rd page)
3. Approach (1 paragraph)
    a. A brief technical description of how the device functions
    b. A comparison to existing technologies and intellectual property
    c. For bonus points: find the patent for this *specific* mechanism
4. Design and manufacture (1 paragraph, exclusive of CAD requirements)
    a. What material and manufacturing process was most likely used for each part?
    b. Fully developed CAD drawings and simulations were also required, but submitted by each student separately.
5. References, and literature cited

Teams

Students in each section of the course were formed into teams of 5-6 (skills-based year) or 8-9 (project-based year) using CATME [15].

Comparison group (end-to-end, project-based format)

The year prior to our intervention the class was taught in an immersive, project-based manner. Students were presented with a real, unsolved clinical challenge, and worked in teams to solve the problem. Teams were required to progress through all of the stages of the engineering design process, including iteration. To this end, for the first half of the semester teams went through formal exercises in problem identification, research, and brainstorming. They were also formally trained in CAD. These steps were completed by mid-semester.

Teams then transitioned to hands-on design-build experiences. They were required to create both first- and second-generation prototypes of a functioning device, the former informing the latter to force iteration of the design process. Thus, an equal emphasis was placed on the latter stages of the engineering design process – fabrication, testing, and iteration – as on the early stages. In fact, 50% of the course grade was determined by the two physical builds, and a final invention disclosure.

Greater amounts of time were spent in a machine shop in this project-based format (a minimum of 2.5 hours per week for 7 weeks) than in the intervention format (1-2 hours per week for 4 weeks). While it was an immersive experience, in the project-based format, students and teams learned fabrication skills on an *as-needed* basis. In contrast, students in the non-immersive, intervention (skills-focused) format were *required* individually to accumulate a broad range of skills.

Metrics

<u>Engineering design self-efficacy:</u> We previously measured *engineering self-concept* (self-association with engineering) as a psychological construct, and found that it did not change over the course of a single semester, and possibly not even over the course of an entire career [16].

Thus, in the intervention year we instead measured *self-efficacy* – self-perceived ability or willingness to engage in engineering – using the 36-item "Engineering design self-efficacy instrument" [17] – that is, whether students believe they will be:

1. *Able*, and
2. *Motivated* to engage in engineering design tasks, whether they feel they will be
3. *Successful* in doing so, and how
4. *Apprehensive* they would be in performing such tasks.

Likert responses on these four dimensions were scored on a 0-10 scale, with 0 being low confidence, 10 being high confidence, and 5 being moderate confidence.

<u>Textual analysis:</u> *Self efficacy* was not measured in any year prior to the intervention, and class assignments differed so greatly from previous years that direct comparisons of assignment performance were not possible. However, because we were most interested in the psychometric measure of self-efficacy, we instead performed textual analysis on the two corpora of free response section of the end-of-semester course evaluations. These were mined using a web-based text analysis environment [18], and results were displayed as force-directed graphs. These graphs showed linkage between terms of interest (learning and skills), and other terms in the free response text.

Statistics

End-of-semester course evaluation scores were compared by unpaired, 2-tailed t-test. Pre- and post-semester scores on the *engineering design self-efficacy* instrument were compared using paired, two-tailed t-tests. Effect sizes are reported as Cohen's d.

Results and discussion

<u>Student perceptions of their own learning improved in a skills-focused format relative to a project-based format:</u> End-of-course evaluations were significantly improved for the course itself ($p = 0.023$), but not for the instructor ($p = 0.152$). Typical student comments in the project-based year included references to perceived disorganization of the course resulting from the uncertainty of a real-world design challenge. Respondents also made frequent reference to not feeling as though they learned very much in the class. In contrast, typical student comments in the skills-focused year often referred to having learned a great number of practical skills that they felt could be used later.

We used a semi-quantitative text analysis technique to further dissect these perceived relationships. The free responses of the anonymous course evaluations were used to generate a work linkage map surrounding the five most often used words; when they were not originally part of the set, we forced inclusion of variants on the words "learn" and "skill". A comparison of the linkage maps from the project-based and skills-focused semesters is shown in Figure 1.

Note that in the project-based semester (Figure 1, left), variants of "learn" are connected strongly only to a single, specific skill (CAD), and neither to variants of "skill" nor to the broader concepts of "course" or "class." "Skill" was only weakly associated with any other words, and again neither to "course" or "class." We interpret the lack of association between skills, learning, and course as indicating that students perceived a classroom environment where their learning expectations were not met. "Time" was another dominant word, and its linkage to pejorative terms was notable.

