Mini-Design Projects in Capstone: Initial Design Experiences to Enhance Students' Implementation of Design Methodology

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Designettes in Capstone: Initial Design Experiences to Enhance Students' Implementation of Design Methodology

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Abstract

Capstone design courses are intended to provide a culminating experience for senior undergraduate engineering majors. Universities vary in how they implement the instruction and implementation of the design process in their capstone courses. For example, many have a separate class in design methods, followed by a one-semester capstone course where teams work on a "design, build, test" project. Other institutions teach design methodology incorporated into the capstone design project in what is often a two-semester capstone sequence. In the cases where design methodology is incorporated into a two-semester capstone course, it is possible that this is the students' first extensive exposure to design methods and process. In that case, students may be experiencing methods such as "Customer Needs Analysis", "Functional Decomposition", "Concept Generation", "Concept Selection" and "Prototype Planning" for the first time. From a constructivist educational standpoint, it can be problematic for students to apply these design techniques for the first time on what is often a complex, real world capstone design problem. One solution to this problem is to incorporate a short design experience at the beginning of the two-semester capstone course. This can allow the students an initial experience with the design methods that can provide a "learning scaffold" for their implementation of the full suite of design methods over the course of a two-semester project. For the last three years, we have implemented three versions of a short, introductory design project (i.e. designette) in our two-semester capstone design sequence. In our uses of the designette project, the suite of five core design methods mentioned above were taught in an abbreviated form. However, in one year the designette lasted ten class hours, the next year's designette lasted 14 class hours, and this past year's project lasted seven class hours. The longest designette allowed for greater depth in the initial coverage of the methods and also provided greater time for prototyping and testing. Of course this was at the cost of consuming a greater percentage of the overall time allocated for the actual capstone design project. This paper reports on the implementation details of the designette projects, focusing in particular on advantages and disadvantages of the different implementations in the most recent years. Faculty and student feedback indicated that the use of the designette does increase student familiarity with the design methods. However, more subtle questions such as the number of lessons allocated for the designette and the depth of coverage of the design methods have much more complicated assessment results.

1. Introduction

Capstone design courses have become ubiquitous in engineering education programs for many reasons. They bring together many elements of a student's previous engineering education in an integrated, project-based learning experience prior to award of a degree and work as a practicing

engineer. The capstone design experience achieves the outcomes desired of accrediting bodies and approaches learning through a different pedagogical model by making the learning more hands-on, interdisciplinary and purpose-driven. As a typically late course of instruction in engineering curriculum, failure to solidify key engineering tenets and the design process does not leave time for recovery, therefore, it is imperative to seek ways to optimize their learning outcome results. The following subsections will continue to introduce the use of capstones and how this research seeks to understand an improved approach to increased learning in capstone experiences through use of early, short design exercises in the capstone course.

1.1. Engineering design education in capstones

The purpose of a capstone engineering design project is rooted in the need to provide a culminating experience to engineering students. The design and creation of a system with multidisciplinary teams are key tenets of the Accreditation Board for Engineering and Technology (ABET) recommended student outcomes.[1] While the ABET "General Criterion 3: Student Outcomes A-K" are meant to be satisfied throughout an entire curriculum, the course outcomes of most engineering capstones seek to meet most of these outcomes in an integrated fashion during capstone design courses. The following outcomes are used to frame and assess the capstone engineering course in the department of this research.

1. Given a statement of customer need, students design a system to satisfy that need based on commercial product development best practices.
2. Students will demonstrate the ability to effectively communicate their design.
3. Students will demonstrate the ability to fabricate a functioning prototype of their design.
4. Students will demonstrate the ability to be effective interdisciplinary team members and leaders.
5. Student designs will comply with a realistic level of engineering codes and standards and shall include considerations such as environment, economics, manufacturability, sustainability, health and safety.

While these outcomes could be applied to the design of one final project during capstones, the intent of this paper is to show how possibly an iterative approach towards a capstone design experience may improve learning for the students.

Capstone engineering courses are typically taught through one or two semester-long courses.[2] In the former case, the capstone is typically paired with a separate, previous course that covers the theoretical concepts of the design process. In the latter case with a two semester long capstone, the design process steps are woven into the project of interest throughout the two semesters. There is some research that suggests that engineering capstones are beginning to emphasize the post-conceptual phase considerations in design leading to more two semester long capstone courses.[3] The full experience of typical design process steps simply takes time to fully explore in meaningful ways for complex engineering projects.

While this move towards longer capstone courses is supported for the above reasons, a question remains of what is the most effective method to impart the design process in these capstones. With a single, linear approach to the design process over the course of two semesters, students

can fail to understand the implications of early design steps until much later in the course which does not allow for reflection and improved learning. One of the key early design process steps is the analysis of customer needs. Through experience it has been observed that students struggle to grasp the importance and nuance of this stage of design. This unfortunately can lead to further churn, rework, and major schedule impacts later in the time-constrained capstone. This struggle is not limited to only the educational domain, but is a challenge for many in the engineering design industry.[4]

Without a clear understanding of what lies ahead for a student, there is a tendency to take each step only at face value, without appreciating the integrated fashion in which engineering design should be approached. Such a single, linear approach to the design process can also be contrary to the learning styles of many of the students. Typically, students drawn to engineering majors are of the "sequential" learning style;[5] however, complex engineering challenges require a "global" perspective that relies on divergent, innovative thinking styles. The former style fits well in traditional elementary and secondary education models, but the capstone experience forms the intersection of sequential learning and global considerations for complex engineering projects. The course framework for both learning styles should take this into consideration.

In addition to the sequential/global learning balance, there also needs to be a balance of induction learning and deduction instruction methods.[5] Traditional instructional methods can lean towards presenting the general case for a concept (deductive method) and then provide examples (inductive) that support that generalization (though, good instructors will balance this approach with inductive methods). Students, on the other hand, tend to form a framework of understanding based on specific experiences of examples and then accept a general concept – inductive learning. As a largely experiential course, the capstone can support the inductive learning style well. The necessary deductive-style teaching of accepted engineering design steps should be balanced with the inductive learning of the students. The challenge lies in allowing the experiences of the students' inductive learning to occur with enough time to reflect and build their cognitive framework.

