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The Nexus of Science and Engineering: Structuring Individual Studies to Inform Senior Design Projects

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(1) Introduction

Engineering can be described as the application of science to identify and solve problems.[1] An engineering student spends years learning about how the universe works then builds upon this knowledge constructing a mental framework of engineering principles. Ideally, upon completion of an accredited engineering program, the student's mental framework will be robust and flexible enough to process and respond to any problem within their specialized area of concentration in an effective, ethical, and clearly communicated way. Tying all the subjects of an engineering education together into a professional toolset, however, is difficult.

ABET, the higher education accrediting body that helps set an engineering student onto the road towards professional licensure, puts forward several criteria that help shape the student's experience and make it more likely they will be successful in their chosen field. Specifically, ABET General Criterion 3 (Student Outcomes) and General Criterion 5 (Curriculum) outline an education grounded in math, science, and engineering that is capped with an all-encompassing design experience.[2] Crucially, this design experience helps the student make the necessary connections between their education to date and their ability to shape the world of tomorrow.

At many institutions, including the authors' own, all senior engineering students practice design in a group-based capstone design course. Separately, select students (particularly highly-accomplished and motivated students) can choose to complete additional advanced individual studies. These experiences are meant to be open-ended and a synthesis of knowledge. With little faculty oversight, students must push their intellectual boundaries to first identify and understand the problem at hand before formulating a response to it.

For both course offerings, however, time becomes a limiting factor. All too often, one of two things happens. In the first, a clear understanding of the problem is glossed over in the rush to start the design and turn in an incompletely-analyzed product within the limited time window for the course. In the second, a self-conscious student gets bogged down trying to plug their scientific knowledge gaps related to the problem then glossing over the actual design process in a similar rush to turn in their term project.

Such rushing defeats the purpose of the curriculum and short-changes the student. Is there a better way to focus on the engineering design process without losing the required depth of scientific understanding? This paper proposes sequencing an independent study with a linked senior design project within the context of an example senior environmental engineering waste-to-energy design project. This curriculum model is easily transferable to other engineering disciplines. However, academic departments must be cognizant of the potential strain placed on available student resources if this model is implemented too broadly.

(2) Background

Facilitating learning for novice designers can be difficult and a delicate balance between self-directed learning and coaching; the advisor must build the student's confidence in seeking and overcoming independent intellectual challenges. One of the hardest things to teach is how to recognize and deconstruct a problem. Novice designers may focus on generating solutions instead of fully understanding or analyzing a problem.[3] Furthermore, Smith et al. suggest that students' lack of context for the principles of design make it hard for them to at first practice the act of design.[4] From their different approaches, both authors seem to suggest that practical experience is the best way to build context and learn how to respond to a design challenge.

Increasingly, project or design-based learning is advocated as a method to give context to past knowledge passively gained in lecture-based coursework.[5] Gomez-Puente et al. find that practice in the iterative nature of the design process "opens up a new experiential and discovery situation, which promotes reasoning and development of higher-order skills."[6] Chua et al. note that through this iterative process, the student's perception of the problem (and hence their proposed solution) changes over time.[7] In fact, in another publication, Chua claims that the more a student participates in project-based learning, the better the student grows in critical thinking and generates better project-related products.[5] For similar reasons, Rasul et al. advocate early, deliberate preparation of a student before their senior year capstone project.[8]

The importance of capstone design courses in an engineering education is well-documented.[9] Ward writes that capstone projects "bring all aspects of an undergraduate student's experience together".[10] Ward further notes that the completion of capstone projects do not only benefit the student but also serve as validation by potential employers of the student's ability to apply knowledge and generate designs. Additionally, Eppes and Milanovic observe that integrative capstone experiences feature conspicuously in many programs' student outcome assessment evaluations, which are so important for accreditation, like ABET, and program rankings.[11] It is in the interests of the student and the higher education institution, then, to offer the best senior integrative engineering experience possible.

Assessing students' professional growth through near open-ended design can be difficult. Student reflections are often used to address this problem. Student reflections can serve two purposes benefitting the student and the curriculum assessor in turn. Reflections give students the opportunity to consider alternatives, understand professional practices, and grow further within the engineering profession.[12] Reflections also inform the instructor or curriculum assessor on how to iteratively improve design courses.[13]

(3) Current Curriculum Model

In the current curriculum model employed at this institution, advanced individual studies and an advanced environmental engineering design course are separate and distinct. Any environmental engineering student can elect to complete a 3.0 credit-hour individual study. However, qualified students desiring to graduate with honors are required to complete the individual study in the fall semester of their senior year. "Qualified" students are those that achieve an overall GPA of greater than 3.0 with a 3.5 GPA within their major; they are the typically the most driven, intellectually curious students. Typically, one fourth to one third of an academic year cohort will seek completion of an independent study. Students usually work with their faculty advisor to select a topic of interest to themselves and organizations with whom they are affiliated. The student and faculty advisor then formulate a work contract. In the contract, the advisor and the student outline expected student outcomes specific to the project topic, minimum semester work hours, and project deliverables. At this institution, students are required to log 80-120 hours of individual work for their projects (two hours for every one hour that would be spent in class) over the course of the semester. The students must produce a term project report (typically 10-20 pages in length) and present a research poster during the academic institution's Projects Day.