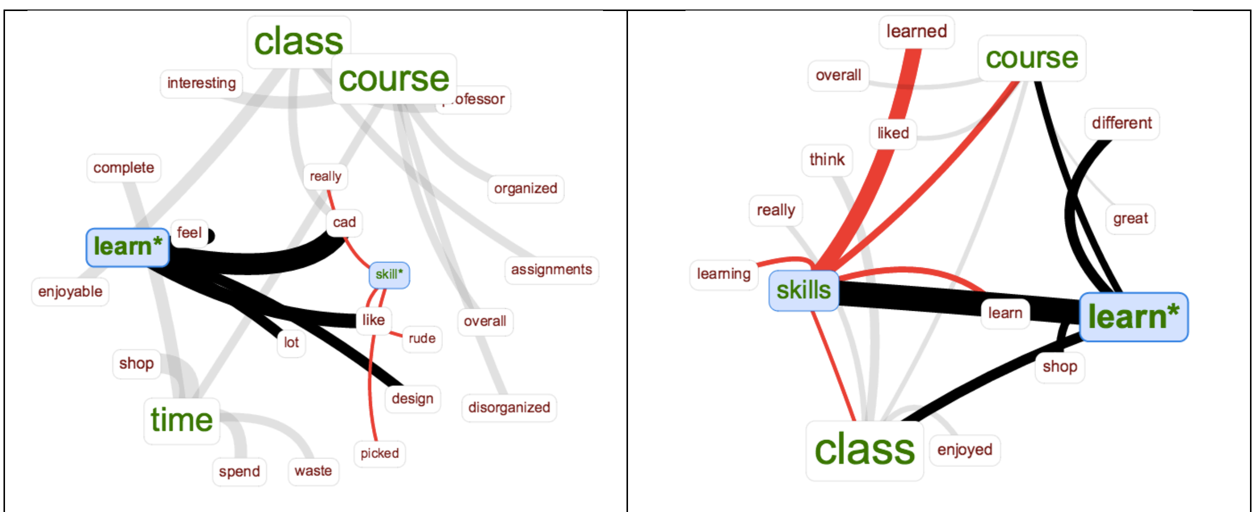

Figure 1: Linkage maps for learning-related (red) and skills-related (black) words. Left: the project-based semester. Right: the skills-focused semester. The size of each word group is proportional to the number of uses in student free-responses, while the width of the connecting lines shows the frequency with which the two words colocate (within three words) in the corpus of student free-responses. The 4-5 most commonly appearing words in the text are shown in green.

In contrast, in the skills-focused semester (Figure 1, right), variants on "skill" were very strongly linked to variants on "learn," and both learning and skills were very well linked to "course" and "class." We interpret this as being a classroom environment in which students perceive the structure and the outcomes of the course to be well aligned with one another, and with their learning expectations.

A skills-focused format improves self-efficacy over the course of a single semester: Students in the intervention year began the semester with moderate belief in their engineering design *ability*, moderate *motivation* to engage in such tasks, moderate confidence in their ability to be *successful* in such tasks, and low-moderate levels of *anxiety* about performing such tasks (Table 1). We noted, however, that students' belief in their *ability* to construct a prototype (3.8 ± 0.4) was significantly lower than the next lowest *ability* score ($p = 0.023$, N=84); that is, of the array of engineering design skills listed, students self-declared *ability* was lowest for fabrication. Students similarly had the highest *anxiety* about prototype construction ($p = 0.039$, N=84).

Table 1: Beginning of semester (pre) scores for engineering design self-efficacy, expressed on a 0 (low) – 10 (high) scale. Note that low *apprehension* scores are desirable, while high scores for *ability, motivation*, and *success* are desirable. Errors are expressed as standard error of the mean.

	Ability	*Motivated*	*Successful*	*Apprehension*
Conduct engineering design	4.8 ± 0.3	6.01 ± 0.31	6.4 ± 0.4	4.2 ± 0.4
Identify a design need	6.7 ± 0.3	6.4 ± 0.3	7.3 ± 0.4	3.4 ± 0.4
Research a design need	6.5 ± 0.4	6.2 ± 0.4	6.6 ± 0.4	3.0 ± 0.4
Develop design solutions	4.8 ± 0.3	6.6 ± 0.4	6.7 ± 0.4	4.4 ± 0.4
Select the best possible design	6.4 ± 0.3	7.1 ± 0.3	7.3 ± 0.3	4.3 ± 0.4
Construct a prototype	3.8 ± 0.4	5.8 ± 0.4	6.5 ± 0.4	5.8 ± 0.4
Evaluate and test a design	5.5 ± 0.4	6.9 ± 0.3	7.3 ± 0.4	3.7 ± 0.4
Communicate a design	5.9 ± 0.4	6.1 ± 0.4	6.4 ± 0.4	4.6 ± 0.4
Iterate a design / redesign	5.3 ± 0.3	5.7 ± 0.3	6.1 ± 0.4	4.8 ± 0.4