The capstone experience is not just the last course in the an undergraduate engineering education, it can also be viewed as a precursor to degreed engineering work in industry with higher risks to project performance and the standards expected of engineers in later phases of design. The ability to understand these risks and manage them appropriately is something that capstone has a real potential to improve.

1.2. Risk management

A major concern of hands-on academic projects, especially in a research and development (R&D) environment engineering students must function within, is the increased potential for safety incidents to the students or bystanders. Universities that apply emphasis on safety throughout technical courses, labs and projects should experience lower injury rates than those institutions that do not actively emphasize safety. Electing to include simple risk and safety assessment tools into classes, projects, and even designette teams can yield significant benefits to individuals performing duties as student and later as industry professionals.

Unfortunately, undergraduate students are often not adequately exposed to risk and safety practices until after accidents happen. This reactive approach to hazards, instead of conducting critical thinking beforehand to understand the associated risks or hazards, places students in an unsafe situation and hinders the ability to successfully conduct noteworthy research and design. Structuring technical projects to incorporate risk mitigation and safety applications will produce better results as well as decrease the potential for personal injury, or worse, fatality of a student. If applied correctly within academic research teams, these applications will aid students to 1. Identify hazards, 2. Assess hazards, 3. Develop control measures, 4. Implement controls, and 5. Supervise and evaluate the steps taken to mitigate associated risks.[6,7] These basic assessment steps students take help develop their attitude regarding safety making them an advocate for safety practices. Moreover, failure in recognizing the importance of risk mitigation can result in devastating outcomes.

One particular incident reported by Yale University in 2011 cited the tragic death of a student while operating an industrial tool to work on a senior design project. A 22 year old undergraduate Physics student was killed by a machine shop lathe within one of the school's hazardous areas.[8,9] Furthermore, one could assume this type of accident resulted from a lack of operator training on safe operation of the equipment, or potentially, substandard safety culture within the facility. Since achieving zero mishaps is unlikely given the industrial environment technical students learn in, a more realistic approach is to properly educate and train students on risk and safety procedures that create a culture of safety-mindedness. Therefore, institutions of higher learning should strive to introduce students to risk and safety applications as soon as possible through a hands-on demonstrative approach such as at the institution of this research. To support this training demand, the hosting department of this research administers a semester-long tool familiarization course open to all students.[10] Moreover, this course is mandatory for mechanical engineering students and it is the basis for developing a foundation of safe practices. Students exposed to hazards within the department's engineering facilities are able to identify the potential risks associated with a task or other technical action. Throughout the institution's tool safety course, students are provided un-interrupted opportunities to review, analyze, and operate a variety of industrial equipment and tooling.

Considering the premise of undergraduate technical projects, the probable risk is higher since most students have not been exposed to manufacturing processes at this point in his or her life. Nevertheless, this limited experience should not prevent students from participating on teams and serves to highlight a critical need to incorporate risk management into the planning process. When applied correctly and proactively, the results of risk management support a vital requirement to apply specific personal protective measures while conducting rudimentary R&D such as initial and interactive prototyping applications. Implementing risk mitigation steps will highlight hazards associated with any project students are assigned by their instructors or curriculum.

Another benefit of strong safety processes within technical academics is the freedom this provides to students. Under a structured safety program, students are confident in their abilities to work on projects both in and outside of class time. Thus, the overarching risk and safety programs at this institution empower students to maximize the use of facilities in order to conduct detailed research and analysis on a variety of projects. This emphasis on risk

management in capstones is a unique and key enabler for engineering students conducting capstone research.

Risk mitigation and safety are integrated into our designettes. As with all of the design process steps, this allows for scaffolding type learning for the students. Of particular note is the fact that the projects used in the designettes are chosen so that students can gain initial experience with the tools in the lab during the prototyping process, but the projects themselves are relatively safe compared to some of the extensive projects undertaken for the remainder of the capstone. For example, we used design of an innovative alarm clock as one of the designette projects where as design of a formula car is one of our full projects. It is obvious that the safety issues associated with design of the alarm clock are far less than those of the formula car, providing a safe scaffolding step for students to engage with risk and safety issues.

2. Related research

Research in recent years has explored the question of how to most effectively teach a design process throughout an engineering curriculum. Of particular relevance to this paper's research is the concept of a "designette."[11,12] Originally coined at the Singapore University of Technology and Design (SUTD), designettes[a] are described by the originators as "glimpses, snapshots, small-scale, short turnaround and well-scoped design problems that provide a significant design experience."[11] The use designettes was "found to increase students' self-perceptions of their ability to solve multidisciplinary problems."[12] Within this design instruction paradigm of designettes, the methods proposed in this paper would most easily align with the "2D" level of designettes. In addition to the concept and framework of designettes, its originators have also provided an extensive overview of their benefits and a review of various universities' approach to capstones. Following this review of other programs, ten "designette characteristics" were proposed to aid others (i.e. this research) in developing designette implementations.[11] These ten characteristics were considered in the development of the current research.

There have also been extensive reviews of different formats and delivery methods of design education.[3,11,13] Through those and the direct experience of the authors, it was found that there are many approaches to the delivery of design education in capstone. As discussed in earlier sections of this paper, capstone design experiences can take the shape of one and two semester courses. Introduction of design process steps can take the form of lecture, case study, design exercises, textbook reading, process summaries in advance of application, and other approaches. The capstone projects themselves also vary widely within each institution making comparisons between projects and across domains difficult. There is research currently being conducted to provide a framework of understanding for different capstones.[14] Its goal will be to determine if there are correlations with student learning outcomes and a suite of capstone characteristics (e.g. length, team size, funding type, degree of constraints, system level, agility of design process, etc.). This paper's incorporation of a designette would represent one aspect of the suite of capstone characteristics that should be considered in the framing of future offerings.

[a] Originally, designettes were referenced as "designiettes."[11] The spelling was changed in subsequent publications[12] by the original author.

The current research is also a continuation of previous research in the area of mini-designs, which are highly related to the concept of designettes. In that study, a comparison of the incorporation a small mini-design experience at the beginning of capstone was assessed for its effectiveness. The use of mini-designs was shown to create students with a "more holistic understanding of the design process," and achieve a "slightly more rapid increase in understanding."[15]

3. Research approach

Capstone design projects are typically either a one or two semester experience occurring during the undergraduate engineering major's senior year. In some schools, the capstone experience is preceded by a previous course in design methodology. However, in many cases, the capstone project is the student's first experience implementing the full design process. In some cases, the two semester capstone sequence is separated into a first semester where design methods are taught, and the students practice these methods, but the final design project is not introduced until the second semester. In other cases, the final project is the focus for the design team for the full two semester sequence.

