AN UNDERGRADUATE-LED, RESEARCH-BASED COURSE THAT COMPLEMENTS A TRADITIONAL CHEMICAL ENGINEERING CURRICULUM

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INTRODUCTION

Chemical engineering has been an interdisciplinary field since its inception in the late 19th century, arising from a need to synthesize the knowledge of mechanical engineering and chemistry for mass processing and production of chemicals.[1-3] Industrial and academic expectations of chemical engineering graduates have evolved in response to the discipline's continued transformation, from its beginnings in unit operations to its adoption of insights and techniques from molecular engineering, materials science, mathematical modeling, and computer science to its emerging contributions within the fields of biotechnology and nanotechnology.[2, 4, 5] However, aspects of the field's evolution in the last few decades have not been formally incorporated into core undergraduate chemical engineering curricula despite the fact that this evolution continues to shape our discipline's contributions to the growing body of scientific and engineering knowledge.[6] Undergraduate students can gain a more holistic understanding of the discipline through seminar-style lectures, hands-on laboratories, and computational work that introduce students to ongoing efforts in chemical engineering research. At the University of Michigan, we, a group of undergraduate students, developed and instructed a new course that incorporates these elements. In this work, we present an example of how undergraduate students can harness departmental support to supplement a chemical engineering curriculum by developing a research-based course.

The Case for Integrating Research into Undergraduate Chemical Engineering Curricula

Advantages of Integrating Research into Curricula. Although the chemical engineering discipline has evolved drastically over the past century, undergraduate curricula have not typically adapted to the disciplinary changes. As such, the current core curriculum covers topics such as material and energy balances, thermodynamics, fluid mechanics, transport phenomena, separations, unit operations, kinetics and reaction engineering, and process controls.[7] In recent decades, however, there have been new discoveries and opportunities in areas such as biological processing, biochemical engineering, microelectronics, nanomaterials, and computational science, and the core curriculum has not expanded to broadly expose students to such emerging arms of chemical engineering.[8, 9] While students gain hands-on experience with traditional chemical engineering equipment as juniors or seniors in the unit operations lab,[10] we believe that they can benefit from an additional, research-based lab course earlier in the curriculum that exposes them to current advancements in the field while nurturing the skills further emphasized in the unit operations course.

There are numerous benefits to exposing undergraduate students to the most recent advancements in chemical engineering research. Because many of the technological advancements that result from state-of-the-art chemical engineering research can directly impact industry jobs in the long-term, exposure to research will help students understand the prior and continued evolution of chemical engineering in academia and industry. This awareness will help students recognize the diverse opportunities available outside of traditional careers in the chemical and petrochemical sectors.[2] Furthermore, such a curriculum can directly prepare students who wish to attend graduate school and pursue research careers. Not only will students have a better understanding of their department's research thrusts (which will aid in deciding which laboratories to join), but a hands-on lab component will also equip them with basic, transferable skills to jump start their work in a research group.

Integrating research can also help students contextualize the theoretical frameworks they learn from existing curricula. A curriculum supplemented with research can help students understand how chemical engineering theory is employed in various academic and industrial settings to uncover new knowledge or create new chemical products relevant to societal needs.[11] In the process, students benefit from early exposure to how the synergy between experimental and computational work can drive innovation in an increasingly data-driven world.

Finally, integrating research into the curriculum can arm students with core competencies transferable to the diverse chemical engineering career options. With the expansion of the chemical engineering discipline to the nanotechnology, biotechnology, consumer products, and microelectronics industries, the importance of learning core competencies, such as critical thinking and communication skills, in addition to technical knowledge, is becoming increasingly apparent.[12, 13] Moreover, core competencies can be effectively taught in experiential learning environments, such as a research-based laboratory course.[11] For example, practicing the scientific method can help students develop critical thinking skills by teaching them the art of forming a hypothesis and devising experiments to probe it. Reading, writing, and presenting scientific work can improve communication skills critical for most career paths. Most importantly, the next generation of chemical engineers can be exposed to the advantages of collaboration through an introduction to ongoing multidisciplinary research efforts.