We next calculated difference scores to compare *self-efficacy* at the end of the semester to the beginning (Table 2). Students gained significantly in their belief in their *ability* to perform all steps of the engineering design process. Gains in other dimensions of self-efficacy were less uniform. For example, the largest gains, and gains in all four dimensions of *self-efficacy*, were seen only in the step of "construct a prototype." This is perhaps not surprising given the emphasis in this course on fabrication skills building. Perhaps most surprising is that there were gains in three dimensions of "iterate a design," even though there was no iteration in this class format. Similarly, "identify a design need" saw gains in three dimensions of *self-efficacy*, though this was addressed only through the lens of product archaeology, not through immersion in a design project.

To reduce the risk of inferring significant difference by chance, we summed all the scores in each dimension to give a composite score. It is noted that the number of questions and responses in each dimension were identical. The composite score shows that while students report feeling more *able* and *motivated* to perform engineering design, and less *apprehensive* about doing so, they remain no more convinced that they will be successful in completing the task (p = 0.888, *d* = 0.012, N=84 for *success*). This is in contrast to students to first-year students in a very similar immersive project-based design class taught by us, who showed significant gains in the *successful* dimension over the course of a single semester [11]. This may reflect a limitation of the skills-focused approach; students do not see the end product of a design experience.

Table 2: Gain and in loss in dimensions of engineering design self-efficacy over the course of the semester. Note that net loss in apprehension is desirable, while net gains in the other three dimensions are desirable. Gains/losses highlighted green are significant by classic standards (p<0.05). Gains/losses highlighted in gold are significant at the level of p<0.10. Errors are expressed as standard error of the mean. N=84 in all instances.

		Ability	Motivated	Successful	Apprehension
Conduct engineering design	*p*	<0.001	0.063	0.358	0.438
	Gain	2.08 ± 0.45	0.65 ± 0.43	-0.36 ± 0.5	0.3 ± 0.57
Identify a design need	*p*	<0.001	0.001	0.487	0.035
	Gain	1.43 ± 0.44	1.28 ± 0.46	-0.3 ± 0.51	-0.96 ± 0.52
Research a design need	*p*	<0.001	0.052	0.063	0.589
	Gain	1.79 ± 0.47	0.77 ± 0.53	-0.77 ± 0.56	-0.24 ± 0.52
Develop design solutions	*p*	<0.001	0.052	0.372	0.062
	Gain	2.62 ± 0.46	0.8 ± 0.49	0.3 ± 0.53	-0.89 ± 0.59
Select the best possible design	*p*	<0.001	0.358	0.191	0.193
	Gain	1.82 ± 0.42	0.36 ± 0.47	0.54 ± 0.47	-0.66 ± 0.61
Construct a prototype	*p*	<0.001	0.002	0.028	0.055
	Gain	2.58 ± 0.52	1.19 ± 0.53	0.89 ± 0.55	-1.01 ± 0.6
Evaluate and test a design	*p*	<0.001	0.090	0.438	0.259
	Gain	1.96 ± 0.49	0.75 ± 0.46	0.3 ± 0.46	-0.54 ± 0.53
Communicate a design	*p*	<0.001	0.055	0.550	0.330
	Gain	1.61 ± 0.5	0.65 ± 0.53	-0.24 ± 0.53	-0.42 ± 0.59
Iterate a design / redesign	*p*	<0.001	<0.001	0.885	0.005
	Gain	2.08 ± 0.44	1.43 ± 0.45	-0.06 ± 0.48	-1.25 ± 0.54
Composite score	*p*	<0.001	<0.001	0.888	0.036
	Gain	17.62 ± 2.54	7.62 ± 2.51	0.3 ± 2.79	-5.65 ± 3.52

It is worth noting that the effect size for *ability* was large (*d* = 0.758), while those for *motivation* and *apprehension* were small (*d* = 0.331 and *d* = 0.175, respectively). In fact, the overall change in the *ability* dimension and the effect size was similar to that found in the above-mentioned first-year engineering design class [11].

Conclusion

A skills-focused approach to teaching an introductory design course offers certain practical and pedagogical advantages over an open-ended, project-based approach. The time commitment of instructors is reduced, students better connect learning to skills development, and students achieve significant improvements in the *able*, *motivated,* and *apprehensive* dimensions of engineering design self-efficacy. Further, this approach is consistent with modern learning strategies. By analogy to *problem*-based learning,

> "there have been 11 meta-analyses relating to problem-based learning based on 509 studies, leading to an average small effect (*d*=0.15). It hardly seems necessary to run another problem-based program to know that the effects of problem-based learning on outcomes are small. The reason for this low effect seems to be related to using problem-based methods before attaining sufficient surface knowledge." [19]

We hypothesize that, like obtaining surface knowledge before engaging in problem-based learning, developing early student competencies in the skills underpinning engineering design will lead to improvements in design projects in the later years of engineering students' education. These underpinning skills ought not be restricted to mathematics and computation, but also include fabrication. We assert that these skills are best gained through overt training rather than "as needed" in the context of a project-based class.

