Increasing Accessibility to Undergraduate Research: A Semester-Long, Course-Based Research Model to Enhance the Engineering Classroom

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***Abstract*— This innovative practice paper explores how undergraduate research experiences can play a formative role in a student's educational development and long-term career aspirations. The research process in its entirety, from literature review to publication and presentation, offers students the opportunity to build confidence in a subject and communicate their findings. Each step of the process offers valuable skills -- such as hypothesis formulation, data collection and analysis, technical writing, and oral presentations -- that are transferable regardless of their post-graduate plans, whether that be attending graduate school or joining the workforce. However, engaging in research is not always accessible to undergraduate students. Currently, the process requires a student to initiate a conversation with a faculty member regarding potential positions in their lab, and if hired, take on tasks that might focus strictly on executing a single aspect of the research methodology, as opposed to experiencing the research process in entirety. The introduction and incorporation of research opportunities into undergraduate courses allows students to explore engineering through an interdisciplinary lens, as opposed to a lecture-based class, which might focus strictly on technical theory. In this work, we present a structure for a semester-long, course-based research project that was piloted across two semesters for two distinct engineering courses.**

The structure of the proposed classroom model is equal parts theory, research, and communication. The first third takes the form of a traditional course introducing engineering concepts. The technical skills developed here supplement the rest of the coursework, giving students the relevant background needed to make meaningful and informed decisions in their problem sets and research. The second third is dedicated to introducing the research process and applying that process to a general set of research questions. In the first pilot course, Introduction to Analog and Digital Communications, 23 students were broken into teams of two to three students, with each team exploring the coexistence of two spectrum stakeholders, e.g., 5G terrestrial users and Federal Aviation Administration (FAA) radar altimeters or radioastronomy (RAS) and large low earth orbit (LEO) satellite constellations. The research and communication components focus on developing undergraduate students' skills synthesizing technical findings, assessing stakeholder pain points, and framing of solutions in an actionable manner. This work discusses the semester-long structure and provides a class-by-class breakdown of the content, assessment, and learning outcomes. Additionally, it summarizes the learnings of the course pilots and offers recommendations for engaging with and applying this course model at other institutions and across disciplines including at the first-year or capstone level.

Keywords—undergraduate research, project-based learning, accessibility

I. Introduction

Dozens of studies empirically show that undergraduate students benefit from engaging in undergraduate research experiences (UREs) [1], yet these opportunities are rarely available and accessible to all. To obtain a research role, students are commonly required to approach a faculty member outside of class and participate in research on either an independent study course credit, compensation, or voluntary basis. After obtaining a position, a student rarely participates in the entire research process, and may instead be limited to executing specific laboratory experiments. Students who do not approach faculty, but may still be curious about research, report it can feel intimidating to initiate a conversation with faculty members or graduate students.

Introducing UREs into the curriculum of required courses, would expose more students to the research process in entirety and would level the playing field for obtaining valuable skills such as: independent critical thinking skills, technical writing, and oral communication [2]. In addition to these skills, UREs can enhance a student's confidence as an engineer, and solidify their decision to pursue a graduate education or career in STEM. Research publications and presentations increase visibility in the scientific community, and in turn benefit the college or institution.

As a bridge between research and the traditional problem-based classroom, a semester-long, course-based research experience was designed to incorporate accessible research engagement opportunities into a real-world, project-based classroom. The course was piloted at Olin College of

Engineering, an undergraduate-only university built on a project-based educational model, with the support of the National Science Foundation (NSF) SpectrumX.

Previous studies have shown that students in project-based environments report higher levels of elaboration, critical thinking and metacognition [3, 4] Additionally, project-based courses found that students reported higher autonomy support, or the degree to which they perceived their instructors supported their opportunities to think independently [4, 5].

This paper discusses the curriculum of a thirteen week course that consists of three parts: theory, research, and oral communication. This multifaceted model combines an analytical foundation, practical application, and effective communication, to provide a comprehensive educational experience. The research "third" incorporates a semester-long, course-based research project. One key feature of the research project in this course model is that the topic contains both a technical and policy element, as it is imperative that engineering students comprehend and appreciate the impact of technology on society and the regulations that govern these systems.

This course structure was piloted and then implemented across two distinct engineering courses, one being an elective and the other a part of the core curriculum. This research-based course model was first piloted in Fall 2022 in an introductory wireless communications course, and was later implemented in a course in Spring 2023 on satellite systems. In each course, the thirty students formed teams of two to three around either a spectrum coexistence scenario or a satellite policy issue. There were ten teams of students in the course pilot in the fall and five teams in the satellite systems course in the spring.

