2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #37726

Three-Year Capstone Design: An Innovative Interdisciplinary Preparation for Authentic Engineering Practice

Dr. Mary K. Pilotte, Purdue University, West Lafayette

Mary Pilotte is a Professor of Engineering Practice from the School of Engineering Education at Purdue University, West Lafayette, Indiana. She instructs a range of Multidisciplinary engineering coursework, and from 2014-2022 was Director of the Engineering Education undergraduate programs in Interdisciplinary Engr. Studies and Multidisciplinary Engr. She is co-creator and co-director of the Fusion Studio for Entertainment & Engineering (FSEE) from inception to 2023. The FSEE serves as a hub for theatre technology, engineering and innovation at Purdue University, and is a recognized leader in education at the nexus of entertainment and engineering within the broad community of entertainment practice.

Prof. Rich Dionne, Purdue University, West Lafayette

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Abstract

Every engineering student enrolled in an ABET-accredited engineering program encounters a culminating design experience that is formulated to require the use of engineering standards, present a context with multiple constraints, and exercise the students' acquired knowledge and skills from their program coursework (ABET 2021). Historically recognized disciplines of engineering practice (I.e. Mechanical engineering, civil engineering, chemical engineering, etc.) have well-established pedagogical approaches for presenting these challenges. However, new/emergent fields of engineering offer an opportunity to re-examine and re-align the pedagogies of instruction for such capstone experiences.

Integrated across the College of Engineering (multidisciplinary engineering) and College of Liberal Arts (theatre program), theatre engineering students complete what is known as a "three-year capstone design experience". Rather than a single penultimate capstone design experience in the senior year, students in this unique multidisciplinary engineering program experience the habits of mind and practice of engineering over three years, with their final year being used in leading the design/build solution finding for a live theatrical performance.

This work examines a novel instance of engineering capstone design inspired by Wiggins and McTighe's backward design instructional approach (Wiggins & McTighe, 2005), informed by the CAP- Content, Assessment, and Pedagogy framework (Streveler, Smith & Pilotte, 2012), and executed as an instance of practice-based education (Mann, Chang, Chandrasekaran, et. al, 2021).

Utilizing a qualitative case study research design this formative and integrated (engineering/performance arts) experience is examined sharing critical aspects of content, assessment, and pedagogical differentiation. Features of the three-year experience include scaffolded and repetitive instances of engineering design practice for live performance with incremental leadership, formative "just-in-time" instruction, and the use of public critique.

Introduction

Preparing high-quality and work-ready engineering graduates in support of societal needs is an essential goal for any school/college of engineering. In educational institutions where research and the development of engineering research scholars is a priority, the "how" of engineering education can become a source of great debate. The definition and debate of educational priorities (Duderstadt, 2007) and pedagogical approaches are made more complex by the physical boundaries and domain-specific silos that continue to exist at universities/colleges. Additionally, the influence exercised by critical stakeholders including employers and accrediting bodies also plays a role.

Within Purdue University, exists a thriving educational experiment of sorts. What began as a chance collaboration between the College of Engineering and the College of Liberal Arts Theatre Department arose common ground and shared values across disciplinary domains, minimizing competing priorities and institutional power dynamics, all to prepare thriving, high-quality, engineering practice-ready professionals, from a shared student body.

This paper will provide a detailed overview of a unique, entertainment industry-focused, theatre engineering concentration that resides within an ABET-accredited multidisciplinary engineering program. Using a case study approach grounded in the CAP framework (Streveler, Smith & Pilotte, 2012), intricate elements of content, assessment, and pedagogy will be discussed. Exclusive to this program is a pedagogical innovation for enabling "practice-ready" engineering design competencies. Known as the "3-year capstone design", students advance to successfully meet ABET requirements for a penultimate engineering design experience while preparing professionally in ways that make them highly sought after by entertainment employers upon graduation. Essential programmatic norms and values are also discussed, exposing how this interdisciplinary and rare cross-campus collaboration continues to spawn intersectional educational innovation between engineering and the performing arts communities.

Background

Current environment

Industrial firms urge educators to focus more curriculum and time in the classroom on broadening the range of practice-ready skills for engineers beyond the strictly theoretical or technical (Schön, 2017). Skills often noted as missing include practical hands-on exposure (Fiesel & Rosa, 2005), communication (Schultz, 2008), and critical thinking/problem-solving (Wagner, 2010), each of which is deemed essential for a successful transition into the world of the engineering workplace. The urgent need for engineering graduates to be able to "hit the ground running" is heightened by unprecedented generational retirements (Pilotte & Evangelou, 2012) and an accelerated surge in workforce departures related to the pandemic (Montes, Smith & Dajon, 2022).

To that end, educational institutions continue to explore ways to ready the college-level workforce more effectively. Such efforts include everything from a renewed emphasis on co-op and internship work experiences embedded in the school experience (Kotys-Schwartz, Besterfield-Sacre, and Shuman, 2011), to experiential learning course offerings and programs that emphasize active learning (Kolb, 2014). Concurrently, using such pedagogical approaches, engineering educators must also be mindful of how pedagogical innovation is meaningfully supporting essential student learning outcomes associated with ABET 2021-2022 (Seshagiri & Goteti, 2014). Being attentive to the guidance (and oversight) related to ABET accreditation offers students, parents, employers, and society the assurance that a college or university program is meeting a standard of quality that is required in the professional engineering domain. A purposeful trajectory toward a rigorous engineering education is critical, in a race to safely, methodically, and ethically address complex technological systems meeting the speed and financial pressures of creative design (Dekker, 2011).