Common Strategies for Integrating Research into Undergraduate Curricula. Given the benefits of integrating research into undergraduate curricula, various academic programs have sought to promote it as a tool for undergraduate learning. Several strategies have been explored that broadly fall on a spectrum of the breadth versus depth of topics covered: from incorporating research seminar series for a brief overview on an array of topics, to special topics courses for an in-depth focus on specific areas such as drug development[14] and microfluidics.[15] Seminar courses can summarize contemporary research in the field without requiring major overhead costs or extensive faculty-level management and can be of particular benefit to freshmen looking to make a more informed decision on which major to pursue.[11, 16-18] Special topics courses, on the other hand, can be extremely valuable to upper-level undergraduates interested in further exploring specific areas that interest them.

Unlike "research methods" courses offered to early stage graduate students (e.g. "Research Skills for Graduate Students" at Colorado School of Mines[19]), most of the aforementioned strategies for undergraduate research learning, especially those targeted at underclassmen, have been limited to teaching about research advances from a purely theoretical perspective. Recent years have seen a rapid growth in implementing practical elements of learning along with established theoretical pedagogies to enhance the benefits of such courses. Most notable of these are the rise of Vertically Integrated Project (VIP) and Course-Based Undergraduate Research Experience (CURE) programs. CUREs invite the incorporation of practical experimental and computational modules into a course-based setting. Although CUREs have specifically been molded as specialized lab-based courses geared towards scientific discovery,[20] the term is also frequently used to represent and inspire course-based research that is embedded into undergraduate curricula. CURE-based initiatives can serve as a short-term, low-risk, and relatively controlled opportunity for undergraduates to experience authentic research and enhance their in-depth knowledge on advanced topics,[21-24] while also providing additional benefits.[25-27] VIP, an initiative utilized by a global consortium of 36 institutions (vip-consortium.org) pioneered by Georgia Institute of Technology, provides students with long-term (up to three years) project-based learning experiences that enable a deep dive into the student's field of interest and allows them to make tangible contributions throughout their undergraduate experience.[28, 29]

Despite their many pedagogical benefits, current iterations of CUREs have been applied mostly to special topics courses. Unlike programs in biology and chemistry where CUREs are implemented most often,[22] a specialized CURE course would be of interest to a limited student population in a highly diverse major like chemical engineering, which encompasses radically different sub-fields ranging from energy to health. While this could be overcome by having multiple CUREs focused in several different areas, organizing and executing multiple specialized courses would require significant faculty-level planning, material resources, overhead costs, and complex logistics, making implementation difficult. Additionally, the success of long-term VIP programs usually hinges on students having a strong sense of which specific field interests them most, a feat that is challenging to achieve without structured exposure to the diverse areas of a discipline like chemical engineering. A third approach to incorporating research into a chemical engineering curriculum would be a single course that exposes students to multiple research areas through seminars and practical skills modules that adequately represent the diversity of the field. Therefore, we sought to provide an avenue for early-stage undergraduate students to build critical scientific thinking and hands-on research skills while gaining exposure to chemical engineering research, thereby improving their confidence in exploring more involved research opportunities.

Additionally, our approach to designing the lab element of the course mirrors emerging efforts in biology education that seek to deviate from verification-based, cookbook style to inquiry-based, hypothesis-driven labs.[30, 31] The underlying motivations of this approach align closely with ours, and researchers in this field have shown that graduate teaching assistants who teach these courses benefit tremendously in the form of honing their own research skills, which serves as further justification for inquiry-based courses.[32]

The Case for Undergraduate Leadership.

Tenure-track professors at research institutions are actively conducting research on the cutting edge of the field, so they may initially seem the obvious choice to lead initiatives for incorporating research into curricula. Faculty members, however, are stretched thin between mandated research, teaching, and service expectations. Similarly, graduate students and postdoctoral researchers, whose primary motivations are to conduct research and publish, are not well positioned from a time commitment standpoint to lead such an initiative. Nevertheless, graduate students, postdoctoral researchers, and faculty members are critical to the success of research integration into curricula. As such, the additional responsibility of creating research-based classes can be alleviated through undergraduate leadership.