In the case where there is no design methods class prior to their capstone course, and where the final project is introduced at the beginning of the two semester capstone sequence, the students will be implementing the full design process for the first time on their final, most likely real-world, project. The lack of familiarity and experience with the design process can have significant drawbacks. In particular, students have difficulty seeing how the different parts or steps in the design process relate to each other. They may also question why they need a process at all; believing that a simple "brainstorm-build-test" process may be sufficient to produce quality results and would also avoid the time consuming design methods such as Customer Needs Analysis, Functional Decomposition, Ideation, Concept Selection and Prototyping. While experienced designers know that the implementation of a quality design process will significantly increase efficiency and effectiveness, students often do not have the experience or the training necessary to internalize these facts.

Constructivist learning theory applied to this situation would suggest that some initial experience with the methods may provide the needed mental scaffold for the students to gain an initial understanding of the interrelatedness of the different parts of the design process as well as to appreciate the value of the process itself. It is with this in mind that we developed our research questions.

Research Question: Is it effective to incorporate a designette before introducing the final design project in a capstone design course?

Effectiveness of the designette will be assessed based on five variables: 1) time taken to perform the designette, 2) increase in effective team dynamics, 3) increased understanding and correct implementation of the design methods, 4) change in team motivation, and 5) increased familiarity with risk management and safety issues. Over the last three years, we have

implemented four different versions of our capstone course with respect to the use of the designette. Table 1 below provides an overview of the four implementations.

Table 1 – Four Implementations of the Designette

Year 1a	No designette	Immediate introduction of the final design project at the beginning of the course. Only a brief overview of the design process before beginning implementation in the context of the final project.
Year 1b	10 class-hour designette	Self-directed implementation of major design process steps spread over 8 course hours with 2 hours at the end for presentations and prototype demonstrations.
Year 2	14 class-hour designette	Lecture and implementation of design process steps spread over 12 course hours with 2 hours at the end for presentations and prototype demonstrations.
Year 3	7 class-hour designette	Lecture and implementation of major design process steps spread over 6 course hours with 1 hour at the end for presentations and prototype demonstrations.

While a full design process will include numerous steps (as can be seen in the Figure 1 below), our implementation of the designette only includes a subset of the methods in the full design process. The methods we have included in the designette are: Customer Needs Analysis, Functional Decomposition, Ideation, Concept Selection and Prototyping.

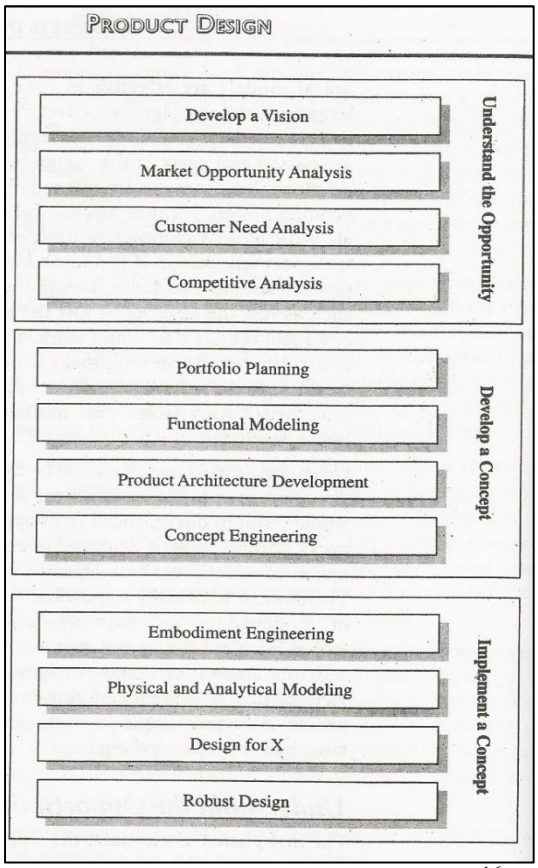

Figure 1 – Product Design Process[16]

In the first year of implementation, two groups were identified. One group participated in the capstone with no change from previous offerings where the final project was introduced immediately, and the design process steps were introduced in traditional lecture. A second group was exposed to a designette approach where they were given eight hours of self-directed class time to achieve a working prototype of a scoped mini-project (this is four classes in our syllabus as the capstone design course has two hours of contact per lesson). This second group was provided with review material of the design process that they were exposed to in previous courses. Following the 8 hours of class work time, the students presented their designs to faculty in a competition.

In the year two implementation, these methods were covered in lecture and then implemented during 14 hours of class time. This allowed for a relatively substantial development of the methods, normally allocating 30-45 minutes for each of the five design process steps and then allowing the team to implement that step over the course of another hour or so of class time before the next process step was introduced.

In the year three implementation, the five steps were covered in much less detail. Specifically, all five were covered in approximately 90 total minutes of lecture. The teams then implemented these process steps over the following three hours of in-class time (in addition to whatever out of class time they dedicated).

In addition to the differences in implementation of content for the designette in years two and three, the projects used for the designette were different as well. For year two (14 hour implementation) the project was to design, build and prototype an innovative alarm clock for use by students. In year three (seven hour implementation) the project was to redesign a small quadrotor. Issues related to the characteristics of the project used for the designette as well as results in the five assessment categories (time taken to perform the designette, increase in team dynamics, increased familiarity and correct implementation of the design methods, change in team motivation and increased familiarity with risk management and safety issues) were assessed.

4. Results

The following subsections of results come from several sources. The first year implementation of a mini-design/designette with a control group was assessed based on faculty and student perceptions and reported in a previous publication.[15] That research concluded that "the use of a [10 class hour] mini-design competition at the beginning of a capstone course produced beneficial effect in student understanding and application of the design process."[15] For a comparison of the second and third year implementations, there were three methods used which are presented below. First, a faculty poll was used to establish initial thoughts on the year three designette implementation in context of the prior year implementations. Second, specific faculty members were invited to provide comparative observations on their designette experiences. These explore both a horizontal (within the same year implementation) and vertical (across multiple implementation years) comparison of implementation. Finally, all faculty involved in

the study participated in a group discussion to clarify answers solicited in the poll and provided additional insight.