Capstone design as professional preparation/readiness

The concept of creating multidisciplinary or interdisciplinary capstone design courses at the post-secondary education level is not, in and of itself novel. A simple Google Scholar search will generate over 24,000 citations elaborating upon such efforts. Peer-reviewed research on this topic can be summarized into categories of innovation and specialized project development - including industry involvement (Goldberg, Cariapa, Corliss, et. al., 2014); professional preparation, and attribute/competency development (Hotaling, Fasse, Bost, et. al., 2012); and capstone best-practices, pedagogy and assessment approaches (Newell, Doty, & Klein, 1990; Behdinan, Pop-Iliev, & Foster, 2014). Noticeably, however, the presence of *recent innovative* scholarship in this area appears scant.

Looking back however to 1990, Newell, Doty, and Klein suggested that anecdotally, there are many positive outcomes associated with the development of truly interdisciplinary (multidisciplinary) courses for students, making connections to what they referred to as "integrative studies" (p.1). Their work suggested that bringing together students from distant disciplinary homes of practice offers the potential to create "more sensitivity to ethical issues…ability to synthesize or integrate…enlarged perspectives or horizons,…more creative, original, or unconventional thinking,…more humility or listening skills" (p.70-71), and more. Likewise, Hotaling, Fasse, Bost, et. al. (2012) provide favorable empirical evidence, suggesting that students that work on multidisciplinary capstone teams not only produce improved solutions they increase their chances for employment upon graduation.

With these beneficial outcomes for students in mind, why is it that single-discipline design courses – particularly those for engineering capstone design, still prevail? Research offers long laundry lists of difficulties associated with developing collaborative design coursework including systemic challenges (Behdinan, Pop-Iliev, & Foster (2014); Bannerot, Kastor, Ruchhoeft, & Terry (2004)). An 11-year review of the literature suggests that while providing students with authentic interdisciplinary practice is important, the ability to model and teach in interdisciplinary ways is lacking (Van den Beemt, MacLeod, Van der Veen, Van de Ven, van Baalen, Klaassen, & Boon, 2020).

The hypothesis of Newell, Doty, and Klein (1990) referenced above, suggested that the existence of complex systems necessitates a common interdisciplinary/multidisciplinary framework and approach, for joint professional problem-solving to emerge in such instructional situations. This system's approach to work requires each professional discipline working together to either forgo their disciplinary approach for complex problem-solving in favor of the other disciplinary approaches or negotiate a new jointly authored framework. In academic settings where ownership of ideas leads to scholarship, and scholarship to promotion and notoriety, facilitating so-called "shared ownership" within interdisciplinary coursework approaches and outcomes is exceptionally rare.

Muñoz, & Jeris (2005) have suggested that this university culture and rigid specialization which thrives within the university enable the absence of collaborative, cross-disciplinary work. They suggest that there will be resistance to such boundary-spanning activities (i.e. joint course execution) that are inherent in complex interdisciplinary design problem solving, "…where boundaries are tightly drawn in response to competition for scarce resources, departmental personnel policies related to promotion and tenure, and a host of other issues arising from highly bureaucratized systems" (p.64). Further, other scholars suggest that within the domain of engineering education, there is "limited understanding of what resources hinder the development of engineering programs designed to support interdisciplinarity" (Van den Beemt, MacLeod, Van der Veen, Van de Ven, van Baalen, Klaassen, & Boon. 2020. Pg.508).

Given these impediments to interdisciplinary collaborations on campus, this work will elaborate on one enduring instance of a successful, collaborative, interdisciplinary approach aimed toward improving engineering education. Specifically, this case study will describe an approach for enhancing student professional preparation, through a series of authentic interdisciplinary design experiences, known as the 3-year capstone design.

Method

This research utilizes a narrative, intrinsic case study design, and analysis (LeCompte & Schensul, 1999; Mills, Durepos, & Wiebe, (2010)) to uncover the details of a novel multidisciplinary engineering capstone design pedagogy. This approach is well suited for this type of scholarship (Stake, 1995), and will be presented as a bounded system (Creswell, Hanson, Plano, & Morales, 2007) for which the essential program elements, process rituals, risks, and rewards are shared. The case study will elaborate upon a series of structured courses as examples of a reconceptualized, post-secondary, gradual release of responsibility instructional framework (Salehomoum, Revelle, Duke, & Pearson, 2022), and practice-based education framework (Mann, Chang, Chandrasekaran, Coddington, Daniel, Cook, & Smith, 2021). Together, the courses described form what is known as a 3-year capstone design pedagogy (image #1) whose aim is to support the formation of practice-ready engineers for the entertainment industry.

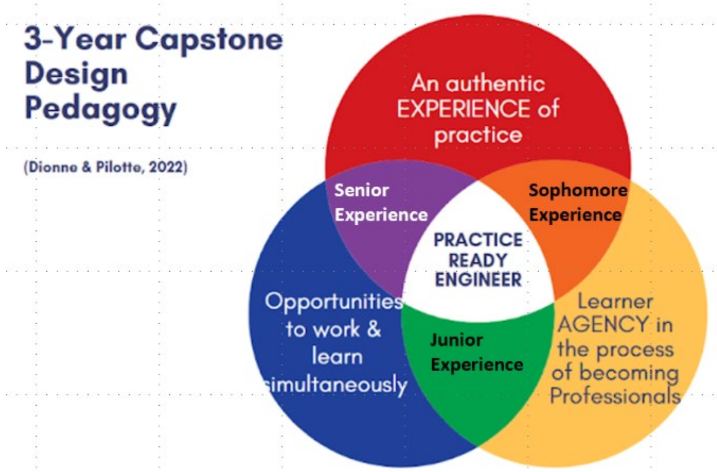


Image 1 citation: Original work by Dionne and Pilotte (Dionne & Pilotte, 2022). Informed and inspired by the work of Mann, Chang, Chandrasekaran, Coddington, Daniel, Cook, & Smith. 2021.