Spectrum coexistence scenarios include two radiofrequency services, generally an entrant and incumbent, proposing to operate in the same spectrum. One example of such a scenario consists of 5G terrestrial users (entrants) identifying bands adjacent to or in-band with Federal Aviation Administration (FAA) radar altimeters. Another scenario is the operation of low earth orbit (LEO) fixed satellite service constellations in or adjacent to radioastronomy services (RAS). There is both a technical and regulatory element to ensuring the two services operate without causing harmful interference. Students provided feedback voluntarily at the end of the semester. Because this is acknowledged as a less accurate form of assessment [1], our work focuses on presenting the framework of this course with the aim of evaluating its impact in future work.

II. Semester-Long Course-Based Research Model

The proposed classroom model embraces a dynamic and holistic approach to learning, divided into three equally important components. The first segment emphasizes theory through traditional, yet brief lectures, classroom discussions, and problem sets. This foundational stage equips students with the essential theoretical knowledge required for engaging with the subject matter. The second component introduces the research process, where students conduct literature reviews, actively participate in conversations with stakeholders, and implement theory from the course into modeling exercises to further their research. This experience not only deepens their understanding of the material but also fosters critical thinking and the application of theoretical concepts to real-world scenarios. The final third of the model is dedicated to honing communication skills. Through technical writing exercises and oral presentations, students learn to articulate their research questions, findings and future work effectively across a diverse audience.

Implementing these three approaches (theory, research, communication) simultaneously is a crucial part of this model. This integration is designed to be mutually reinforcing, creating a dynamic learning environment in which each component complements and enhances the others.

These goals were considered when determining the deliverables for the research project which include: a literature review, stakeholder interviews, a conference style presentation, and a comprehensive written report. The report can take the form of a conference paper, and may follow a provided template. Mid-term and final presentations along with occasional research updates are presented orally in class. At the mid-term students record themselves presenting on their phones or computers, and are assigned to later watch their recording and reflect on their habits and delivery. In this reflection, students identify their strengths and weaknesses of their skills and identify areas of improvement for future presentations in the class. The importance of rehearsing presentations is stressed on a weekly basis.

A shared folder divided into sub-folders for each team offered a means for easily storing all deliverables. By providing a centralized platform for document sharing, students could easily share insights and offer constructive critiques. This collaborative environment not only encouraged active participation but also promoted a sense of community and collective ownership of the learning process. Additionally, students had the opportunity to learn from the diverse perspectives and approaches of their peers, enriching their understanding of the subject matter and enhancing the quality of their own work.

An example of a thirteen week course structure is provided in Table 1. The goal of this table is to provide students with clear guidelines for in-class and take-home assignments pertaining to both the presentation and technical writing component of their research project. The thirteenth day of class consists of a community wide presentation. On this day, final presentations and a written report are due.

TABLE I. EXAMPLE CLASSROOM BREAKDOWN

Week	In-Class Activity	Class Deliverable	Overall Assignment	Research Assignment	Written Report Assignment
1	Research Topic Introduction and Team Assignment		Create a presentation with 5-6 slides including a title slide with a descriptive name that captures the topic (1); an introduction slide that broadly describes the scenario, its technical and policy aspects, and any open questions (1); additional slides cover more depth on the topic (2-3); and a References slide using IEEE reference formatting (1).	Find three relevant scholarly articles, include them in your reference slide and in your research introduction	
2	Topic Introduction Presentation and Feedback	Topic Introduction Presentation (5-6 slides)	Receive and incorporate in-class feedback from faculty and peers, as well as expand slides to include a historical timeline of the topic and other information learned in deepening research.	Continue to research the nuances of the topic.	Outline the technical report that will cover the topic from a technical and regulatory angle; Generalize section titles
3	Brief (2 min.) Update on Research Progress	Expanded presentation (8-10 slides), rough outline of technical report	Continue to supplement and polish the presentation. In parallel, add bullet points to your technical writing outline.	Find additional sources to supplement the slide deck and written report	Begin supplementing written reports, these can be bulleted sections.
4	Brief (2 min.) Update on Research Progress	Expanded outline	Continue to supplement and polish the presentation.	Identify at least 6 relevant stakeholders (researchers, affected parties, etc.) to contact and interview.	Expand bullet points to paragraph forms - identify any schematics (timelines, graphics, etc.) that can complement the technical report
5	Working session: Confirm stakeholders and 1:1 research progress review with faculty	List of Stakeholders	Review stakeholders and overall research progress with faculty / course assistants. Begin contacting stakeholders for interviews via Linkedin or email.	Find additional sources to supplement the slide deck and written report	Give feedback for another team's presentation and paper -- directly comment using "suggesting" / track changes
6	Midterm Practice Presentation (7 min)	Peer Feedback and complete Midterm Presentation; Record yourself presenting	Continue to supplement and polish presentation, incorporating feedback from peers	Begin stakeholder interviews; Record your draft midterm presentation.	Incorporate feedback given by the other team, complete first draft
7	Midterm Presentations (7 min)	Polished presentation; 2-3 paragraph reflection on observations from presentation recording			
8	Project Plan	Project plan and timeline for the rest of the semester	Incorporate feedback from Midterm Presentation and begin research policy / regulatory issues	Continue stakeholder interviews and begin scaffolding the policy / regulatory issue	Implement feedback from Midterm Presentation and begin drafting Policy section of report
9	Present Project Plan and Stakeholder Interview outcomes (3 minutes)		Wrap-up stakeholder interviews and explore how one can incorporate quantitative analysis to inform the policy recommendation.	Add 2-3 slides introducing the policy / regulatory issues	Expand the policy section - include technical modeling in the report.
10	Policy Issue Framing	Complete Stakeholder interviews	Incorporate outcomes of interviews into presentation and technical report.	Expand upon the policy issue incorporating relevant scholarly resources	Expand policy section of technical report
11	Policy Recommendation	Form Policy Recommendation	Finalize slides and technical report. Propose your own policy recommendation.	Give feedback on another team's slides using "suggesting" / track changes	Incorporate policy recommendation and make final adjustments to report
12	Practice Final Presentations (present new content)	Final Presentation and Report Draft Due	Practice presentation and incorporate feedback from in-class presentations		Incorporate any remaining feedback

In the course pilot, students gave weekly presentations in the form of either a full presentation or a brief research update. Feedback was provided that replacing some of the research briefs with full-class periods for research and 1:1 feedback was a better use of time. Several studies stress the importance of mentoring in UREs, along with the demand 1:1 engagement can place on faculty members [1, 6]. As a result, the structure was updated to include a mid-term and final presentation along with practice presentations and occasional research updates.

Beyond collaborating with other students, reaching out to industry stakeholders is a crucial part of the research process. Engaging with them, however, can be the most daunting part of the course. Providing students with sample text to send to stakeholders requesting an interview can support them in this project component.

Hello [RECIPIENT NAME],

I hope this email finds you well! My name is [STUDENT NAME], and I am a [SCHOOL YEAR] at [UNIVERSITY/COLLEGE] currently taking [PROFESSOR NAME]'s [COURSE NAME]. We have broken into research teams focusing on various aspects of the [TOPIC] industry. My team is investigating the [SPECIFIC TOPIC] and developing a proposal for [PROPOSED SOLUTION].

If you have the time, we have attached a brief overview of our idea and have included some questions we would love to get your opinion on. We would appreciate your help fleshing out our knowledge of the field and any comments you have. We really value your expertise!

Best,

[STUDENT NAME]

on behalf of the [Project Team Name] Team

[(LIST ALL PROJECT MEMBERS)]

[PROVIDE A LINK TO YOUR PRESENTATION ONLY]

Giving students the scaffolding to pursue their project in an impactful way involves providing them with the necessary support and structure to navigate the complexities of their research effectively. This can take various forms, including clear guidelines, resources, mentorship, and opportunities for collaboration. By doing so, educators empower students to pursue their projects with confidence and competence, enabling them to make meaningful contributions through the coursework and beyond.

III. Learning Outcomes

Learning outcomes serve as a framework to guide instructional design, assessment strategies, and overall educational effectiveness of a course. These explicit learning outcome statements articulate what students are expected to know, understand, and be able to do upon completion of this educational experience [7]. The coursework for this model was developed with six outcomes in mind:

1. Develop and Apply Knowledge, Skills, Approaches and Methods
2. Think Critically
3. Develop and Apply Self-Directed Processes to Achieve Desired Outcomes
4. Collaborate Successfully
5. Communicate Effectively
6. Develop Personal and Professional Identity

The first of these, "Develop and Apply Knowledge, Skills, Approaches and Methods" encapsulates the most traditional goals of undergraduate coursework. It requires students to successfully understand and apply their learning, enabling them to design experiments essential for gathering data and drawing conclusions to strengthen their theoretical background. However, this learning goal includes the caveat that a course's goal is not only to amass information but to use it purposefully and discerningly, ensuring a holistic capacity to navigate complex challenges. Through the inclusion of lectures and problem sets, these needs are met and give students an appropriate foundation for approaching technical challenges. Ideally, each student applies this theoretical foundation to aspects of their research product via quantitative modeling or data science to support their policy position and research findings.

Once students develop their technical skills, they will be able to achieve the second learning goal: "Develop and Apply Self-Directed Processes to Achieve Desired Outcomes." Giving students the agency to identify their learning needs and set goals that resonate with them allows for a more proactive and autonomous approach. This is crucial for the success of the research project, which relies on students choosing a relevant topic about which they are passionate. Through this project, students are tasked with scoping and planning deliverables, continuously evaluating their progress, navigating uncertainty and adversity, and pivoting as the work evolves. Through the cultivation of these self-directed processes, students not only enhance their academic proficiency but also develop valuable skills for lifelong learning and adaptability.

In cultivating opportunities to "Think Critically," students are encouraged to actively analyze, evaluate, synthesize, and apply a diverse range of information and experiences. This goal empowers them to make informed decisions, shape attitudes, take purposeful actions, and express themselves effectively. By engaging in these cognitive processes, students not only enhance their problem-solving abilities but also develop a capacity for nuanced and informed decision-making. In the theory third of the class, students analyze and evaluate diverse information presented during lectures and apply theoretical concepts to problem sets. During in-class research, critical thinking is emphasized as students synthesize information gathered from stakeholder interviews, literature reviews, and modeling exercises to inform decision-making and action.

The learning goal of "Collaborate Successfully" emphasizes the development of interpersonal skills that are crucial in professional settings. In this two to three person team research project, students are challenged to create and sustain effective

working relationships, demonstrate accountability for their contributions, and adeptly identify and resolve interpersonal conflicts within team dynamics. This collaborative competency is essential for achieving common goals and thriving in diverse and interconnected environments.

"Communicate Effectively" is a cornerstone of success in any endeavor. This learning goal focuses on the manner in which students express engineering concepts proficiently through oral, written, and visual media to a variety of audience members. Additionally, students are guided to actively listen, to provide meaningful feedback to their peers. By honing these communication skills, students are better equipped to convey their ideas, fostering understanding and collaboration in both academic, public and professional contexts.

Finally, "Develop Personal and Professional Identity" invites students to actively reflect on their backgrounds and experiences. The aim is to integrate these reflections into an evolving sense of self. By understanding and embracing their personal and professional identities, students can navigate their educational journeys with a deeper self-awareness, enabling them to make informed choices and contribute meaningfully to their academic and professional communities. In engaging with stakeholders, students are able to see potential careers that could be a part of their future if they desire. In reflecting on their presentation skills, students are able to hone in on areas of their personal communication styles they'd like to develop.

IV. Research-Based Course Model Pilot and Implementation

In a post course survey, students offered feedback that the research presentation better enabled them to more effectively address the six aforementioned learning objectives identified prior to piloting this research-based course-model:

1. Develop and Apply Knowledge, Skills, Approaches and Methods
2. Think Critically
3. Develop and Apply Self-Directed Processes to Achieve Desired Outcomes
4. Collaborate Successfully
5. Communicate Effectively
6. Develop Personal and Professional Identity

One student said, "I absolutely loved the research projects we did the entire semester. I had never had an experience like that before and it was meaningful to be able to do work that mattered." Others shared that in the future, they could see themselves in similar roles as stakeholders and were motivated for the first time to consider graduate school. Students also shared they appreciated when the topics in the theoretical portion of the course related directly to the quantitative analysis required in their research project e.g. interference geometries and link assessment, or orbital dynamics.

Researchers from the NSF funded SpectrumX Research Center were pleased with the pilot and several members attended the final presentation in person and recorded the student's final presentations [8]. These videos were later published on the NSF SpectrumX Center website as a means for the general public to learn more about spectrum coexistence issues. Students were also eager to use the recordings in their portfolios for job and higher level education interviews, with several citing it as their go-to talking point when applying for post graduate options.

Acknowledgment

The authors would like to thank the support of the National Science Foundation SpectrumX Research Center (Award Number 2132700) for funding the pilot and publication of this classroom model. Additionally, the authors would like to thank Sreenidhi Chalimadugu for serving as a course assistant to both classrooms, Professor Randall Barry for piloting the classroom model with a pair of students in his research group during Summer 2022, and to members of SpectrumX for recording the final projects and hosting them on the SpectrumX website.

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