4.1.Faculty poll data

Following the second year implementation (14 class hour designette), all involved capstone faculty were informally polled for their impression of the designette experience. Observations included bimodal support for the designette (i.e. most faculty either loved it or hated it with few neutral opinions), students gained a better appreciation of the customer needs solicitation step through use of a consumer-level product design task, and there was concern over the length of the designette at the expense of the larger capstone project. The bi-modal support was perceived to be dependent on the manner in which the competition structure was implemented following the designette. Those teams which were supportive of the competitive nature of the designette competition were generally supportive of the designette. Those who were not intrinsically motivated towards the competition were also not supportive of the designette approach. The second year implementation also used a consumer-level product (an alarm clock) that enabled an extensive customer needs analysis phase. This seemed to allow the students to better appreciate that design step and was able to understand the importance of it in their later capstone projects. There was also concern over the length of the designette, in that it began to be perceived as consuming time that would otherwise be allocated directly to the capstone final project. Rather than viewed as contributing to more effective use of the capstone time, it seemed to be in competition with that time in a "zero-sum" way. Based on these observations, the capstone director adjusted the designette experience for the third year implementation.

Following the third year implementation (7 class hour designette), all involved capstone faculty members (n=7) were polled for their perception of the designette experience. The following figures (2-10) display the response data to 7-point Likert scale questions.