Undergraduate researchers are capable candidates for leading the integration of research into curricula for the following reasons: (1) they are most attuned to the connection (or lack thereof) between research and the standard core curriculum, (2) their mentorship of younger undergraduates through courses they plan and teach can promote future undergraduate research involvement, and (3) the professional development they receive through this opportunity will prepare them to be leaders in the chemical engineering discipline. Current undergraduates have the most up-to-date perspective on how other undergraduates perceive the standard core curriculum and how incorporating research can stimulate their peers. This fresh perspective can facilitate mentorship in research, career, and graduate school planning between undergraduates who teach and take the research-based courses. This type of mentorship between undergraduates can facilitate the development of a culture where undergraduate research is seen as "normal," thereby promoting further undergraduate research participation.[33] Furthermore, leading the development of courses serves as professional development for students interested in academic careers; it provides a unique opportunity that is unavailable even to many graduate students. Graduate school training rarely requires any formal training in engineering education and curriculum development, and many new faculty may not have sufficient time to develop their teaching skills, as they are pressured to excel quickly in research.[34] Undergraduates involved in these efforts gain early experience that would benefit them as future educators, while also developing their leadership and communication skills and increasing their confidence and motivation. Similar motivation has led to a student-designed, led, and taught upper-level graduate course on research methods for first-year graduate students.[35]

Many schools have created programs that encourage undergraduate students to design and teach courses along with appropriate faculty oversight (e.g. Stanford SICs, Berkeley DeCal, Carnegie Mellon StuCo).[36-38] We have combined the approaches of these programs and that of CUREs to pilot a new course in the Chemical Engineering Department at the University of Michigan: Introduction to Experimental and Computational Research in Chemical Engineering. This course incorporates the investigative nature of CUREs modules and the breadth of research seminars, while also teaching students basic literature review, hypotheses formation, and common experimental and computational skills.

An Undergraduate-Led, Research-Based Course.

Within the University of Michigan Chemical Engineering Department, we identified a difference between undergraduate and graduate education that represents an opportunity for improving how we prepare undergraduates for the modern chemical engineering discipline. At the graduate level, students are exposed to modern advances in chemical engineering, yet at the undergraduate level, students do not learn about current contributions and directions of the field as part of the core curriculum. Since research serves a critical role in the rapidly evolving and interdisciplinary nature of our field, we posit that introducing it to the undergraduate curriculum is an ideal approach to bridging the aforementioned difference. Our approach involved designing a course that enables students to explore the breadth of the field through exposure to ongoing research efforts, while also acquiring valuable bench, computational, and soft skills that can be applied to their future endeavors. Various considerations for the initiation, development, and operation of an undergraduate-led, research-based course are outlined in Figure 1, and they can serve as an initial template for any department that seeks to introduce research to its core undergraduate curriculum.

Establishing a Vision and Support Structure

Understanding the Department's Specific Needs. We began with the realization that undergraduate students often lack

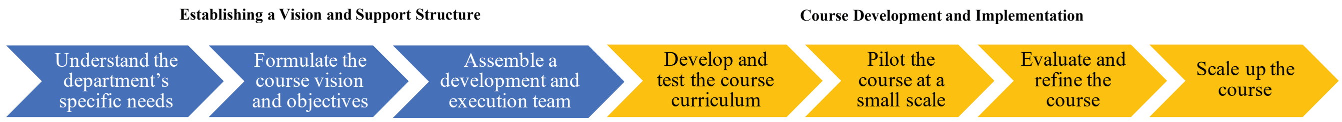

Figure 1. *A strategy for developing a research-based course and introducing it to an undergraduate curriculum.*

the requisite elementary research skills to contribute rapidly and effectively to a research group. Prior to proposing our idea for a research-based course, we sought to thoroughly understand our department's undergraduate research landscape and gauge our idea's merit. We conducted interviews with faculty and administered surveys to undergraduate students, graduate students, and postdoctoral researchers in our department. We simultaneously administered surveys to the individuals whom we envisioned would directly and indirectly benefit from the course: undergraduates who would gain research skills and graduate students and postdoctoral researchers who would be mentoring students who are better prepared for research. Details of survey and interview methodology can be found in Section I of the Appendix.