The principle of the gradual release of responsibility model taken from primary and secondary education assumes that the student gradually grows into full responsibility for performing a task, as the teacher reduces their responsibility for the instruction (Salehomoum, et. al., 2022). To facilitate this effort successfully, Fisher and Frey (2021) recommend the incorporation of specific instances of focused learning, guided learning, collaborative learning, and independent learning. In addition, three essential elements are embedded in applications of this practice-based education framework: (1) authentic practice, (2) acknowledge and scaffold learner agency in professional development ready for practice, and (3) incorporate contexts to work and learn simultaneously. Multidisciplinary teaming is an additional component associated with this framework as well. The definition of multidisciplinary teams in the context of this case study draws upon the definition used by the American Society of Civil Engineers, and can be thought of as "composed of members from different professions —for example, a civil engineer working with an economist.“ (ASCE BOK, 2008, p.69.). In the paragraphs that follow, more will be said about how the use of multidisciplinary teams facilitates the 3-year capstone design approach.

Results

The following narrative presents the nature of the 3-year capstone design experience, using the organizing structure of CAP curricular design (Streveler, Smith & Pilotte, 2012). This framework advocates for an alignment of content, assessment, and pedagogy (course delivery), as a logical extension of Outcome-Based Education (OBE). Using a systems view (Pellegrino, 2006) and a design engineering approach, course/program developers are urged to begin with the result of course outcomes in mind (Wiggins and McTigue, 2005), when developing new coursework. This case study is organized by the content, assessment, and pedagogies deployed within the three-year capstone.

Context

The 3-year capstone design pedagogy resides within a four-year bachelor of science in engineering degree program, with a concentration called theatre engineering. This concentration was formally developed in 2016 and was designed to support the needs of an increasingly technology-laden entertainment industry, combined with growing student interest in broad-based areas of entertainment. This concentration is one of many unique concentration options available to students in the ABET-accredited multidisciplinary engineering program (MDE) in the College of Engineering at Purdue University.

Acceptance into the theatre engineering concentration is a competitive process admitting up to four students annually from the First-Year Engineering program (FYE). FYE is the common first-year educational pathway that every beginning engineering student must go through before declaring their engineering professional program (i.e. Civil engineering, mechanical engineering, multidisciplinary engineering, etc.). Students are selected in the late spring term of the first year based on self-selected interest, achieving a minimum 2.5 GPA in FYE coursework, and passing a formal portfolio screening process conducted by the theatre department within the College of Liberal Arts. Once accepted into the MDE program theatre engineering cohort, all students follow an established plan of study (Appendix 1.) designed specifically to incorporate the 3-year capstone design pedagogy, and culminating in a senior capstone design experience.

Three instances of the course Production and Design Seminar (THTR 59700) appear on the plan of study and are the backbone of the 3-year capstone design pedagogy. The course is taken once per year in the sophomore (year 1), junior (year 2), and senior year (year 3) of their curriculum, with course content, roles, and assessments progressively changing as outlined in the narrative that follows.

Content

The Production and Design Seminar course is tightly connected to realized practice: students in the course are assigned responsibilities directly related to one of the productions mounted by the theatre department during the year (typically two per semester). Students from all three years of the theatre engineering program are enrolled in this course alongside students completing an MFA program in technical direction for theatre. (“Technical director” in live theatre typically refers to someone who safely and successfully manages the construction of scenic elements and their on-time and under-budget completion; this work often includes the application of structural design, mechanical design, and control systems knowledge.) In the course, students at all levels (sophomore, junior, senior, and graduate students) are expected to complete and present deliverables consistent with the level of responsibility for their experience. Before these deliverables become "public"—part of the ongoing process of mounting a production—they are critiqued openly during class by faculty, professional staff, and their classmates, some of whom possess greater experience, others with less. Once critiqued and revised, the deliverables are shared with the rest of the team working on the production to which they have been assigned.

In addition to the production-specific deliverables and critiques, students in the Production and Design Seminar must also participate in a public review of a professional portfolio for their entire body of work accomplished to date. This public critique involves each student receiving feedback from the faculty in the theatre department, from graduate students in the theatre department, and their undergraduate peers–both in theatre engineering and in the non-engineering theatre major (College of Liberal Arts).

Finally, students in the Production and Design Seminar must participate in larger, group discussions with students from other disciplines in theatre (i.e. costume design and technology, sound design and technology, lighting design and technology, scenery design, stage management, directing, and performance) multiple times per semester. These discussion sessions focus on the design and production process, with an emphasis on identifying "what worked and what didn't," reinforcing the practice of self and peer critique.

The production-specific roles assigned to students increase in both complexity and relative authority/autonomy each year of the enrollment progression. During the sophomore year, theatre engineering students are assigned the role of "deck carpenter" on a production. In this role, students are directly responsible for inspecting and maintaining completed scenery, and ensuring a safe environment on stage for each technical rehearsal and performance over two weeks. This typically involves a pre-performance and post-performance inspection and safety check; completing minor repairs and troubleshooting; supervising students who operate/handle moving scenic elements; and escalating issues/concerns along a decision tree (which could include determining that an effect or element is unsafe and cannot be utilized during a performance). Their work is informed by the work of other members of the team, led by a graduate student technical director from the College of Liberal Arts (CLA).

During the junior year, students are assigned the role of "assistant technical director." The assistant technical director works closely with the CLA graduate student assigned as technical director for a production. The faculty instructor–in consultation with the graduate student technical director–assigns the assistant technical director one element of the set for which they are directly responsible. This element should not require significant engineering analysis–it should be able to be completed through the application of prequalified construction techniques–so that the assistant technical director can focus on the application of project management techniques–cost estimates, time estimates, build schedules, construction drawings, and installation plans. Each of these deliverables is generated in consultation with the technical director and the other production-specific stakeholders, including the set designer, the director, the scenic shop supervisor, and the paint shop supervisor. The scenic shop supervisor (professional staff within the university) then leads the construction team comprised of undergraduate and graduate student employees through 1) the construction of the scenic element, and 2) executing the build and installation plan based on the deliverables the assistant technical director provides.