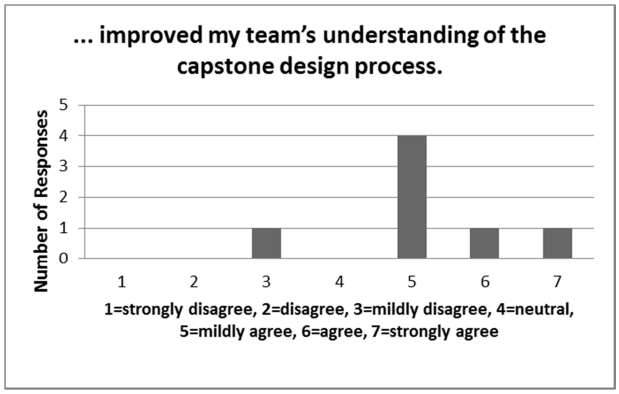

Figure 2 – Faculty poll results- Question 1

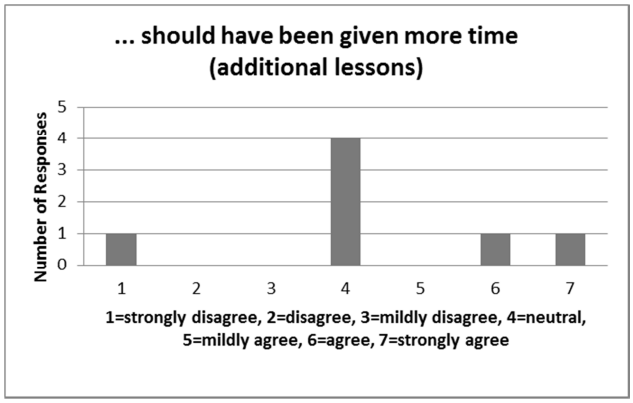

Figure 3 – Faculty poll results- Question 2

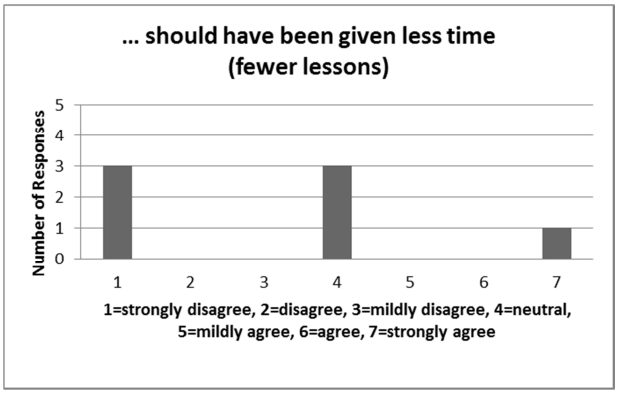

Figure 4 – Faculty poll results- Question 3

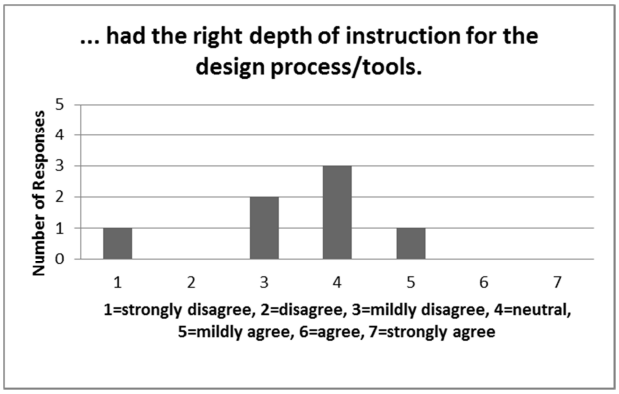

Figure 5 – Faculty poll results- Question 4

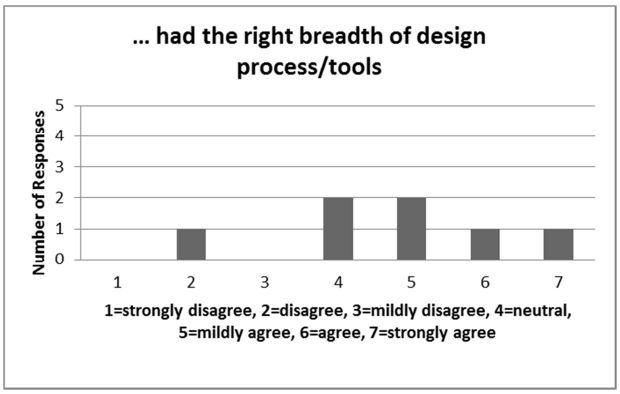

Figure 6 – Faculty poll results- Question 5

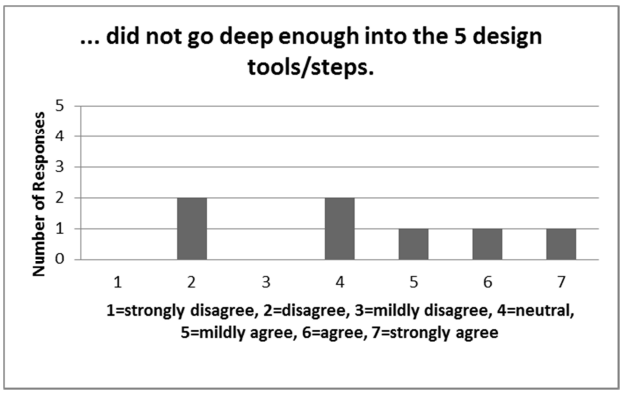

Figure 7 – Faculty poll results- Question 6

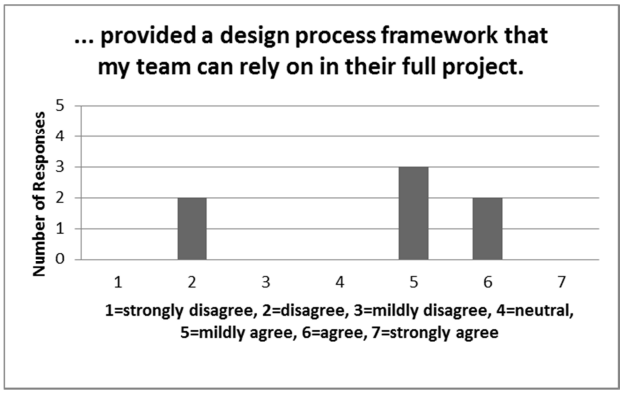

Figure 8 – Faculty poll results- Question 7

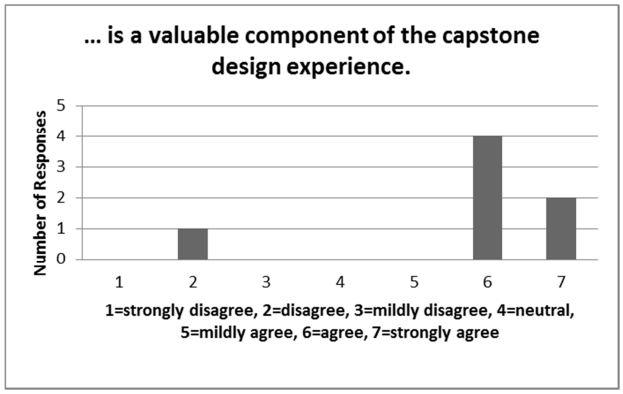

Figure 9 – Faculty poll results- Question 8

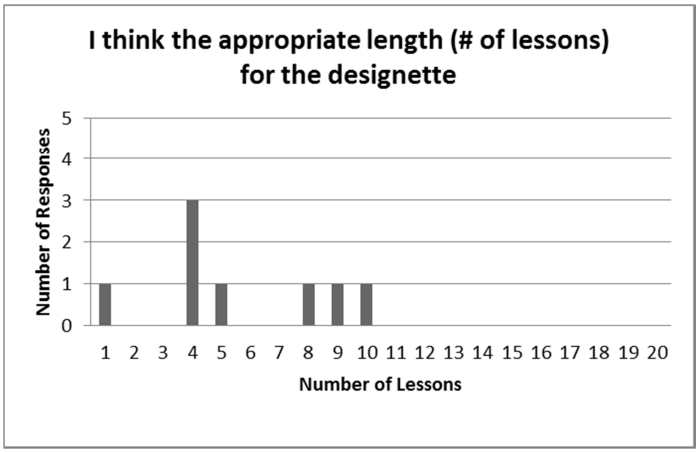

Figure 10 – Faculty poll results- Question 9

From this data and subsequent clarifying discussions, several observations were made. First, it was observed that the faculty, in general, agreed that the designette improved their students' understanding of the capstone experience. Second, there was not clear agreement on the optimal number of lessons that would be appropriate for the designette, but most responses supported a 4-5 lesson (8-10 class hour) designette implementation. Note that Figure 10 includes a response that indicated the designette should be either one or nine lessons (two or 17 class hours) long. In regards to the questions of having the right depth, breath and value for the capstone, there was general, but not strong, agreement that each were positive for the designette in the 7 class hour implementation. These observations are limited in their justification given the small number of faculty involved in the poll; however, each respondent represented several years of capstone advising experience. Therefore, despite not having "N" large enough to observe statistically significant conclusions from the data alone, it is felt that the outcomes of the research are still of value for informing others of similar implementations of designettes.

4.2. Comparative designette observations

The first summary of faculty observations is a comparison of the length of implementation of the designette approach. The faculty member's observations are based on advisement of a team in the second year (14 class hour) implementation and in the third year (7 class hours). The second summary of faculty observations is in the form of a comparison of two designette teams under the supervision of one faculty member in the third year (7 class hour) implementation.

4.2.1. A comparison of the implemented length of the designette

As can be noted from the previous section and Appendix A, the individual instructor thoughts on how the designettes should be administered were extremely varied. When the responses were averaged for each question, the results in most cases fell between 3 and 5, or basically around neutral (4). This likely suggests some uncertainty in the overall goals of the mini-project that are important to each instructor along with some variation on outcomes. It should be noted that only two instructors were able to administer the course for each case (no mini-design, long mini-design and short mini-design) and three had experience with the two mini-design projects. These instructors had the benefit of comparison between the projects rather than only the experience of

a single mini-design. At the same time classes can have personalities and what might be perfect for one class may not work so well with another. All of these issue being noted, an effort has been undertaken to understand the pro and cons of both mini projects and how the effected the overall outcome of the final design product.

For the 14 hour designette, there was much more time for hands on building of a prototype from the ground up. The positives outcomes of the 14 hours prototyping design were (1) early laboratory experience (2) team dynamics became very clear, (3) long-term there appeared to be a better understanding of the required elements for a design. The negative, or less desirable outcomes, were (1) the time lost on the larger project, (2) motivation of the team, (3) some design goals were not completely met and (4) lack of innovation in design generation.

With regard to the second year (14 hour) designette positive outcomes, most students were very excited at the prospect of being in an environment to build a physical product, the alarm clock project. It allowed for full prototyping of an example product. The students were very excited about this concept; however, in reality getting a product to work in the allowed amount of time proved to be more difficult than some of them anticipated. The real benefit to this was noted later in the class when the students devoted more time to understanding the specifics of their capstone design projects and leaving more time for prototyping. The team dynamics that became apparent during the designette also proved to be unexpected in some ways. Some teams designated a leader for the designette and other teams allowed the overall structure to develop during the project. In some cases students who put themselves forward for the leadership roles proved to be poor leaders. This is not a completely unusual phenomenon even in non-academic settings. The designette project allowed these issues of leadership to become clear within the first two weeks of the course, on a fairly low threat item, rather than during the capstone project. The issue of leadership did require the faculty instructors to step in and encourage the teams to rework the leadership roles based on what was noted during the mini-design, but it was very beneficial for the larger project. The full benefit of the designette was not realized until the spring semester, at which time more concrete decisions are made about designs and prototyping for the critical design review (CDR). Then the benefits of having struggled with a physical prototype were excellent at driving the teams forward when it came time for building prototypes and making manufacturing decisions.

For the more negative aspects of the 14 hour designette, using 14 hours of class time for the smaller design project proved to be somewhat stressful to the teams when it was time for the capstone projects. This issue is tied to the second concern was which was motivation of the team. After the designette project was completed the teams seemed worn down. In an effort to develop a working prototype in such a short time, the students had neglected other classes and priorities, which now needed attention. They also seemed somewhat burned out with the course in certain cases, making motivating them to work on their actual capstone project difficult. As the fall semester continued it also became much clearer how little time was remaining before the teams' preliminary design reviews (PDR). The fall semester took on almost a frantic pace at times in an effort to be ready with the required content for PDR. The customer needs for the student alarm clock did not require much variation among the different needs and methods for determining those needs, this meant that class and instructor time was still devoted to something that was expected to be covered during the designette. The need for a working prototype at the

end of 14 hours in some ways forced the teams to select a design very early on and commit to making that design work, as there was no time for building more than one prototype.

For the seven hour designette the pros and cons were somewhat different from the 14 hour. The project being more defined, in that it had to be the modification of a quadcopter, changed the comparison. The positive aspects of the seven hour designette were (1) team building, (2) innovation, (3) early experience in preparing and presenting their work. The less desirable aspects were (1) struggling to understand that the level of work for the mini-design was not acceptable for the capstone project and (2) lack of prototyping experience.

For the more positive aspects of the seven hour designette, these were mainly related to the adjustments to project itself. The modification to the quadcopter allowed for more innovation in deciding what the system should be able to do along with a variety of customer needs. The variation in customer needs also allowed for multiple methods for collecting data to determine the needs. This allowed the entire class to see how different methods for collecting customer needs data might produce better results. The teams were allowed more time to be innovative with the design because they were less concerned that they needed a working prototype as the quadcopters already flew. Most teams tried out 2-3 designs before selecting their final option. The quad-copters also proved to be very enjoyable for the students to work with and for the development of customer needs. Without all of the time devoted to prototyping a design, the presentations given by the teams were more complete and of a higher quality. As there are several presentations given to customers and faculty members giving the students a chance to receive feedback on their presentation skills early in the class helps them produce high caliber work later during PDR and CDR.

For the less desirable outcomes of the seven hour designette, some teams had difficulty with being given cursory information and expectations on a project early in the semester followed by higher expectations later in the semester. Some teams tried to apply the same level of analysis or research to the full capstone project as in the designette. While the lack of prototyping a product from the ground up opened up some other very positive outcomes in the shorter designette, there was a decided lack of understanding of how much of a time sink prototyping can be for a team. Not having the hands-on experience of having to make something work was very apparent in early decisions related to manufacturability, availability of off-the-self products proposed for use with or general user friendliness of the proposed designs.

While most of the pros and cons of both the seven and 14 hour designettes can be instructor and team specific, if there are clear goals for the project, a well thought out designette can start the capstone design course off in a very positive manner. In particular, if there are concerns that the students are unfamiliar with or have forgotten the design process a quick reintroduction can lead to better choices and designs later in the course.

4.2.2. A comparison of two seven-hour designette teams

The seven hour designette implemented in year three was experienced by seven different teams by several faculty advisors. In an effort to eliminate the variable of the effect of different faculty

advisor on a team, the following observations were made by a faculty member that directly advised two teams.

The designette was experienced by two capstone design teams tasked later with developing innovative military technologies for Department of Defense Laboratory customers. The designette began on the first lesson, and the teams presented their solution on the fourth lesson, giving them three lessons, or approximately one week to complete the project.

Abbreviated design process content was presented to the teams that they applied to the designette. In particular, the teams were tasked with producing the following design products:

- Project Plan
- Customer Needs
- Functional Decomposition
- Ideation
- Decision Matrix
- Prototype

Given only one week to perform this, it was clear to the faculty that the teams had to work very quickly through these tasks to finish on time. Nevertheless, the teams were quickly bogged down in details of each step, and quickly fell behind. It was encouraging that the students earnestly attempted to perform these design process steps thoroughly, but it left insufficient time for prototyping later in the designette.

For example, both teams spent significant time developing Customer Needs (CN) surveys, and surveying fellow students to compile CN data. This spanned two lessons and four to five days, which is nearly two-thirds of the time allotted for the designette. In a real-world design project, accurate CN data is critical to project success, but for this exercise, it was not. To save time, instead of extensive surveying, the students could be tasked with developing the CN survey, then the faculty could provide them with pre-conceived, representative CN data that they will carry forward with the project. This would provide them an abbreviated CN collection experience without the significant time expense.

Unfortunately, due to the time spent on CN data collection, there was limited time for the critical Ideation step, and the teams were limited to using only the 6-3-5 Ideation technique.[17] The teams were directed to perform the 6-3-5 ideation in the context of "Historical Innovator Principles," which are "best practices" that draw from renowned innovators throughout history.[17] In particular, the teams were asked to perform 6-3-5 ideation while attempting to generate concepts that would:

- Question Assumptions
- Change the Physics
- Do the opposite

In retrospect, the faculty would have preferred more time to spend on additional ideation techniques. Nevertheless, both teams developed workable prototypes by the end of the designette by working outside of class hours.

During the designette, significant team forming occurred, and the faculty advisor was able to observe the team's dynamics and identify the students' personality traits and other strengths and weaknesses. This observational period was used by the faculty to select the Team Leads and other roles on the teams that would be used during the capstone design project. This faculty member found this to be a particularly valuable result of the designette, given the critical nature of selecting the right Team Lead. After six months of working with the teams on the capstone project, it is very apparent to the faculty that the best student team leads were indeed selected for these two teams, which would have been very difficult to achieve without the designette.

These two particular teams embraced the designette with great enthusiasm, motivated in part by the competition, and by the intrinsic fun of the project. In the opinion of the advisor, this enthusiasm carried over to the capstone project.

When the capstone design projects began on the fifth lesson, both teams had a better understanding of the design process they were embarking on. This resulted in increased commitment to the early steps in the process, as the students appreciated how they would be used later in the process. The designette experience also set an expectation that significant work is required to successfully innovate in product design, and that a sense of urgency is critical throughout the process. Furthermore, the disproportionate amount of time spent on CN underscored the need to establish a schedule and follow it.

The design content provided during the designette was not comprehensive, however, and would not be sufficient to completely equip the teams to perform their capstone projects. Therefore, additional design content was presented to the students as-needed throughout the semester, as is traditionally done in capstone design courses. This created some redundancy in lesson content, but this likely resulted in better overall understanding of the process.

Some faculty advisors are concerned that the abbreviated design content and accelerated design process create false expectations in the students and set an initial, low standard for their work that may be carried into their capstone projects. While it is true that the standards for acceptable products during the designette are significantly lower than they are for the capstone projects, a reduction in product quality was not observed later in the year in these two teams. In fact, these two teams performed much better than is typical (though it cannot currently be concluded that this increased performance is a direct result of the designette).

Finally, many faculty advisors agreed that it could be beneficial to spend more class time on the designette so that the design tools could be introduced and experienced with more depth and breadth. However, faculty are also hesitant to accept the tradeoff that this would require of forfeiting lessons from their capstone design projects. The four-lesson (7 class hour) designette used here consumed 10% of the fall semester contact hours, or 5% of the entire capstone course pair contact hours.

One possible compromise is to run the designette in parallel with certain steps of the capstone project. In particular, collecting real-world CN data can be time consuming because there are delays between when surveys are sent to customers, and when results are received. Therefore, one possible approach would be to spend the first one or two lessons of the course developing

and dispersing CN surveys for the capstone project (with heavy assistance from faculty), then running the designette while the teams are awaiting CN survey results. This would allow the designette to occur during a natural lull in the design process. If combined with the previous recommendation to use an abbreviated CN collection process during the designette, with representative CN data provided to the students, the students would have more time to spend on the most beneficial elements of the designette, such as ideation. Because they would have already experienced the real-world CN data collection process, it would be less-critical to thoroughly perform it during the designette.

4.3.Faculty discussion

In addition to the two comparative discussions in the previous section, all seven capstone faculty participated in a discussion following the year three implementation of the designette. Of the faculty present, two had participated across all three years of the designette study, and three had participated in the last two years of the designette study. As a starting place for the discussion, the poll data was provided to faculty. This included both the Likert scale data from section 4.1 and the short answers provided by faculty to more open-ended questions. All responses to this latter set of data can be found in Appendix A. Much of the responses have already been discussed in the comparative observations sections.

Of particular interest was an observation of the early instruction and awareness of risk mitigation and safety issues. In previous offerings of the capstone without a designette, safety issues were not as well considered by teams until a phase of development where major laboratory tools were being used. With an earlier focus on safety and how to identify, characterize and plan for risks, the students were able to practice various mitigation approaches while stakes were low. Even during this rapid, low complexity design primer, the students began habit forming with respect to personal safety equipment, proper procedures for tool usage, and what activities were inherently safe or ill-conceived in the full laboratory environment. A highly related area observed in this study was that of the larger idea of risk mitigation. With consequences of injury on the line, safety risks were focused on early in the designette. This safety culture was important to highlight and develop as the laboratory is unique in allowing undergraduates to work after hours, unsupervised on most laboratory projects and equipment. While other design courses may have still been in conceptual phases where safety could only be discussed and not observed directly, the designettes provided a direct method to practice it as soon as possible in the course. After illustrating mitigation methods for those safety risks, an easy parallel could be drawn to other important system development risks in their full project, namely technical, schedule, and budget risks. The characterization and mitigation approaches of each of these types were similar therefore faculty advisors had to spend less time explaining the framework in which to manage risks on a program.

Following the discussion on safety and risk mitigation, the faculty also discussed the advisor poll results. The question, "What are the objectives of the designette?" was used to assess if the capstone faculty understood and could communicate why the designette was being used. In general, faculty seemed to appreciate that the designette's intent was to provide an early framework or overview of the design process on which to build upon later on their capstone projects.

In response to the question, "If I could emphasize one aspect of the designette more, it would be?" faculty provided several areas to consider. Faculty indicated that they would like the framework and interrelation of the design steps to be made clearer. They also indicated that they would like to see more emphasis on customer needs, ideation, prototyping, and presentation skills. As these remarks span a majority of the design steps presented, it may indicate that the time to cover any one process was too short, a difference of opinion of what should be emphasized more in a design overview, or a combination of both. During the faculty meeting it was indeed observed that it was a combination of both reasons why there were several areas desired to be emphasized more.

The question "The best part of the designette is?" produced several observations on team dynamics and the increase in intrinsic motivation of the students. This initial motivation was felt to be a good way to start what is known as a very demanding, but ultimately rewarding capstone experience. Faculty appreciated that a designette to start teams off in a fun, low-threat, high feedback manner was a good thing.

When the question, "Things I believe we should change about the designette project?" was discussed it was observed that a few faculty felt the standards that cadets were exposed to early with the designette should be increased to establish them early. It was also voiced by a couple faculty that possibly the interrelations between the design tools could be better presented to seed the students' learning scaffold. There were also several ideas discussed to ensure that the short time allotted could be best used in the creative, human-centered tasks of design. For instance, and as discussed in section 4.2.2, customer needs might be provided to students following their survey creation to shorten the collection timeframe and allow for focus on the other design steps.

In general, the faculty that participated in the designette implementations felt they were beneficial to student learning and remain committed to improving the experience to achieve their stated objectives.