Formulating a Vision. Responses to the interviews and survey questions confirmed the need for such a course, and the encouraging feedback we received helped shape key elements of our vision. The interview and survey topics we allude to in the previous section may suggest that our sole vision for the course was to prepare undergraduates for research experiences. Indeed, a single-objective approach furnished two key initial advantages: it focused our efforts to understand our department's needs and it seeded the course's ultimate vision. Additional discussions with our department's leadership figures and undergraduate, graduate, and postdoctoral researchers inspired us to contemplate how this initiative fits into our discipline's past, present, and future — ultimately expanding our vision to the following elements:

- equip students with introductory research skills so that they can contribute more rapidly and effectively in their future research endeavors within and beyond academia.
- expose students to the chemical engineering department's ongoing research to prepare them more effectively for the evolving nature of our discipline.
- introduce students to hands-on experimental and computational applications of a chemical engineering education earlier in the curriculum.
- better inform the decision-making process for students considering chemical engineering as a major.

The elements above are collectively motivated by the field's evolution and by the specific needs of our department's curriculum. Therefore, we suggest that other chemical engineering departments that seek to design such a course also tailor their vision, in part, to the needs of their curricula. Furthermore, establishing a concrete vision was critical to the effort in two ways. First, it demonstrated to our department a clear path for the potential impact of the course on its students now and beyond graduation, which bolstered our proposals for funding and laboratory space. Second, it provided us with a scaffolding on which to build the course during development.

Establishing Departmental Support. After developing a detailed vision for the course, it was crucial to establish departmental support in the form of funding, guidance, and other resources such as space for the course's laboratory component. Having demonstrated to our department leadership the need for the course along with our plan for developing and executing it, they granted us support to commence its development, connected us to a faculty advisor, and supplied us with all of the requisite resources, which included lab and lecture space along with funds for materials and staff (undergraduate and graduate teaching assistants). The department leadership included the Chair, the Director of Undergraduate Studies, an Instructor of Record, and members of the Undergraduate Program Committee. Ultimately, a clear vision, a thorough development plan, a detailed budget, and persistent self-motivation undergirded our success in establishing credibility and departmental support.

Assembling a Development Team. Extracting the essentials of a field as wide ranging as chemical engineering and constructing a course around them necessitates a dedicated team of interdisciplinary researchers. Following the department's approval, we, the initiative's undergraduate leaders, harnessed our department's diverse areas of expertise in both experimental and computational areas by recruiting the help of several graduate students and postdoctoral researchers. Together, we developed and tested all of the course's content while periodically reporting updates to our faculty advisor.

Course Development and Implementation. The course was divided into two phases: one focusing on experimental and the other on computational research. Structuring the course as such enabled us to focus the expertise of our team and department during course development and operation. For the pilot operation of the course during the Winter 2019 semester, we limited enrollment to 15 students, with 11 ultimately completing the course. In addition, the course was listed as an elective worth two credit hours, which within the University of Michigan's Chemical Engineering Department amounts to three hours of instruction per week: two for labs and one for lecture. The two credits students received for the course counted towards the three-credit engineering elective requirement, and the intended audience was freshmen who were considering chemical engineering and sophomores who had just completed the major's introductory course.

Labs. The course included weekly, two-hour laboratory sessions. Seven sessions were experimental and five were computational (Table 1). We sought to teach students introductory bench and computational research skills while exposing them to the rich variety of chemical engineering research thrusts. Testing and optimization of the lab content began in September of 2018 and concluded in December of that year. It involved all of the authors carrying out the tasks of each lab period to ensure the feasibility of the exercises within time and resource constraints, iterating until the lab content was deemed ready for students who would enroll in the course.

Prior to each lab session, we provided students with a handout that explained the week's topic and facilitated their completion of a pre-lab assignment. Through the pre-labs, we sought to expose students to one of the most important aspects of research: the design of experiments to probe hypotheses. In addition to introducing students to the concepts of the week's topic, the pre-lab assignments and lab handouts guided them through the process of hypothesis formulation and experimental design, which were the assignments' central assessment factors.