Finally, during their senior year, the theatre engineering students are assigned the role of "technical designer" for a production. In this role, they coordinate with the technical director to complete all of the engineering design and project management for a specific engineering challenge that has been incorporated into the production. These challenges are–to the extent it is possible–designed around each student's specific educational focus area: a structural design challenge, a mechanical design challenge, or a controls-based challenge. The theatre engineer serving as Technical designer is responsible for all of the collaboration and project management work on this project, which they had previously practiced as an assistant technical director. In addition, they are responsible for meeting all of the ABET-related outcomes central to engineering design/analysis, and testing/standards, which they are required to demonstrate within the execution of the challenge they have been presented.

As indicated above, each of the deliverables in the junior and senior years is critiqued publicly in the Production and Design Seminar class. Note that the sophomore year experience does not include traditional "deliverables". The sophomore year is literally "experiential," as students put into practice the inspection and maintenance of the scenery on a nightly basis. This public critique is a form of assessment (see below); however, it is also an element of content in that students are learning the purpose and process of public critique from each critique session.

Students who are receiving critiques are gaining valuable learning from the comments shared by faculty, staff, and peers. Beyond that, students who are earlier in their journey have the opportunity to observe the critique received by those who are further along than they are. These less-experienced students can learn from the successes and opportunities for growth they observe in the critiques their peers receive. Additionally, students further along in their journey have the opportunity to pass on knowledge and experience to those less experienced, activating their own learning and knowledge base in new ways, further helping them internalize their experience more fully as they explain it to others.

The importance that the productions each student is working on are fully realized, with robust design and production teams working on them cannot be overstressed. These projects have immovable deadlines; the show must open, after all, and students can't expect any leniency in deadlines for deliverables the way they might from an unrealized project or on a capstone project for whom the stakeholders are imaginary. Additionally, these productions have finite budgets as well as finite material and personnel resources; design decisions must adhere to these constraints. Further, because these productions have large teams of stakeholders (i.e. producers, directors, choreographers, designers, painters, other technicians, etc.) in technical elements with conflicting needs and competing design criteria, students must learn to collaborate and communicate effectively with them. A unique skill when speaking with stakeholders who likely know little about their specific engineering background/discipline.

Assessment

Three primary assessment artifacts/activities are used throughout the 3-year capstone design experience:

1. A professional portfolio, inclusive of a public oral defense. (Years 1, 2 & 3)
2. Participation in the fabrication and "back of stage" execution of a live entertainment performance. (Years 1, 2 & 3)
3. A functional, full-scale design artifact incorporated into the performance, inclusive of all design support. (Year 3 only)

Year 1 & 2 Assessment

Assessments associated with the first two years of coursework focus primarily on ABET outcomes 3 (communication), 4 (professional responsibilities), and 5 (teamwork & project management) (Appendix 2.).

In the first year (the "deck carpenter" assignment) most assessment is observational. The instructor of the Production and Design Seminar watches the student perform the pre- and post-performance checklists and tasks during technical rehearsals over the one week that they occur ahead of the scheduled performances. Additionally, the instructor solicits the feedback of the technical director, assistant technical director, stage manager, and other parties as necessary. Specifically, the instructor is looking at the following observable criteria:

1. an ability to effectively communicate questions about and their understanding of the production-specific responsibilities with appropriate stakeholders. This includes demonstrating an understanding of pre- and post-performance inspection checklists, decision trees, troubleshooting plans, and safe operation of scenic elements.
2. an ability to complete their assigned role with an appropriate professional demeanor (including timeliness, appropriate attire, professional communication tone, and language)
3. an ability to communicate problems/concerns clearly and promptly.
4. an ability to collaborate with stakeholders to troubleshoot promptly when issues arise.
5. an ability to apply technical skills to effectively make repairs to damaged scenic elements.

In the second year (the "assistant technical director" assignment), students are assessed both through observation and through the critique of deliverables appropriate to their responsibilities. Students are assessed on the following criteria:

1. an ability to perform project management tasks (based on the following deliverables):
    a. a back-of-the-envelope parametric/analogous estimate of scenic elements at a preliminary design presentation.
    b. a definitive cost estimate and time estimate for a fully-designed scenic element using prequalified construction techniques.
    c. a design/build plan based on a critical path analysis presented using a Gantt chart.
    d. a full set of construction drawings sufficient for a scenic shop to build with minimal additional input from the assistant technical director.
    e. an installation plan and a tear-down ("strike") plan based on available personnel resources.
    f. a pre- and post-performance safety/inspection checklist, FMEA, and troubleshooting plan.

2. an ability to collaborate with other stakeholders (based on observation and feedback from stakeholders).
3. an ability to effectively communicate through drawings, paperwork, and oral/written communication.

Year 3 Assessment

In the third year, or the course to be recognized as meeting the requirements of an ABET-compliant penultimate design experience, all artifacts and related assessments must demonstrate meeting a satisfactory level of achievement (C- or better) for *all* the individual student outcomes of ABET criterion 3 (*Accreditation Board of Engineering & Technology, (n.d.)*). These include:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
3. an ability to communicate effectively with a range of audiences.
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Additionally, under ABET criterion five (5) Curriculum, students must engage in “a broad education component that complements the technical content of the curriculum and is consistent with the program educational objectives”, as well as “*a culminating major engineering design experience that 1) incorporates appropriate engineering standards and multiple constraints, and 2) is based on the knowledge and skills acquired in earlier course work*.” (*Accreditation Board of Engineering & Technology, (n.d.)*).

Students' work is reviewed for achievement of these outcomes one time in their first semester of the senior capstone design experience, and two times during their final semester; once mid-term and a final instance at the end of the semester. The review process for semester one simply involves having the student articulate their planned scope of work (Ref. engineering design image below: Project identification and early stage specification development). At this time the student articulates early ideas for how the second semester will be planned for the remaining product design cycle steps (i.e. firm specification development, conceptual design, detailed design, delivery, testing, and iteration).