Unlike individual studies, the mandatory semester capstone design course (3.5 credit-hours) is classroom-based and is offered in the spring semester of a student's senior year. Students meet formally over the course of the semester to learn about the classic aspects of engineering design. Additionally, student groups are assigned set environmental engineering projects to develop over the course semester. Groups are made up of 3-4 students, and academic year cohorts usually range from 10 to 20 environmental engineering students. At the end of the course, groups submit a paper and poster describing their design and, when appropriate, produce a 3-D printed scale model of that design.

In the underlying case study for this paper, students and faculty members recognized the untapped potential of animal waste-to-energy using anaerobic digestion for biogas production at an on-campus equestrian center and dog kennel. Students had previously completed an engineering applied microbiology course as well as a waste water chemical and biological treatment course. Beyond Monod kinetics and theoretical basin sizing calculations, however, neither course focused on the material details of designing a functioning bench-scale biological reactor with gas collection. The students acutely felt their knowledge shortfalls and spent several weeks researching how best to design their systems. Furthermore, once they built their bench-scale reactors, the students had to wait nearly half of a semester for the desired microbial population to mature and produce appreciable amounts of biogas. The slow microbial kinetics limited the time students had to study their reactors' behaviors, draw conclusions, and inform a practical design within the timeframe of one semester.

To remedy these limitations, the students' individual study advisor and future capstone design professor had the students focus on studying and tweaking their reactors during their individual study semester instead of trying to complete the design as well. During the capstone design course in the following semester, the students continued their work in teams and used the data from the bench-scale reactors to design a biogas generation, collection, and utilization system for the on-campus equestrian center and adjacent dog kennel. This happenstance became the impetus for this paper advocating the continuance of individual study work in a follow-on capstone design course.

(4) Proposed Curriculum Model

In the new, proposed curriculum model, individual study topics dictate the topic pool for the capstone design course. Previously, project topics were completely divorced from individual study topics. This model would require select students to be assigned an engineering problem one semester early. In an independent study, the student may spend the semester exploring their engineering problem by designing and conducting controlled experiments. Following this semester, the student can take what they learned and, with a group containing members who did not complete individual studies, design a solution for the problem at hand. In this way, students will be less bound by time and knowledge constraints. Students may better synthesize scientific knowledge into engineering applications and more fully appreciate the iterative nature of the engineering design process within the sometimes complex environment of a group setting.

Submission requirements in each semester will be similar to those for the current curriculum model. At the end of an individual study, the student will still be required to complete a brief reflection paper and produce a research project report. However, in this report, more emphasis will be placed on thinking about the implications of the research findings to prime the student and their group for future design application work. The requirements for the capstone design course will be the same. Greater expectations, though, will be placed on the students' analysis of their design's limitations and benefits.

(5) Benefits of Proposed Curriculum Model

More fully enumerating the benefits of the proposed curriculum, this model allows: 1) students to optimize their time and efforts in thoroughly understanding the science behind a problem before continuing in the design process; 2) adequate time for model building, testing, and iteration; 3) a more informed student population to feed technical discourse between peers and thus spawn professional growth.

By marrying individual studies and a capstone course, the proposed model better meets the intent of ABET General Criterion 3 and General Criterion 5. These criterion sketch the knowledge bridge this proposed curriculum model seeks to build. ABET Student Outcome Criterion 3-a, 3-b, and 3-e outline the need for the student to demonstrate the ability to apply math and science by designing and conducting experiments related to an identified problem. Then, in Student Outcome Criterion 3-c and Curriculum Outcome 5-c, ABET requires that the student be able to apply this knowledge to "design a system, component, or process to meet desired needs within realistic constraints…"[2]

Studying engineering is intensely time-demanding. There is little time for reflection, and students can easily fail to make important connections between their courses' subject material. As much as possible, then, it makes pedagogical sense to draw common threads through coursework, especially as students approach the apex of their scholastic experience. The proposed model presents such a thread. It helps close the loop for why and how math and science classes/knowledge inform engineering design and decision-making.

As discussed in Section (1), time is a limiting factor in producing meaningful term projects. While this limitation may be true to professional life, it becomes a great disruption within the incubated world of aspiring engineers. Students need the time to reflect and not just react to deadlines. The proposed curriculum model affords them more time to develop a deeper appreciation for the iterative nature of the design process. This iteration may start in the lab. For instance, students working on the animal waste-to-energy project found that their gas evacuation tubing size had a great effect on their daily gas collection efficiency. Ultimately, an experiment-based individual study gives a student the time to build bench-scale models of their project and note practical material details, like the tubing size, that would have otherwise been over-looked in quick, theoretical model building. This hands-on experimentation helps build the student's technical capacity and problem identification/solving skills.

Giving more time for the student to reflect and iterate does not only benefit the individual. It also helps create a more informed student body that in turn allows deeper discussions on the nature of design and its application in a given project. Moreover, this meaningful technical discourse will raise the likelihood that a design group will produce a near-marketable product. The net effects of this discourse and its potential implications may be a growth spurt of professionalism, satisfaction in the engineering field, and the desire to pursue a lifetime of learning.

(6) Limitations of Proposed Curriculum Model

Despite its benefits, this model is no panacea. The model can be difficult to scale up due to resource constraints for individual studies. Faculty time, laboratory space, and materiel limit the broad application of this approach, especially in larger programs. Additionally, individual study requires a high level of self-motivation that may not be present in all students.

Individual studies are meant to put the student in the driver's seat. However, faculty members are not disengaged. They serve as project advisors. Since students necessarily are pushing the bounds of knowledge, faculty members must conduct a concurrent literature review to best direct the student and mentor their research efforts. The role of project advisor, from a departmental perspective, is a duty additional to other everyday requirements. On average, the faculty project advisor puts in five hours of work per project getting students started on their work; thereafter, one hour a week per project staying abreast of student progress and combing literature as appropriate; and approximately five more hours per project at the end of the semester to provide students feedback on their final project reports. This adds up to about 25-30 advisor hours per project per semester, a significant time investment. Given other time demands at this institution, an advisor at most can support five projects before the quality of interaction with advisees diminishes. When looking at the pool of available, qualified advisors within an academic department, it becomes readily apparent that a curriculum model requiring a large number of students to conduct individual studies (e.g. 50 students) as a pre-requisite for their capstone engineering design course is self-limited.

In addition to faculty advisor time, adequate laboratory space may not be available to support a large number of concurrent individual study projects. Not only would individual study students be competing with each other for lab bench space but the academic department's mission to teach other lab-inclusive courses could be impeded.

Some projects may require specialized equipment or samples that may be difficult to procure, stretching budgets or further limiting student hands-on time during the semester.

Unlike a structured engineering design course, individual studies, by their nature, require students to be diligent, dedicated, and self-motivated. Not all students are comfortable with the level of autonomy and initiative required to successfully complete an individual study. The students working on the animal waste digestion project exceeded the minimum 80 hours of required contact hours and logged between 96 and 111 hours of work. This level of dedication highlights traits typical of the sort of student who will get the most out of an individual study.

(7) Countering Limitations

Many of the limitations presented can be overcome with small changes to the proposed curriculum model. However, decision makers should take care and try to anticipate unintended consequences.

One way academic departments can alleviate the strain on resources available for individual studies is to create small independent groups. This approach will foster a team approach to the design process. Intellectual teamwork can be difficult, but it is beneficial to help aspiring engineers learn to work in groups as much as possible; it will be relevant to their professional lives. Additionally, this approach will help all group members and not just an elite few really understand how and why things work; all will have the capacity to contribute to the final product.

This approach, too, has its drawbacks. Group work raises the expectations about the quality of work the group will generate. If there are freeloaders in the group, this increases the burden on their team members. Grade-weighted peer evaluations may help combat this eventuality. Additionally, conducting group independent studies followed by group design work may become a de facto year-long design class. Course administrators will need to explicitly state the desired student outcomes of each semester so that a significant curriculum re-write is not needed.

A second approach is to have honor students complete individual studies then lead groups during the design course continuing their work. In this approach, each design team then will have a subject-matter expert. Since the population of honor students is limited, institutional resources will most likely not be painfully stressed.

However, the "cons" list to this approach are significant. First, only a limited population will benefit from two semester project model. This may lead to secondary unintended effects, namely intellectual territorial disputes and poor group dynamics due to the initial proprietary disparity of project-specific knowledge.

In a third approach, academic departments may promote theoretical model-based individual projects as opposed to lab-intensive projects amongst cohorts of senior students. This approach may give all students the opportunity to conduct an individual study while lessening the relative pressure on laboratory and materiel resources.

At the same time, though, faculty member time may be more strained. Additionally, students will benefit less from kinesthetic learning and detail-oriented design (e.g. they would not see that a given evacuation tube is too small for gas collection). When a mix of theoretical and laboratory-based studies are happening concurrently, potential social stratification among project types may develop and leave some feeling disenfranchised instead of empowered by the work they are doing. Course administrators may also be faced with a new challenge of which projects to continue in the group work-based capstone design course. Again, their choices may lead to some distracting resentment. Clear and timely communication can help alleviate these eventualities.

(8) Post Independent Study Student Reflection

Immediately following their animal waste-to-energy individual study projects, students were asked to reflect on: their prior knowledge going into the individual studies; how the students felt their individual studies would inform their group design projects; and how they would characterize their interaction with knowledgeable faculty and staff during their studies.

Students responded that, despite having two applied microbiology courses, they felt they only had a basic understanding of biodigestion going into their individual projects. Countering these self-perceived knowledge gaps and creating successful experiments helped build their technical confidence, self-discipline, and technical capacity.

Building on these gains, one student anticipated the knowledge gleaned from the individual studies would jump-start their work in integrated group design teams. The student estimated that their individual study would presuppose two weeks of background research the design group would otherwise need to do. The student felt that this time could instead be used for more in-depth analysis of the client's requirements and the underlying assumptions the group would use to formulate and defend their final design.

Students cited technical lessons learned when asked about future design work. Students regretted not spending more effort first understanding the problem and then focusing their bench-scale reactor design variables. At the completion of their independent studies, the students listed unsolicited, specific changes to their experimental designs to achieve more focused, informative results. This reflection demonstrated the expected synthesis of knowledge in the proposed curriculum model and a healthy appreciation of the engineering design process' iterative nature.

Lastly, students enjoyed the challenge of struggling with a problem on their own with the certain knowledge that they could call upon faculty and technical experts if needed. Additionally, students were motivated by the enthusiasm and genuine interest the faculty had in the student's creative work. For these reasons, the students expressed a strong appreciation for this balance of autonomy and tutelage during their independent studies. They looked forward to the application of their findings during their second semester group design project.

(9) Follow-up Group Design Project Student Reflection

Midway through their capstone group design projects, the students who completed individual group projects were asked to reflect again on their work. Namely, the students were asked: how, in practice, their individual studies informed their group project work; how group integration worked moving from individual studies to working with other students who did not complete individual studies; and what their greatest learning points were as future members of the engineering profession.

Students stated that their independent studies helped them better understand the science behind anaerobic digestion. However, they felt that their experiments were tunnel-visioned on gas production, limited in scope, and not directly applicable to practical design. The students again presented specific short-comings in their individual experiments and proposed even more specific experimental design model changes than three months previously (e.g. plug flow vs. batch reactors and floating domes vs. fixed domes). Despite their misgivings, their feedback indicates intellectual growth and deeper professional awareness of the state of the science.

Group integration worked more smoothly for this cohort than the authors anticipated. The students who completed individual studies were each joined by other environmental engineering students who had not. The individual study students shared their final reports and posters from the previous semester to bring their new teammates up to speed within a day. All the students stated that their team members brought renewed excitement and interest, new perspectives, and new tools to work on the engineering problem at hand. The smoothness and benefits of this integration process may be attributed in part to the institution's small program (roughly 10-20 students in each academic year cohort) and unique, sustained team building opportunities. Further research is needed to see if different cohorts will behave differently at the authors' institution and in larger programs. Regardless, students also suggested integrating teams with broader experiences and perspectives (e.g. electrical engineering) for a more comprehensive scope of the final design.

Students agreed that their greatest learning point was to plan better (e.g. spend more time understanding the problem and how to approach the problem) by learning from others first. They identified that a good literature review helps to focus and direct their research questions and inform their designs. Through this experience, the students again agreed that they felt better equipped, more motivated, and more resilient in approaching the design process.

(10) Conclusion

Semester-long advanced individual studies in engineering are dictated by the interest of the student and his or her advisor. Definitively, the topics of these studies push the student to the edges of the student's knowledge and are often quite specific in scope. The exploration of specific topics necessarily requires the student to seek out specialized knowledge exceeding the depth and/or breadth of previous course work. This exploration can be distracting to the intent of learning about the engineering design process if rushed.

Tweaking the curriculum model slightly can help counter this distraction. The capstone design course director can use students' individual study topics as term projects for further development in the capstone class. This topical linkage has little effect on current course design, extends the design cycle to one academic year within the curriculum framework, and allows: 1) students to optimize their time and efforts in thoroughly understanding the science behind a problem before continuing in the design process; 2) adequate time for model building, testing, and iteration; 3) a more informed student population to feed technical discourse between peers and thus spawn professional growth. Though not easily scalable to large programs, teaching design in this way allows students to more productively focus on learning hands-on the design process as opposed to being distracted by their knowledge shortfalls for a given study topic.

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