Moreover, because it is an integral tool for organizing research, data integrity, and continuity, students were trained in proper lab notebook maintenance for planning experiments, noting observations, organizing results, and outlining experimental protocols. Students were given lab notebook templates and examples in the beginning of the semester, and a portion of the first lab session was dedicated to outlining the role of notebooks in this course and research in general. Students then submitted their notebooks as post-lab assignments wherein they reflected on their work and results after each lab session. The grading criteria comprised the students' presentation and analysis of data along with evaluation of their overall lab notebook compared to the aforementioned template. To expose students to a crucial reality of research — experiments not transpiring according to plan — we emphasized sound and rigorous assessment of results irrespective of their agreement with expectations. We wanted students to learn and practice the key skill of troubleshooting an experiment or computational routine while properly documenting it because they will inevitably encounter such a situation during their future endeavors.

To facilitate these labs, we prepared, posted, and graded pre-lab assignments that aimed to prepare students for the lab session. We also oversaw the lab sessions during which we answered student questions. Outside of the lab, we graded post-lab assignments that included an opportunity for students to provide anonymous positive and negative feedback on the lab, and we held office hours to answer student questions. For interested readers, a concrete example of lab operation is provided in Section II of the Appendix.

TABLE 1
Lab topics

Week	Description
Phase 1: Experimental	
1	Introduction to Basic Skills (Part I): Safety, Notebook Maintenance, Basic Data Analysis and Presentation
2	Introduction to Basic Skills (Part II): Solution Preparation, Serial Dilution, pH, Centrifugation
3	Electrostatic Interactions between Macromolecules
4	Nanoparticle Synthesis and Characterization I
5	Nanoparticle Synthesis and Characterization II
6	Antimicrobial effects of AgNPs
7	Troubleshooting the Previous Experiment
Phase 2: Computational	
8	Stochastic Simulations in Netlogo
9	Machine Learning: Regression and Neural Networks
10	Molecular Dynamics Simulation of a Peptide
11	Monte Carlo Simulations
12	Density Functional Theory Calculations

Lectures. The course's hour-long lectures were given by a different faculty member every week. We solicited participation from faculty in our department weeks before the course began, providing detailed guidelines for their lectures, including lecture objectives, topics, and assignment ideas. Most importantly, we ensured that they were aware of the course's objectives, so that they could tailor their lectures appropriately. During planning and development, lecture topics were a key consideration; we sought to broadly represent our department's and the field's research thrusts while teaching universal research aspects. We further refined our planned lecture topics based on the areas of expertise represented on our team of students, such that we would be able to develop related laboratory content for each lecture. Table 2 outlines the chosen lecture topics along with literature review assignments that complemented most lectures. Students were also responsible for a short, take-home quiz administered by the guest lecturer. With the students chiefly in mind, we designed the lectures to be an environment wherein undergraduates felt comfortable interacting with faculty members — on matters ranging from specific technical questions to the speaker's personal research journey — and learning how their work fits into our discipline's contributions to the body of scientific and engineering knowledge.

Literature Review. Literature review is a critical skill for chemical engineering students irrespective of their career paths. Reading research articles, however, is as challenging as it is important, especially for undergraduates during early phases of their careers. As a result, we ensured that it was a central component of our course.

Our strategy involved "throwing students into the deep end" initially and then gradually teaching them the skill step-by-step so that they could experience their improvement first-hand throughout the semester. In the semester's first assignment, we provided students with a list of papers to read and equipped them with the tools to find other articles should they wish to review a paper not on the list. We provided no guidance as to how students should approach the papers apart from a list of questions that covered a paper's research area, problem(s) to be addressed, results, and conclusions. The questions can be found in Section III of the Appendix.

Subsequent weekly assignments (Table 2) required students to read and answer questions about only one section of the same paper they had chosen for the first assignment, while continuously receiving feedback from course staff. Near the halfway point of the course, each student had individually analyzed every section of their papers; for the remainder of the semester, students chose a different paper every week to complete the same assignment given on the first week of the course. We trained students to approach literature review systematically to provide them with an accessible and generic framework for reading research articles irrespective of their experience in a certain field. Having the relatively overwhelming initial experience of reading an entire paper with little guidance enabled students to appreciate the systematic, section-by-section approach's efficiency and generality.