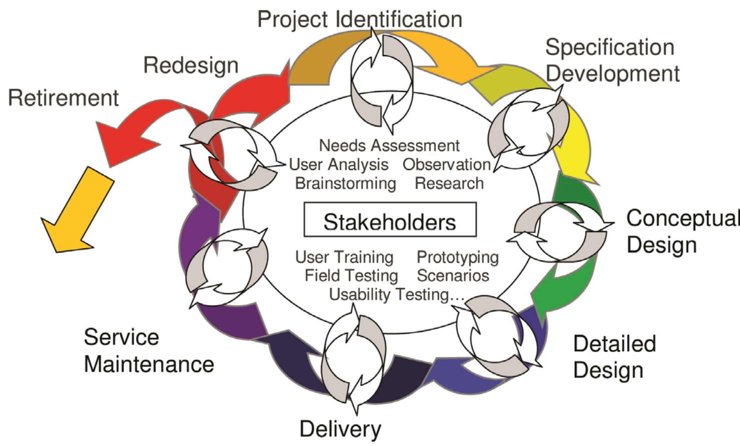


Image 2 citation: Design Cycle Process (Purdue University EPICS (n.d.)

Rather than focusing the first-semester discussion on specific design/project artifacts, the conversation with the student, theatre course instructor, and director of the MDE program revolves around helping the student identify the design "orientation" and engineering tool emphasis. For example, is the design likely to be oriented toward mechanical systems, electrical/electronic systems, or structural systems? Likewise, based on the former design orientation, what are the most likely engineering tools to be put to work in support of developing such a design? For example, an intense mechanical design may lean heavily on CAD (computer-aided design) tools, including pre-production simulation to support proof of concept, material choices, calculations, etc.

While this discussion occurs as a planned yet informal presentation with the course instructor and the director of the MDE program, the spirit of the encounter is best described as collaborative. In essence, this is an opportunity for the student to collect early input and resource outlets/considerations as they enter the more focused semester of engineering design delivery (semester 2).

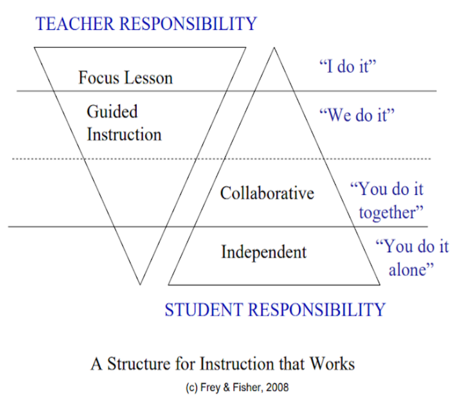
The second-semester review process is more extensive and formal and occurs both at the mid-term and end of the term. The student must plan and present a PowerPoint presentation of their work in progress (or completed work), detailing and expanding with visual evidence each step of the design cycle (i.e. research/ideation, conceptual design, detailed design, delivery, testing, and iteration). The student must orally explain and defend their design decisions, receiving both immediate feedback as well as detailed written feedback using the course ABET assessment rubric (see attachments).

At the mid-term review instructor and MDE director focus feedback on any necessary steps for the student to take to make successful course corrections for the end-of-the-term completion of their work. Because the student must pass the course with a C- or better, the mid-term review presentation is a significant indicator of the student's ability to successfully complete the course. Students successfully meeting minimum expectations at the mid-term review continue forward with their design and delivery of their engineering artifact for use within the assigned production.

The final design review occurs post the execution of the live performance in which the senior design artifact is used. Both the director of the MDE program as well as the course instructor are required attendees for this one-on-one presentation meeting. The timing of the presentation (post-show) allows for the student to elaborate upon the entire design process experienced and reflect deeply on so-called “lessons learned”. The reflective component is critical for students to consider how elements of their design worked or failed to meet their design expectations. Likewise, as a pedagogical instrument, the reflective component of the presentation offers the student a formative opportunity to “rethink” how any future instance of similar design practice might be enhanced.

Pedagogy

Correct content with fitting assessments can only have the greatest impact if aligned with strategic and purposeful pedagogical approaches. The THTR59700 course is at the core active learning-oriented and engages technical knowledge across students' academic advancement, keeping the developmental growth of students in mind. In particular, the pedagogical frameworks that most clearly relay the pedagogical values instilled into the 3-year capstone design approach include “structured teaching” by Frey and Fisher (2008), spiral course design by Bruner (2009), and practice-based education (Mann, Chang, Chandrasekaran, et. al. 2021).



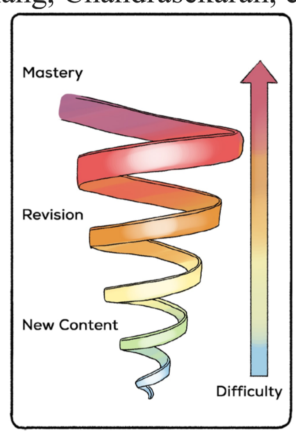


Image 3 citation: Fisher, D., & Frey, N. (2021). *Better learning through structured teaching: A framework for the gradual release of responsibility*. ASCD.

Image 4 citation: *Jerome Bruner (Biography)*. (2020, March 11). Practical Psychology. [https://practicalpie.com/jerome-bruner/.](https://practicalpie.com/jerome-bruner/)

The responsibilities and assessments described above in the first and second years of the 3-year capstone progression are specifically designed to scaffold students toward a robust, realized, engineering design project situated within the context of a theatrical production. This production by definition, comprises a complex group of stakeholders with immovable deadlines and fixed and finite material and personnel resources.