5. Limitations

The study has several limitations in its design, execution, and application. First, due to the sample size studied in each capstone offering, clear conclusions are difficult. Ideally, the study would include several more teams in the same institution or even across several institutions to help eliminate other institutional factors that could affect observed performance. Second, the sample size of the faculty advisor observations may be viewed as small. While this limit is directly linked to the number of teams observed in the study, the experience level of the faculty advisors should be taken into account as well. Third, due to the timing of the second to third year comparison study, objective student performance data could not be compared. The full projects of the third year implementation are not complete, therefore assessment data on the student performance, nor the student perceptions at the end of the overall project were not collected.

There may have been more direct measures possible for the five variables that were of interest to this study: time taken to perform the designette, increase in team dynamics, increased familiarity

and correct implementation of the design methods, change in team motivation and increased familiarity with risk management and safety issues. In the case of increasing team dynamics or team motivation, there could have been student surveys performed where their perception of placement on the team formation lifecycle could have been assessed at various points in the project. For the case of familiarity and correct implementation of the design methods, an assessment of their designette process steps and their full project deliverables could be included as a direct part of such a study. Finally, in the case of assessing the familiarity with risk management and safety issues, a look at the reduction of safety events could be used to observe trends over the years of this study. In this case, however, the sample size studied, lab practices, and several other factors may prevent an appropriate assessment of "improved safety" based only on this seemingly direct measure.

Another limitation of this study was the composition of the teams. While not completely homogeneous in skills (most of the students were mechanical engineering majors with a few systems engineering majors embedded), there are more multidisciplinary team compositions possible, and this characteristic was not directly explored. This spectrum of composition and its effect on capstone design performance is one of many characteristics that is already being studied.[13] Initial conjecture is that the designette approach would also benefit multidisciplinary teams as well, possibly more so. While team members bring different domain skills into a team, there is a good chance that the design processes used in the capstone project will still be new to most of them. For this reason, the designette would still be a good primer before the full project starts. Also, an increase in team dynamics would be of great benefit for multidisciplinary teams. In many cases for multidisciplinary teams, the individual members have little prior interaction with the other members, thereby necessitating some initial period of team formation activities. The designette provides an opportunity to move the new, diverse team further along the team formation lifecycle.

6. Conclusion

Capstone design courses are intended to provide a culminating experience for senior undergraduate engineering majors. In the cases where design methodology is incorporated into a two-semester capstone course, it is possible that this is the students' first extensive exposure to design methods and process. In that case, students may be experiencing specific design process steps for the first time. It can be problematic for students to apply these design techniques for the first time on what is often a complex, real world capstone design problem. One solution to this problem is to incorporate a short design experience, called a designette, at the beginning of the two-semester capstone course. For the last three years, we have implemented three versions of a short, introductory design project (i.e. designette) in our two-semester capstone design sequence. In our uses of the designette project, the suite of five core design methods mentioned above were taught in an abbreviated form. In one year the designette lasted 10 class hours, the next year's designette lasted 14 class hours, and this past year's project lasted seven class hours.

There were five areas of assessment that were of concern through this research: time taken to perform the designette, increase in team dynamics, increased familiarity and correct implementation of the design methods, change in team motivation and increased familiarity with risk management and safety issues. The results reported in this paper come from three

approaches: capstone faculty polls, faculty-provided comparative observations, and a capstone faculty group discussion. Though the number of study respondents is too small to determine statistically significant results, it is still felt that the observations gathered are of value to those implementing new methods in design education. The longest designette allowed for greater depth in the initial coverage of the methods and also provided greater time for prototyping and testing. Faculty and student feedback indicated that the use of the designette does increase student familiarity with the design methods and provides a beneficial exercise early in the capstone design sequence to support team dynamics. Faculty feedback also indicates that a preferred length of the designette may be in the 7-9 class hours implementation; however more data should be sought to draw a firm conclusion with this regard.

Future studies may support the current research through inclusion of student surveys to assess perceived design content learning and capstone project success. Also, implementation of the designettes in capstones can be tried at other institutions to provide a better comparison of approaches and isolation of the variables of interest. In general, this approach of using designettes in capstone has been received well and the authors look forward to continuing improvements in capstone design education.

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Appendix A: Year three implementation faculty poll responses

What are the objectives of the designette?

- Provide common design understanding for the team, provide basic overview of the design tools for initial use, and overcome forming/storming/norming phases of team dynamics before the full project
- Initial Exposure -> scaffold Learning, also good initial team experience
- Introduce the Design Process, Accelerate team formation, Excite cadets for capstone experience, Allow prof's to observe cadets in design process to aid team leadership decisions
- To introduce the design process to the team. Get the team working together before it is high stress. Preparation for the types of presentation required for the class in a low threat way. Allow the advisor to see the team interact and to get to know the students. Start the class/project on a good/fun note.
- Improve cadets' understanding of the capstone design process. Provide a design process framework for the project. Exercise the project
- To give cadets an overall idea of what they are doing for the full capstone project
- Understand/implement design process/tools

If I could emphasize one aspect of the designette more, it would be:

- Framework and interaction of all the tools/steps as a whole
- Prototyping

- Ideation - there are many ideation techniques, and we didn't have time to try many of them. They spent a relatively long time doing CNs. We could ask the cadets to prepare a CN survey, but then provide to them artificial survey results to speed up that process, and more time for ideation.
- Presentation skills as far as being clear about what you did and your explanation of your team's work
- The order and interrelation of the tools
- Applying lessons learned to actual projects
- Customer Needs (but really everything)

The best part of the designette is:
- Demo lesson, team dynamics early
- Basic Exposure to design process and initial positive, motivating experience
- It's fun -> creates enthusiasm
- Getting to see a team have fun and want to produce good work
- Team gets to know each other and interact. Team learns there is a design process framework
- Early hands on involvement
- The students had the chance to build and work in the lab early in the course

Things I believe we should change about the designette project:
- Add an overview, standardize problem statement to compare demo's more effectively, crystallize each tool for immediate application in work hours.
- See comments on CN. It's valuable to have cadets experience every part of the design process, but we could possibly save time by providing data to them… similar to a note taker. The goal would be to reduce /eliminate busy work to allow more time for the most valuable activities. Ideally we would spend 6-8 lessons on this and thoroughly practice each exercise, but we just can't afford to spend that much time.
- I think we should be sure at the early stage of the class to help the team focus inward on producing good work rather than an external competition to verify all teams are starting on the right foot.
- More depth in design tools and their relationship to each other.
- Maybe tougher grading to set high expectations early
- More (better depth) or less (pure breadth) time