Course Evaluation. The four course vision elements introduced in the previous section scaffolded course development and implementation, and their associated, concrete, and measurable learning outcomes are outlined here. Assessment methods for these outcomes are described in this section. As a result of participating in the course, students will have:

- increased familiarity with the following aspects of research: conducting hands-on experiments, planning experiments (developing a procedure to evaluate a hypothesis), performing rigorous statistical analysis on data to draw strong conclusions, finding scientific journal articles, reading and understanding scientific journal articles, and programming (specifically for computational research in ChE or a related area).
- increased familiarity with the following research areas and techniques: laboratory solution preparation, centrifugation, running electrophoresis gels, nanoparticle synthesis, spectroscopy (e.g. absorbance, fluores-

TABLE 2
Lecture topics

Week	Lecture Title	Literature Review Assignment
Phase 1: Experimental		
1	Introduction to Research	Analyze an Accomplishment in ChE Research
2	Fundamentals and Applications of Plasmonic Nanomaterials	
3	Reading Research Papers	Analyze an Abstract and Introduction
4	Introduction to Nanomaterials	Analyze Methods and Materials
5	Introduction to Biochemical Engineering	Analyze Results, Discussion, and Conclusion
6	Applications of Nanotechnology in Biochemical Engineering	Group Journal Club on a Full Paper
7	Energy Applications of Nanomaterials	Introduction to Review Papers
7.5	Research Talk from Undergraduates	
Phase 2: Computational		
8	Modeling Biological Systems	Analyze Paper on Week's Topic
9	Introduction to Machine Learning	Analyze Paper on Week's Topic
10	Molecular Dynamics Simulations	Analyze Paper on Week's Topic
11	Monte Carlo Simulations	Analyze Paper on Week's Topic
12	Density Functional Theory	Analyze Paper on Week's Topic

cence), working with microorganisms, mathematical modeling of biological systems, machine learning, molecular dynamics, Monte Carlo simulations, and density functional theory.

- increased familiarity with research conducted in the University of Michigan Chemical Engineering Deaprtment, how it fits within the overall discipline, its ongoing challenges, and be able to identify their personal interests in it.
- increased certainty as to whether or not chemical engineering is the major for them.

In addition to developing the content, it was critical for us to evaluate every element of the course during the pilot run. Doing so effectively would provide guidance for improvement in subsequent iterations. For the weekly lab sessions and lectures, we administered evaluation forms throughout the semester that collected information along the topics outlined in Table 3 in open-answer format. Coupled with instructor feedback and recommendations, the information above gives future leaders of the course a detailed blueprint for refining specific lectures and labs. We also employed pre- and post-course surveys to evaluate the extent to which the course addressed its objectives. We quantitatively probed the following about our students' experiences with the course:

- their previous and/or current involvement in research-related activities at the high school and college levels
- factors that motivated them to enroll in the course
- how likely they would be to recommend the course to their peers
- the number of hours they spent on the course per week

We also quantitatively probed the effect of the course on their:

- familiarity with our department's research
- motivation to become involved in research
- career aspirations
- familiarity with, and interest in, universal (e.g. literature review, hypothesis formulation, etc.) and specific (e.g. nanomaterial synthesis, machine learning, etc.) research skills
- certainty about chemical engineering as a major

Where applicable, the information outlined above for the pre- and post-course surveys was collected on a one to five Likert scale. The pilot run's surveys helped us assess the course to identify positive aspects and areas for improvement. These surveys for the first course iteration included a Motivated Strategies for Learning Questionnaire (MSLQ)[39] to assess students' intrinsic motivation, extrinsic motivation, and task value for learning the course content, and we plan to incorporate additional published instruments in future surveys to assess the course's goals more objectively and quantitatively. Furthermore, some elements of the objectives can only be evaluated with a longitudinal study that assesses the course's influence on students' trajectories later in and beyond their undergraduate years; we plan to conduct such a study two years after students have participated in the course. As we refine the pre-course, post-course, and longitudinal surveys for subsequent renditions of the course, we will follow the Institutional Review Board (IRB) process to obtain permission to use data in future publications about the course because keeping the academic community abreast of this endeavor's progress will benefit the institutions who adopt it and in turn enhance it through their feedback.

Finally, we are deferring any data to future studies that represent multiple iterations of the course and employ optimized and validated survey questions. But we believe that it is important for the reader to be aware of the degree to which our students and department believed the course to be worthwhile. In addition to our observations of fruitful student interactions with the course content, regular course staff, and faculty guest lecturers, the preliminary survey results convinced our department that the course pilot was worthwhile in a manner sufficient for its continued development and operation. Finally, in Section IV of the Appendix, we share considerations that were critical to the successful planning and operation of this course and that may be beneficial to any department that pursues a similar course.

Course Sustainability. Following the conclusion of the first iteration of the course, we recruited a new set of students to lead the development of the course. We synthesized all of the feedback we received from students and faculty with our own experiences into a report to the department. This report served the purpose of updating the department administration on the outcome of the course's first iteration as well as providing a set of detailed instructions and recommendations for future

TABLE 3
Lecture and lab evaluation elements

Lab	Lecture
Student perceived performance on specific aspects of the lab	How engaging students found the lecture
Student comments on guidance level of the lab	To what extent the lecture piqued the students' interest in the topic
Student positive feedback	Student positive feedback
Student critical feedback on areas to improve	Student critial feedback on areas to improve

teams to run and improve the course.

Scaling the Course. Several considerations are associated with scaling up such a course. Additional lab sections will be needed, requiring available lab space for multiple days of the week. The increase in the number of lab sessions will require more materials and thus a larger budget. Additionally, more undergraduate and graduate student instructors will be needed to oversee and evaluate the additional labs and assignments. Finally, and most importantly, we suggest not scaling up the course until small-scale pilot runs are optimized.

Our course's inclusion of both a lab and lecture component were informed by our department's specific needs in the context of the field's evolution. Other departments' needs and access to resources may warrant only a lecture component, which would be more easily scalable than the model we present herein. Moreover, we believe that if resources are not a major challenge, the course should have a lab component that enables students to further appreciate the course content by interacting with it in a hands-on fashion.

CONCLUSION

The impact that the development and operation of a student-led, research-based course has on the various parties involved underpins its value to the institution. The course is a setting wherein students can discuss research with scientists who are at the frontiers of knowledge while learning valuable skills, directly exploring a potential career path, and becoming better prepared for research opportunities in academia and industry. The undergraduate students leading the initiative gain unique leadership experiences that will contribute to their professional development as leaders both within and outside the chemical engineering discipline. The graduate students and postdoctoral researchers assisting in course development and operation gain valuable experience in mentoring the undergraduate leaders, developing innovative ways of incorporating their research into a course, and/or preparing for the teaching aspects of an academic career. Finally, the faculty guest lecturers have the opportunity to introduce their research to undergraduates in their department, which broadens the impact of their work from a specific research area to an educational tool, and they have the opportunity to increase engagement with students, which is beneficial to the overall teaching environment in the department.

Beyond serving as a potential first step for introducing research to their curricula, we hope that our work inspires departments to foster environments wherein their students are empowered to pursue initiatives such as the one we have described herein. While we generated our initial idea independently, we believe that departments can establish mechanisms to encourage active engagement among their students to enhance their educational experience. For example, focus groups directed at discussing the state of a curriculum should advance beyond merely soliciting student suggestions; departments ought to recruit, encourage, and guide students to lead initiatives that improve their curricula. Additionally, we strongly encourage undergraduate chemical engineering students to actively contemplate their department's curriculum by reflecting on their personal experiences with coursework, industrial internships, and research activities in the context of the field's history and future. By identifying opportunities for improvement, students can assist departments in refining their curricula to align with the contemporary state of the field. While a research-based course may not be the answer to every program's needs, student leadership is a critical resource that should be harnessed for improving chemical engineering curricula.

REQUESTS FOR COURSE MATERIALS

We encourage interested readers to contact Salwan Butrus at salwan@umich.edu with any requests for materials involved in the planning, development, and operation of the course.

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APPENDIX

I. Survey and Methodology for Understanding the Department's Specific Needs

We asked faculty about their interactions with undergraduates conducting research in their groups and how they envisioned improving that experience for students. Current undergraduate researchers were asked about their level of preparation prior to joining a research group, skills in which they wish they had been more experienced, and their opinion on a research-based course in their department. Graduate students and postdoctoral researchers were surveyed on their experiences mentoring students and the level of preparation of their mentees.

II. Lab Operation Example

We discuss one of the labs in detail to provide the reader with a concrete example of course operation. The lab in question is from Weeks 6 and 7 in Table 1. During Week 6, students examined the effect of silver nanoparticles (AgNPs) on yeast growth. To maintain continuity across the lab sessions, students had synthesized and characterized the AgNPs during the previous two laboratory sessions (Weeks 4 and 5). In Week 6, the results did not match the expected general outcome (which was achieved during testing) that the yeast would first grow and ultimately plateau upon complete conversion of nutrients, and that increasing the amount of AgNPs introduced to the yeast would decrease the plateau amount due to the AgNPs' previously reported deleterious effects on microorganisms. All students in fact observed no yeast growth irrespective of AgNP administration. Consequently, we dedicated the Week 7 laboratory session to troubleshooting the experiment. In the pre-lab assignment students hypothesized issues with the initial attempt and outlined approaches to address them, comparing their new results to the previous results in the post-lab assignment. For the students, having the opportunity to troubleshoot their experiments was a valuable lesson about the reality of research that traditional homework assignments and laboratory courses do not aptly capture.

III. Literature Review First Assignment Prompts

The questions provided to students in the first literature review assignment are outlined below:

- What research area(s) is the paper from? (catalysis and reactions, molecular/cellular engineering, biomedicine, micro-systems and nanotechnology, polymers and materials, computing and simulation, energy)
- Do the researchers make clear to you the problem that they're trying to address with this research? If so, in what section of the paper did you find this? What is it?
- What do the researchers claim has been done so far regarding this problem?
- What are these researchers doing differently that has not been done before?
- What are the important results of this work, and how do they relate to the original problem that the research is trying to address?

IV. Considerations for Successful Course Operation

We would like to share considerations that were critical to the successful planning and operation of this course and that may be beneficial to any department that pursues a similar course. New courses that contain a lab and lecture component will inevitably be time and resource-intensive, especially those that feature several lectures and consist of labs that are based on cutting-edge research. Consequently, we suggest that the development team conservatively allocate time for planning the course and acquiring all of the necessary resources. For a research-based course, especially one in a field as interdisciplinary as chemical engineering, content variety is as challenging as it is critical. For the labs, we balanced content variety with uniformity and cohesiveness, aiming for students to explore multiple research topics and skills while striving for an appropriate level of continuity. For lectures, the lecturer positioned at the end of Phase 1 should be selected with the intention of bridging the two phases. They could be asked to give an overview of computational research in ChE by discussing the different subsections and their breadth, popularity, and utility along with explaining how computational work complements experiemental research. Additionally, we suggest including a speaker having an industrial research background so that students are exposed to research careers beyond academia.

During course operation, we suggest using the weekly lab and lecture evaluations to make adjustments during the semester if resources and bandwidth permit while providing organized and easily accessible extra resources for students to consult as they become exposed to new research areas and techniques throughout the semester. Before each lecture, the teaching team should provide a brief biography of the speaker and a link to their lab website to encourage students to learn more about the topic. Lecturers should include a component about their personal research journey, and the main content of each lecture should focus on applications and examples of results rather than in-depth theory; topics should be presented in an interactive, laid-back fashion that encourages students to ask questions throughout the lecture. Furthermore, students responded positively when lecturers made the effort to connect their presentation to the material from classes students have taken, as well as when the lecturers brought graduate students to the lecture to discuss their work.