In year one, students are exposed to how constructed elements fit within the larger production context; they see how good (and bad) practices in construction, communication, engineering design, etc., directly impact the director, designers, actors, and crew in performance. They also experience the impact of well-designed and poorly-designed inspection checklists, FMEA documents, and decision trees.

In year two, students practice project management skills in the theatrical context without addressing engineering design and analysis, to avoid cognitive overload. This also allows students to hone project management skills before layering on the analysis and design work. However, in the second year, students must interact directly with stakeholders, providing key experience in understanding stakeholder needs and how to communicate with stakeholders of differing domain backgrounds. By year three, these experiences–as well as students' experiences in engineering analysis through their other engineering coursework, are then combined to form a comprehensive capstone experience. This structured approach, with students receiving more responsibility while concurrently realizing less support, step-walks students into greater independence to authentically tackle their capstone design challenge.

In addition to the 3-year capstone experience, concurrent with their sequence of engineering-specific courses, students will engage in at least two instances of engineering analysis and design courses in the department of theatre (i.e. "Structural Design for the Stage," "Mechanical Design for the Stage," "Control Systems Design," etc.). In these courses, students are re-exposed to concepts they have seen in their engineering courses (statics analysis, materials analysis, linear circuits, logic controllers, physics of motion, etc.). Further, in the Production and Design Seminar course, students observe (as deck carpenters and assistant technical directors) others (technical designers and CLA graduate student technical directors) applying these concepts in their work and participating in the critique of this work. In this way, students are exposed *and re-exposed* to concepts, techniques, and skills repeatedly throughout their three years in the program. Each exposure allows for–encourages–deeper engagement with, and understanding of the concepts, thereby progressing them toward an ability to independently apply them in their senior capstone design.

Finally, as pointed out above, each student must engage with and activate their knowledge in a realized context. There is no pretending in this practice-based experience that the stakes aren't real. Tickets are sold for the productions the students work on; there are eight live performances. Additionally, the work of other students–designers, technicians, stage managers, actors, dancers, etc.,--is all interdependent. A theatre engineering student's failure impacts not just them, but potentially dozens of others. Finally, because students are applying their knowledge and skills to a "real thing," that knowledge is activated and remembered in a way that simple conceptual projects cannot replicate: students see the real impact of their choices, of their application of skills, of their ability to be timely and to accurately complete analyses.

Other Values/Challenges/Opportunities

The preceding paragraphs unpack the 3-year capstone design approach through the logic of the CAP framework. There are however invisible values embedded in this course design/approach that cannot be simply described using the CAP framework. The following offers a glimpse at the values, challenges, and opportunities associated with such a collaborative course/program approach.

Values: Practice-centered

University momentum aside, there exists a role within the ranks of some colleges and universities that stands apart from the intentional and unintentional motivations associated with tenure and research faculty. This role is sometimes known as faculty of practice. According to Pilotte, Bairaktarova, and Kajfez (2014), a primary benefit of those filling the role of faculty of practice is to increase collaboration through explicit boundary spanning, unpacking of authentic engineering practice, and help students face down the inevitable challenges and "messy complexity" that they will face in the workplace. Both authors of this work are faculty of practice, bringing with them deep experiential expertise from respective domains (theatre and engineering). As such, the shared value of representing authentic-to-practice design experiences was an immediate opportunity for shared/common ground. Likewise, as practitioners, both authors are accustomed to the give-and-take negotiations that evolve in the world of work to accomplish a common goal, be that putting on a complex performance or developing an engineered solution to an urgent manufacturing problem. Finally, the habits of practice found in industry have a cadence (pace) and dialect (language) that sets it apart from the academic community. While each industry is unique, the translation between dialects and familiarity of a solution-centered cadence was approachable due to the authors shared, practice-focused experience outside of the academy. Upon reflection, the authors feel that the shared value of practice-based experience, while not required, has afforded an extraordinary and harmonious collaboration that has avoided many of the pitfalls expressed in the multidisciplinary collaboration literature discussed earlier in the paper.

Challenges:
The biggest challenge to the 3-year capstone design as it is currently implemented is scalability. Effective and impactful "real" production-based assignments require actual productions. While the specific material resource demands for each theatre engineering student in each of their three years is relatively small (less than $500 in materials per year), the work of these students is situated within larger theatre productions. The overall non-personnel costs for each production might exceed $10,000 for scenery, costumes, lighting, sound, scripts/royalties, marketing, etc. Additionally, it becomes challenging to assign more than one or two students to each production; it is difficult to have two deck carpenters on one production, for example, without one feeling "extraneous"--negating many of the advantages of the practice-based approach. Finally, the pedagogical approach for each of the assignments of the 3-year capstone requires that the production process be spaced out in such a way that students have time for their work to be critiqued and to make improvements before the work becomes "public." These constraints limit both the number of productions that can be produced and the number of students who can be assigned roles in those productions.

The load on the faculty poses an additional challenge to scalability. The mentoring and critique involved require significant instructor-student contact hours. While the pedagogical model is built on scaffolded support, it also relies on the introduction of complexity and difficulty over time. This means that while concepts, techniques, and skills that required/received significant support in the first year should require less attention in the subsequent years, each subsequent year is at the same time expecting students to demonstrate and practice the same skills in a more complex context, integrating new concepts, techniques, and skills–requiring at the very least a similar amount of instructor support time (if not, in some cases, more). Scaling the program beyond four students per year (or 12 total students across the three years) would require additional faculty support.

Opportunities
One unexpected outcome arising from the COE/CLA collaboration on theatre engineering and the 3-year capstone approach was a demand to share the collaborative best practices and curricular programming with others. Contacted by the broader community of theatre and engineering programs across the United States, the authors have met with numerous university representatives from East Coast to West to discuss the "secret sauce" of helping engineering and the liberal arts find common win-win ground in joint program development. At least one university launched a new joint degree program modeled after the theatre engineering program, and another similar program has found support from the authors in pursuit of meeting successful ABET accreditation.