Literature Cited

[1] K. T. Ulrich and S. D. Eppinger, *Product design and development*. Irwin/McGraw-Hill, 2000.

[2] M. D. Murphy, K. L. Wood, K. Otto, J. Bezdek, and D. Jensen, "Building Better Mousetrap Builders: Courses To Incrementally And Systematically Teach Design," presented at the 1998 Annual Conference, 1998, p. 3.129.1-3.129.21.

[3] K. L. Wood, D. Jensen, J. Bezdek, and K. N. Otto, "Reverse engineering and redesign: Courses to incrementally and systematically teach design," *J. Eng. Educ. Wash.*, vol. 90, no. 3, p. 363, Jul. 2001.

[4] V. R. Johnson and R. Bailey, *Becoming a Technical Professional*. Kendall Hunt Publishing Company, 2006.

[5] C. L. Dym, F. Jones, and P. E. Design, "Teaching Design to freshmen: Style and Content," *J. Eng. Educ.*, vol. 83, pp. 303–310, 1994.

[6] C. A. Twigg, "Improving Learning and Reducing Costs: New Models for Online Learning," *Educ. Rev.*, vol. 38, no. 5, pp. 28–38, 2003.

[7] R. D. Rogge *et al.*, "The Innovation Canvas as a Teaching Tool in Capstone Design: A Reverse-Engineering Case Study," in *Proceedings of the 2014 ASEE Annual Conference*, 2014.

[8] K. Lewis *et al.*, "The Assessment of Product Archaeology as a Platform for Contextualizing Engineering Design," p. V001T04A024, Aug. 2013.

[9] J. Tranquillo, "The Product Archaeology Canvas," 2015, p. 26.1565.1-26.1565.23.

[10] D. Faas and D. D. Frey, "Quickly Building Students' Confidence in their Fabrication Abilities," presented at the 2013 ASEE Annual Conference & Exposition, 2013, p. 23.1016.1-23.1016.17.

[11] W. Guilford, A. Blazier, and A. Becker, "Integration of Academic Advising into a First-year Engineering Design Course and Its Impact on Psychological Constructs," 2015, p. 26.995.1-26.995.13.

[12] C. B. Kromann, M. L. Jensen, and C. Ringsted, "The effect of testing on skills learning," *Med. Educ.*, vol. 43, no. 1, pp. 21–27, Jan. 2009.

[13] A. Nimunkar, S. Bernardoni, T. Lark, and W. Tompkins, "Student Initiated Supplemental Training Curriculum For Support Of Bme Design Projects," presented at the 2009 Annual Conference & Exposition, 2009, p. 14.1083.1-14.1083.9.

[14] S. Bernardoni, A. Nimunkar, J. Murphy, and S. Courter, "Student Initiated Design And Implementation Of Supplemental Hands On Fabrication Training Curriculum In An Introduction To Engineering Design Course: A Tqm Approach," presented at the 2008 Annual Conference & Exposition, 2008, p. 13.1108.1-13.1108.23.

[15] R. Layton, M. L. Loughry, M. W. Ohland, and G. D. Ricco, "Design and Validation of a Web-Based System for Assigning Members to Teams Using Instructor-Specified Criteria," *Adv. Eng. Educ.*, vol. 2, no. 1, pp. 1–28, 2010.
[16] F. L. Smyth, B. A. Nosek, and W. H. Guilford, "First year engineering students are strikingly impoverished in their self-concept as professional engineers," *Proc. 2011 ASEE Annu. Conf. Expo.*, p. AC 2011-2087, 2011.
[17] A. R. Carberry, H.-S. Lee, and M. W. Ohland, "Measuring Engineering Design Self-Efficacy," *J. Eng. Educ.*, vol. 99, no. 1, pp. 71–79, Jan. 2010.
[18] S. Sinclair, G. Rockwell, and Voyant Tools Team, "Voyant Tools," 2012. [Online]. Available: https://voyant-tools.org/. [Accessed: 09-Feb-2017].
[19] J. A. C. Hattie and G. M. Donoghue, "Learning strategies: a synthesis and conceptual model," *Npj Sci. Learn.*, vol. 1, p. 16013, Aug. 2016.