This informal community of practice leadership led to the development of a formalized, education-focused center known as the Fusion Studio for Entertainment and Engineering in 2020. This center serves as a hub of innovation for the scholarship of teaching and learning at the intersection of engineering, technology, and the broad entertainment industry.

Discussion
While universities are not ideally structured to support interdisciplinary work in high-stakes instructional classrooms, the instance elaborated upon in this case study offers a template for how others might replicate this approach at the intersection of entertainment and engineering. That said, there must be some direct motivation for migrating away from traditional approaches. To that end, several anecdotal impacts/benefits from this approach have been observed.

Firstly, is evidence of positive impacts on students. Since the inception of the formalized theatre engineering program in 2016, graduate job placement in the entertainment sector is over 90% (91.6%), indicating a strong industrial pull of this unique and specialized engineering talent. Two students (female) who completed the program but chose not to enter the entertainment sector, left roles in engineering all together. Additionally, salaries for the theatre engineering graduates were at the mean value or within one standard deviation of the overall mean multidisciplinary engineering starting salary for their graduating cohorts (i.e. 2016-2021 mean salary, $60,139). To date, no graduates have tested the value of their degree (by starting salary or other metric) in a non-entertainment sector role.

Secondly, the demographic makeup of the theatre engineering cohorts since 2016 deserves some comment. As of this writing, the student cohorts have been between 83% to 100% female. Speaking strictly anecdotally based on interviews with graduating students, something about the degree and pedagogical approaches appear to be attractive to women with an interest in engineering. Some alumni have indicated they might have moved away from engineering entirely if they had not discovered the theatre engineering concentration as an option. Some students in the concentration have indicated it allows them to combine both their "analytical" and their "creative" sides in ways other disciplines might not.

These observations and comments are supported by engineering education literature. One example from 2002 involves the Women in Applied Sciences and Engineering (WISE) Program at Arizona State University (ASU) which documented persistent increases in female engineering student retention and triple-digit female engineering student participation in programming such as ArtVentures in Engineering (Newell, Fletcher, & Anderson-Rowland, 2002). Likewise, more recently, the trend toward hands-on makerspaces has been shown to support a sense of community for females in engineering, favorably impacting areas associated with assessment (Roldan, Hui, and Gerber, 2018). This 3-year capstone pedagogical approach includes rich artistic contexts and involves multiple "maker experiences", embodying core elements proven valuable to female engineering students.

Qualitatively, we have observed that students completing the concentration have been interviewing for–and been hired for–positions in competition with students completing masters-level work in theatre technology. This reflects both on the program concentration and the industry: theatre engineering students–due to the heavy emphasis on their engineering core coursework–have fewer opportunities for practical experience compared to MFA students who have completed an undergraduate degree and a three-year degree focused on hands-on practice. While the 3-year capstone, we believe, maximizes the impact of three intentional and curated hands-on experiences, it does not (cannot) replace multiple years of focused experience. This suggests that there is some added benefit to the integration of engineering concepts *with practice* in the 3-year capstone that employers find attractive. This deserves more exploration, as does the long-term impact on the industry if the balance of expertise at certain levels continues to swing this way.

Also deserving of further exploration are means of addressing the scalability challenge. In particular, there would be a significant benefit in identifying hands-on experiences that might replicate those of the 3-year capstone experience as integrated into realized live theatre productions. A first step toward this might involve developing a richer vocabulary to better decouple the various ways the hands-on experiences engage students. This could provide a framework for developing additional hands-on experiences (including alternate contexts or venues), identifying cross-campus and extra-campus partnerships, and developing expectations for non-faculty oversight and mentorship.

Conclusion

This paper provides a detailed overview of a unique, entertainment industry-focused pedagogical approach for a theatre engineering concentration that resides within an ABET-accredited multidisciplinary engineering program. Grounded in the CAP framework, course-specific elements of the 3-year capstone design course content, assessment, and pedagogy were elaborated upon to highlight an approach toward preparing "practice-ready" engineers for the entertainment industry. This approach, which prepares students for work within the specific industry of entertainment, can successfully meet requirements culminating in a criterion 5 ABET design experience.

Allowing students to utilize their technical engineering know-how and skills, in a developmentally appropriate and gradually increasing stakes and released instruction format, provides authentic performance encounters acclimating them for the rigors of the professional domain experience. Essential course/program values as well as structural challenges were also discussed. Finally, this interdisciplinary, cross-campus collaboration has continued to support educational innovation between engineering and the performing arts in the form of a novel education-based center.

Acknowledgments
The authors would like to acknowledge the foundational collaborations that existed between the College of Engineering (COE) and the College of Liberal Arts(CLA) before them, that made this work, the relationships, and the creation of the Fusions Studio for Engineering and Education possible. This includes the forward-thinking of Dr. Joel Ebarb, professor in the Rueff School of Design Art, and Performance (CLA), Prof. Emeritus Phil Wankat, Clifton L. Lovell Distinguished Professor Emeritus of Chemical Engineering and Professor Emeritus of Engineering Education, and the undying dedication and advocacy for theatre engineering students by engineering academic advisor, Christine Pekny, School of Engineering Education.

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Appendix 1. Theatre Engineering Plan of Study

Theatre Engineering Concentration Plan of Study

Semester 1			**Semester 2**		
CHM 11500	GENERAL CHEMISTRY	4	ENGR 13200	TRANS IDEAS TO INNOV II	2
ENGR 13100	TRANS IDEAS TO INNOV I	2	GEN ED	GEN ED (Found Outcome OC)[2]	3
GEN ED	GEN ED (Found Outcome WC)[1]	3	MA 16600	PL ANLY GEO CALC II	4
MA 16500	PL ANAL GEO CALC I	4	PHYS 17200	MODERN MECHANICS	4
			SCI SEL	FYE SCIENCE SELECTIVE	3
	Total	13		Total	16
Semester 3			**Semester 4**		
IDE 30100	PROF PREP IN IDE SEMINAR	1	ECE 20001	ELEC ENGR FUND I	3
MA 26100	MULTIVARIATE CALCULUS	4	ECE 20007	ELEC ENGR FUND I LAB[6]	1
ME 20000	THERMODYNAMICS[3]	3	MA 26200	LIN ALG AND DIF EQU[7]	4
ME 27000	BASIC MECHANICS I[4]	3	ME 27400	BASIC MECHANICS II[8]	3
PHYS 24100	ELECTRICITY & OPTICS[5]	3	THTR 36800	THEATRE PRODUCTION II	2
THTR 15001	INTRO TO DRAFTING	1	THTR 55000	ADV SCENERY TECH[9]	3
THTR 15002	INTRO TO SCNRY CONST TOOLS & TECH	1			
THTR 15003	INTRO TO RIGGING FOR THTR	1			
	Total	17		Total	16
Semester 5			**Semester 6**		
CE 34000	HYDRAULICS[10]	3	ENGR ELECTIVE	ENGINEERING ELECTIVE[12]	3
CE 34300	HYDRAULICS LAB[6]	1	ENGR SLCTIVE	ENGINEERING SELECTIVE (design)[14]	3
CGT 16300	GRAPH COM & SPAT ANLY[11]	2	IDE 36000	MDE STATISTICS[15]	3
ENGR ELECTIVE	ENGINEERING ELECTIVE[12]	3	THTR 20100	THTR APPRN (Found Outcome H)[16]	3
NUCL 27300	MECHANICS OF MATERIALS[13]	3	THTR 59700	PRODUCTION&DESIGN SEM[17,18]	3
THTR 55000	ADV SCENERY TECH[9]	3	THTR 36800	THEATRE PRODUCTION II	1
	Total	15		Total	16
Semester 7			**Semester 8**		
ENGR ELECTIVE	ENGINEERING ELECTIVE[12]	3	ENGR ELECTIVE	ENGINEERING ELECTIVE[12]	3
GEN ED	GEN ED (Found Outcome STS)[19]	3	GEN ED	GEN ED (Found Outcome BSS)[21]	3
GEN ED	GEN ED[18]	3	GEN ED	GEN ED (300 level or non-intro)[18]	3
IDE 48300	MDE ENGR ANALYSIS/DECISION[20]	1	IDE 48500	MDE ENGR DESIGN PROJ[22]	3
IDE 48400	MDE DESIGN METHODOLOGY	1			
IDE 48700	MDE SENIOR DEVELOPMENT	1			
THTR 59700	PROD & DESIGN SEM[17,21]	3			
	Total	15		Total	12

Appendix 2: Student Capstone Outcomes Assessment Form (Adapted use from Purdue University EPICS student project outcome assessment form, v.2019)

Outcomes	**Indicators** (rate each indicator on a scale from 1 to 4, where 4 is "Excellent", 3 is "Good", 2 is "meets requirements", and 1 is "Inadequate/Unacceptable")	**Rating**
Product Design i. An ability to apply engineering design to create a product[1] that meets the specified needs of this engineering design experience with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. <u>Evaluated</u>: Demo, Project Proposal/Project Description, Design Notebook, Project Documentation	Student was proficient at applying engineering design processes to create the product resulting from this senior design experience.	
	Careful consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors was evident.	
Testing and Analysis ii. An abilitiy to develop and conduct experimentation, analyze and interpret data, and use engineering judgment to draw conclusions related to the development of the product of this engineering design experience. <u>Evaluated</u>: Demo, Project Proposal/Project Description, Design Notebook, Project Documentation	Student demonstrated a strong ability to develop and conduct experimentation, analyze and interpret data in the context of this senior design experience.	
	Student demonstrated sound engineering judgment to draw conclusions related to the development of the product of this senior design experience.	
Problem Solving iii. An ability to identify, formulate, and solve complex engineering problems arising from this engineering design experience by applying principles of engineering, science, and mathematics. <u>Evaluated</u>: Demo, Project Proposal/Project Description, Design Notebook, Project Documentation	This design experience contained elements associated with complex engineering problems (see definitions).	
	Student demonstrated ability to apply principles of engineering, science, and mathematics in the context of this senior design experience.	
Teamwork and Leadership iv. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives associated with this design experience. <u>Evaluated</u>: Team observation, peer reviews	Student demonstrated leadership.	
	Student contributed to creating a collaborative and inclusive environment.	
	Student fully participated in establishing team goals, planning tasks, meeting objectives.	
Communication v. An ability to communicate effectively with a range of audiences appropriate to this design experience in both a written report and oral presentation. <u>Evaluated</u>: Written and verbal communication in, design reviews, Design Documents, Theatre Department open critique	The quality of the student's contributions to the written report(s) associated with this senior design experience was excellent.	
	Student demonstrated effective oral presentation skills.	
New Knowledge vi. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies to complete the engineering design experience associated with this course. <u>Evaluated</u>: Project Description, Design Notebook	Student demonstrated an ability to acquire and apply new knowledge as needed, using appropriate learning strategies to complete the product of this senior design experience.	
Ethical and Social Responsibility vii. An ability to recognize ethical and professional responsibilities associated with this engineering design experience and make informed judgments which must consider the impact of the product of this engineering design experience, in global, economic, environmental, and societal contexts. <u>Evaluated</u>: Project Description, Design presentation/report	Student demonstrated an ability to recognize ethical and professional responsibilities associated with this engineering design experience.	
	Student demonstrated an ability to make informed judgements in the context of this senior design experience.	
	Careful consideration of the impact of the product of this senior design experience in global, economic, environmental, and societal contexts was evident.	

[1] "Product" refers to any device, system, process, software, etc. resulting from this design experience.

Formative Comments for Student: