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Developing a project-focused synthetic biology elective for chemical engineering students.

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Justin Vento graduated with a chemical engineering degree from Manhattan College and became a process engineer in the petrochemical industry. After a few years, he pursued his PhD in chemical and biological engineering from NC State, where he studied and developed tools for microorganisms within the human gut microbiome. He then worked for a few years as a scientist at a synthetic biology company Ginkgo Bioworks in Boston, MA. He is currently a Visiting Assistant Teaching Professor at Villanova University. Justin is passionate about teaching the fundamentals of chemical engineering in an engaging manner while also developing new courses that introduce students to the evolving biotechnology industry.

Work-In-Progress: Developing a project-focused synthetic biology elective course to prepare chemical engineering students for careers in biotech

Abstract

Chemical engineering graduates are increasingly entering biotechnology fields due to the promise of biotechnology to offer cutting edge and sustainable solutions to world problems as well as its inherent connection to chemical engineering principles. Novel elective courses that teach fundamentals of biotechnology-related fields should complement chemical engineering curriculums and provide perspective and skills that better prepare chemical engineering graduates to pursue industry and academia roles in biotechnology. Synthetic biology is a quickly advancing field where cells are engineered to construct useful biological systems for applications including cell therapeutics, cell factories for biochemical production, and bioremediation. This work introduces a new chemical engineering elective course in synthetic biology that teaches the fundamentals of constructing novel biological systems in a largely experiential learning environment. The course is comprised of one 90-minute lecture period and one 160-minute lab period each week in a dual-functioning bioengineering laboratory classroom. A semester-long case study project of engineering baker's yeast *Saccharomyces cerevisiae* to produce a Vitamin precursor chemical is used to simulate an industrial synthetic biology project while applying core concepts covered in the lectures. A broad range of synthetic biology applications are covered in the course content as well as via assessments and through a podcast series where academic and industry representatives are interviewed during class. This synthetic biology course should help others implement similar courses, and the general structure of the course should be beneficial to others wanting to create elective courses in popular chemical engineering-adjacent fields.

Course Description

Villanova University offers a special topics elective course in the chemical and biological engineering department: CHE 5332. In the Fall 2024 semester, this elective was used to implement a new course in synthetic biology. Synthetic biology is the engineering of novel biological systems that serve a function in society, and is a quickly growing industry that has already released impactful commercial products such as a cell therapy for leukemia and a fertilizer alternative [1]. Indeed, synthetic biology offers novel solutions to some of the world's pressing problems, including climate change, next-generation medicines, and food production, and provides a more sustainable way of manufacturing chemicals without the need for petroleum-derived feedstocks [2], [3], [4]. Importantly, synthetic biology provides a new modality to produce fuels, foods, and medicines. Since chemical engineers traditionally work on the scale up processes for large-scale production of these entities, chemical engineering graduates would be better equipped with a basic understanding of synthetic biology principles [5]. While other departments have devised a framework for training students in synthetic biology

[6], course adoptions in chemical engineering curriculums remain scarce. To fill this gap, this course in synthetic biology was designed with three overall objectives:

1. **Learn the fundamentals of synthetic biology**: learn how design-build-test-learn cycles are used to construct novel biological systems that serve a purpose.
2. **Maintain a broad perspective**: explore how synthetic biology is applied in diverse industries to offer solutions to some of the world's most pressing problems and appreciate the interdisciplinary nature of synthetic biology.
3. **Use experiential learning methods**: within the context of a semester-long project, gain relevant wet lab, computational, and communication skills necessary to thrive in synthetic biology industries.

Learning Objectives and Skills Acquired

While the applications of synthetic biology systems can be quite diverse, there is a fundamental methodology guiding the predictable engineering of cells based on iterative design-build-test-learn (DBTL) cycles [7]. This course in synthetic biology aims to teach these core principles while using a semester-long project to highlight their implementation. In this first rendition of the course, the class focused on engineering baker's yeast *Saccharomyces cerevisiae* to produce beta-carotene, a precursor chemical to Vitamin A [8]. While this case study highlights one area of synthetic biology; namely, the sustainable production of important chemicals, lectures, assignments, and a special podcast series were used to introduce applications in other industries including pharmaceuticals, biotechnology, and climate technology.

Below are the specific learning objectives used to guide the content development and structure of the course:

1. Define synthetic biology and explore where it can be used to address diverse world challenges.
2. Understand how novel biological systems are engineered with purpose.
3. Gain abilities to design, build, test, and learn from new biological systems.
4. Learn how to use current state-of-the-art methods to assemble DNA parts and engineer host cells.
5. Explore optimization strategies to improve biological systems for enhanced performance.
6. Appreciate the multidisciplinary nature of synthetic biology.
7. Acquire computational and communication skills relevant to synthetic biology.

This course also aimed to provide a specific set of wet-lab, computational, and communication skills that students could readily apply to any biotechnology career in industry or academia. The skills are mapped to the learning objectives above.

- Designing a synthetic biology experiment with proper controls (LO2, LO3, LO5).
- DNA assembly (aka "cloning") methods, particularly golden gate assembly (LO3, LO4).
- CRISPR-based genome editing (LO3, LO4).
- DNA sequencing methods and analyzing sequence alignments (LO3, LO4).

- Analytical chemistry methods to measure metabolites, such as fluorescence and chromatography (LO3, LO5).
- Molecular biology techniques such as PCR, DNA extraction, and DNA transformation (LO6).
- Microbiology methods such as culturing and constructing growth curves from microorganisms (LO6).
- Benchling platform for keeping an electronic notebook and for interfacing with DNA constructs (LO7).
- Writing a scientific lab report and presenting scientific data (LO7).
- Critical reading of scientific journal articles (LO7).

Course Enrollment and Logistics

This course was taught in a bioengineering classroom that functions as both a laboratory (biosafety-level 1) and a lecture space. The class met on Tuesdays from 3:30 – 4:45 PM and on Wednesdays from 3:20 – 6:00 PM. Although the course was an elective in the chemical and biological engineering department, it was technically also open to other majors at Villanova University. Since synthetic biology is a very interdisciplinary field, it was decided to require no pre-requisites to enroll in the course. Instead, relevant fundamentals of molecular biology, microbiology, and biochemistry were taught in the course as necessary. In the Fall 2024 semester, 24 students enrolled in this course, including 2nd, 3rd, and 4th year undergraduates all pursuing a bachelor's degree in chemical engineering **(Figure 1**). Most students were 3rd or 4th year undergraduates (23/24) and identified as absolute beginners or beginners when asked about their current experience with synthetic biology (19/24). One student dropped the course in the second week of the semester.

A) B)

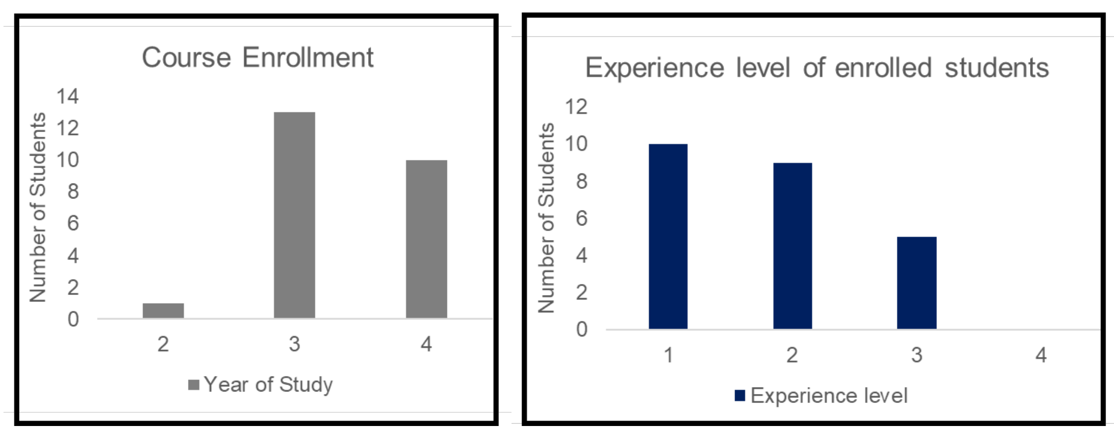


Figure 1. Breakdown of students based on A) year of study in chemical engineering program and B) response to the question "What is your current experience with synthetic biology?" where 1 = absolute beginner (never heard of it); 2 = beginner (heard of it in previous course / research / job); 3 = some experience (studied it closely in a class, used it in a research setting or job); 4 = a lot of experience (I'd like to help teach the class)

Students were assigned a 3-4-person group and a 2-person lab team (aside from one team that only contained one student), where the groups sat together at lab benches. In general, Tuesdays were mostly lecture-based while Wednesdays were mostly for experiential learning where either wet-lab or computational activities were provided to reinforce or supplement lecture content while also working on the semester project. The flexibility of being in a multi-use classroom made it easy to switch back and forth between lecture and lab in the same day, enabling the option to run longer biological experiments that require more than a few hours to complete.

A teaching assistant was assigned to the course to help grade assignments, prepare lab benches with materials, and analyze or run parts of experiments. The assistant was a full-time student enrolled in a chemical engineering master's program, and she dedicated 5-10 hours per week to helping with the course, including attending most lab periods on Wednesdays.

Overview of Course

Over the course of the 15-week semester, the course met 14 times on Tuesday and 14 times on Wednesday. The course was designed in three modules that each had lecture topics, lab activities, and assessments (**Figure 2**). Each module was comprised of a synthetic biology design-build-test-learn cycle to continuously improve the beta-carotene output of the engineered yeast strain. Importantly, the modules progressively provided more independence for the students. The goal of the first module was to teach the fundamentals of synthetic biology while replicating the construction of a biological system from the literature [9]. In the second module, the instructor designed an improved biological system that the class built and tested, and there was more emphasis on analyzing and learning from strain performance. This module also included a full lab session dedicated to designing a genome-editing experiment. In the third module, the students designed their own optimized biological system based on learnings from the first two systems, built, and measured the improvement from their system. This module included a group presentation highlighting the design of each biological system.

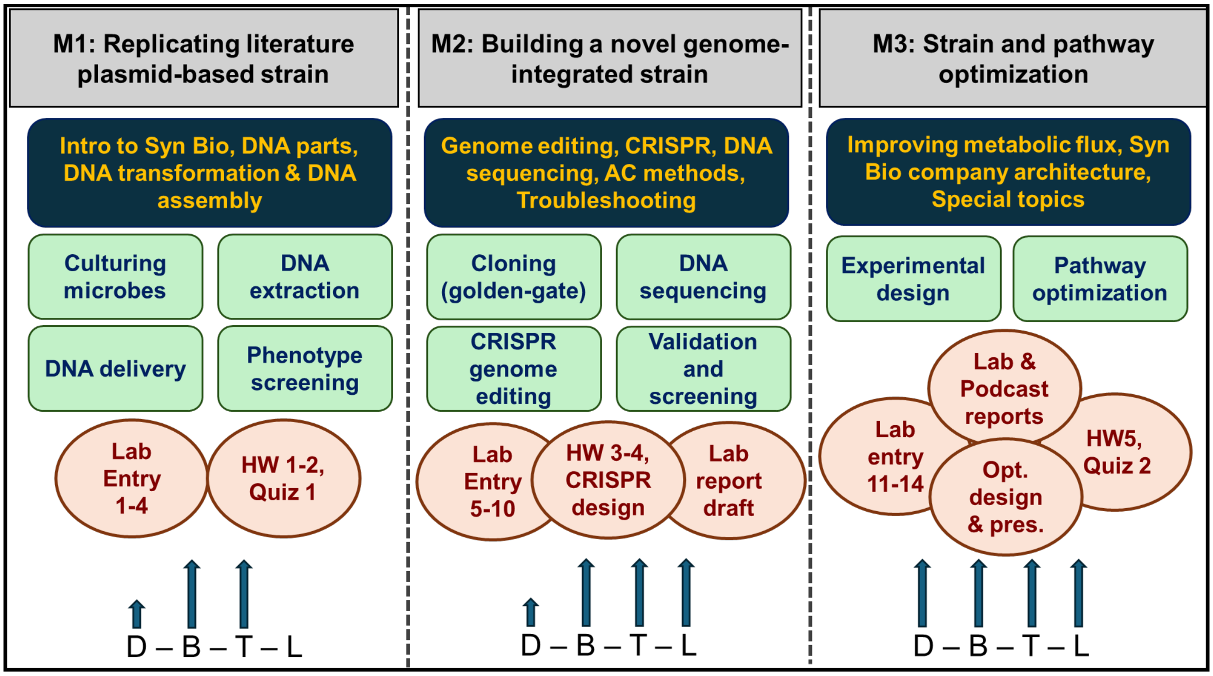


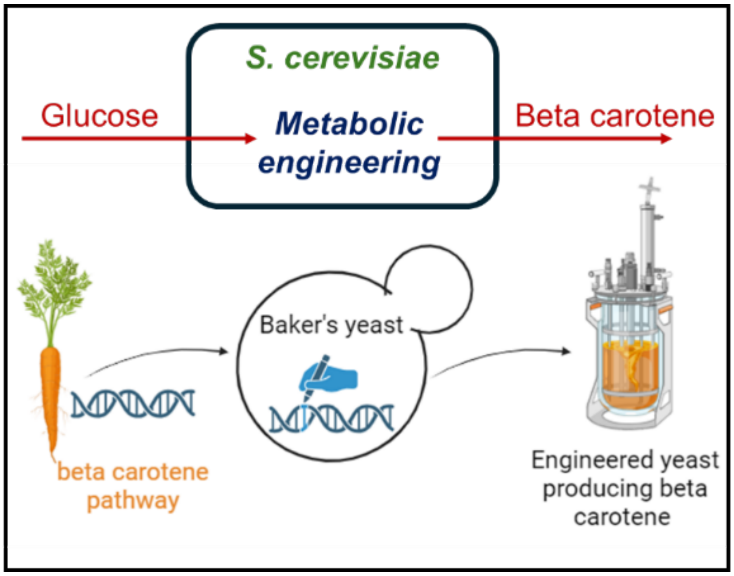
Figure 2. Breakdown of the course into three distinct modules M1-M3. Each module had lecture topics (blue box with yellow text), lab skills acquired (green box with blue text), and assessments (orange circles). For each module, the emphasis on each part of the design-build-test-learn (D-B-T-L) cycle is illustrated by arrow size. AC - analytical chemistry.

Semester Project: engineering S. cerevisiae to produce beta carotene

The 14 lab meetings were all focused on a semester long project to engineer yeast *S. cerevisiae* to produce beta carotene, a precursor to Vitamin A, by adding the beta carotene genetic pathway from the carrot plant *Daucus carota* into yeast *S. cerevisiae* (**Figure 3A**). This project was chosen based on the instructor's research expertise, availability of reference materials, and ease of phenotypic screening (i.e., yeast cells turn orange when they produce beta carotene).

During the first four weeks of the semester, the entire class engineered a *S. cerevisiae* strain that contained a plasmid with the full beta carotene pathway (**Figure 3B**, **Module 1**), based on work by Durmusoglu et. al [9] while learning basic transferable wet-lab skills such as culturing cells and working with DNA. Students were also introduced to the Benchling platform to maintain an electronic lab notebook during this time [10]. The next six weeks of the semester emphasized more advanced lab techniques including DNA assembly and CRISPR-based genome editing as well as computational skills including analyzing a DNA sequencing alignment and designing DNA constructs for genome editing. The result was building a second strain of *S. cerevisiae* with the beta carotene pathway integrated into the genome (**Figure 3B**, **Module 2**) and comparing its beta carotene production to that of the first strain.

A)



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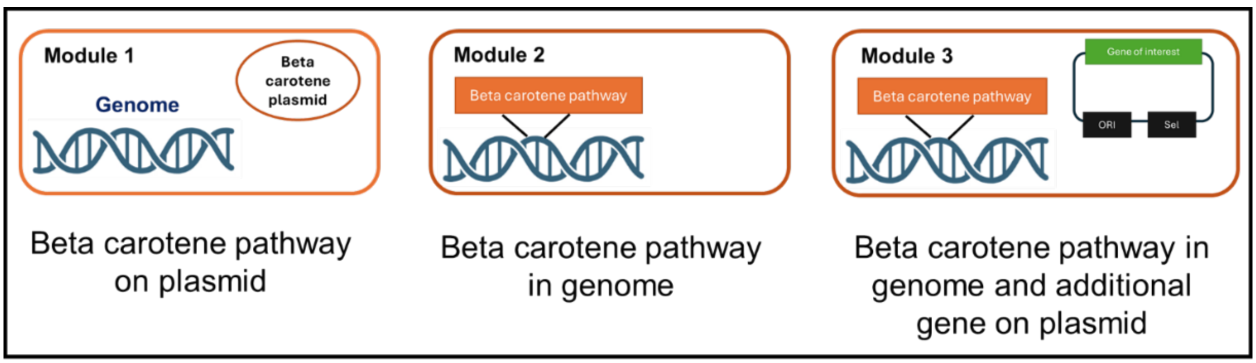

Figure 3. Course semester-long project. A) Illustration of biological system. Beta carotene pathway genes from the carrot plant *Daucus carota* are delivered into *S. cerevisiae* yeast to produce beta carotene, resulting in orange-colored yeast cells. B) The project was broken into three modules where design-build-test-learn cycles were used to generate enhanced beta carotene production strains of *S. cerevisiae*.

The final four weeks of the semester provided more independence to the students where the goal was to build a further optimized yeast strain producing more beta carotene (**Figure 3B, Module 3**). Each group chose a gene from the beta carotene pathway, and worked together to design, build, and test a *S. cerevisiae* strain containing an additional copy of the gene on a plasmid with a proper origin of replication (Ori) and selectable marker (Sel). This resulted in the construction of seven more *S. cerevisiae* strains that provided a comprehensive picture of how different optimization strategies impact the production of the biological system [8].

Week	Module	Lab Activity	Skills Acquired
Week 1	1	Introduction	Pipetting, Yeast cell culturing
Week 2	1	Plasmid mini prep	Bacteria cell culturing, DNA extraction
Week 3	1	Building 1st beta carotene strain	DNA transformation
Week 4	1	Testing 1st beta carotene strain	DNA transformation efficiency, Screening colonies
Week 5	2	DNA assembly	Golden Gate Cloning
Week 6	2	DNA assembly	Screening putative clones, DNA sequencing
Week 7	2	DNA assembly	DNA sequence alignment, CRISPR design
Week 8	2	Building 2nd beta carotene strain	Polymerase chain reaction (PCR), Gel electrophoresis
Week 9	2	Building 2nd beta carotene strain	Genome editing
Week 10	2	Testing 2nd beta carotene strain	Experimental controls, colony PCR
Week 11	3	Strain optimization	Standard curve generation
Week 12	3	Strain optimization	Presenting experimental design
Week 13	**No lab - Thanksgiving Break**		
Week 14	3	Building 3rd beta carotene strain	Strain engineering
Week 15	3	Testing 3rd beta carotene strain	Analyzing analytical chemistry results

Table 1. Weekly lab activities and associated skills acquired.

Table 1 shows the lab skills acquired from each lab activity, where the final set of skills should equip students to pursue a range of industry and academic positions within synthetic biology or related fields. Laboratory and research skills should particularly prepare students interested in pursuing graduate school or entry-level industry roles such as an associate scientist. However, the knowledge gained should also be applicable to traditional process engineering and other roles within chemical engineering fields. The decision to keep the students focused on a single project as opposed to scattered projects with diverse applications was made so the students could see the progression of a complete project and understand how iterating on the design-build-test-learn paradigm leads to continuous improvement in the output of the biological system. This strategy parallels what students would do in the synthetic biology industry, where hundreds to thousands of strains are typically screened before proceeding to the production stage [11].

Assessments

A full breakdown of assessments used in the course can be found in **Table 2**. While most core chemical engineering courses rely on summative assessments such as exams to make up most of the course grade, formative assessments were prioritized in this course to encourage continuous improvement [12]. Numerous lower-value assessments were used instead of fewer high-stakes assessments to allow students ample opportunities to learn the new paradigm of synthetic biology [13]. To this end, assessments were generally given weekly to re-iterate and re-assess important topics and learning objectives [14]. Assessments were split into individual assessments, team assessments (2 people), and group assessments (3-4 people) to balance the tradeoffs of group work [15].

#	**Individual**	**Team**	**Group**
1	Lab Notebook (15%)	Draft Lab Report (15%)	Optimization Design Document (5%)
2	Homework (15%)	Final Lab Report (20%)	Optimization Design Presentation (5%)
3	Quizzes (10%)	CRISPR Design (5%)	
4	Podcast Project (10%)		
Total	**50%**	**40%**	**10%**

Table 2. Assessments in Fall 2024 synthetic biology course. Team assessments were completed in pairs, and group assessments were completed in small groups of 3-4 students.

Students were responsible for individually keeping an electronic lab notebook each week via Benchling to document the purpose, methods, results, and discussion of each experiment. Lab notebooks were exported and submitted as PDF documents after each module. Four individual homework assignments were administered, focusing on critical reading of synthetic biology literature, computational synthetic biology skills such as creating and manipulating DNA sequences on Benchling, and creating high-quality illustrations from experimental data. Two full-period quizzes were administered during the semester that were closed notes and assessed how students were able to apply and retain fundamental synthetic biology concepts. These quizzes were effective in encouraging students to review their notes and come to office hours, supporting the idea that traditional assessments are a driver of learning [15]. Quizzes were relatively low-stakes and comprised of largely open-ended questions where the instructor could provide ample feedback to bolster student thought processes related to problem solving in synthetic biology [16]. A podcast series featuring interviews with ten speakers using synthetic biology in academia or industry was conducted throughout the semester, where students earned points for taking notes and asking questions during the interviews, and then reflecting on a few of the speakers and presenting one topic they found interesting on the last day of class. More information on this podcast can be found in a supporting manuscript (ASEE 2025 *accepted*).

Throughout the semester, teams were allotted time during class to assemble their lab notebooks into a formal lab report, which was assigned to give students experience preparing a scientific manuscript. During midterms, teams submitted a draft of their lab report, where they received feedback on their writing, figure generation, as well as the accuracy and completeness of their work. Teams submitted their final lab report during the last week of class. During Week 7, teams were assigned an open-notes CRISPR design challenge via Benchling where they had the full class period to submit technical details for the design of a hypothetical genome-editing experiment. Finally, groups composed of two lab teams worked together on an optimization project as part of Module 3. The project included preparing a document to communicate the experimental design details to build their optimization strain as well as a 5-minute presentation highlighting the motivation and execution of their proposed experiment.

Pre- and post-course anonymized survey for self-evaluation

During the first class, an anonymized survey was administered via Microsoft Forms. The survey included one question about where students identified their level of experience with synthetic biology (**Figure 1B**), one question asking what students were looking forward to, and ten questions where students self-evaluated their knowledge of synthetic biology principles, societal impact, interdisciplinary nature, and professional opportunities on a 1-5 scale (**Table 3**). Another survey was conducted during the final class that included the same ten evaluative questions as well as the question "What did you enjoy most about this class?". Each question had 21-24 respondents for the pre-course survey and 21-22 respondents for the post-course survey.

The results from the pre- and post-course self-assessment are compiled in **Figure 4**. Interestingly, the only question without a statistically significant increase post-course was related to the student's desire to use synthetic biology in their careers. That aside, the assessment revealed that students felt they better understood the fundamentals and interdisciplinary nature of synthetic biology as well as the career opportunities and societal impact of the field after taking the course. Gaining valuable lab skills and experience was the most abundant response regarding what students enjoyed most about the course (11/22 response, data not shown), further validating a hands-on approach to chemical engineering technical electives.

Question	Question	Category
Q1	Rate your current understanding of the definition of synthetic biology.	Principles
Q2	Rate your awareness of career routes within synthetic biology.	Professional Opportunities
Q3	Rate your understanding of the relationship between engineering and synthetic biology.	Interdisciplinary Nature
Q4	Rate your understanding of how design-build-test-learn cycles are used to create novel biological systems.	Principles
Q5	Rate your understanding of the 5 scales of synthetic biology (molecular, network, cells, communities, societal).	Societal Impact
Q6	Rate your interest in utilizing synthetic biology in your career.	Professional Opportunities
Q7	Rate your appreciation of how synthetic biology can be used to solve worldly challenges.	Societal Impact
Q8	Rate your awareness of industries that utilize synthetic biology.	Professional Opportunities
Q9	Rate your understanding of the multidisciplinary nature of synthetic biology.	Interdisciplinary Nature
Q10	Rate your awareness of synthetic biology commercial products that impact our society.	Societal Impact

Table 3. Self-evaluation questions were assigned on the first day and last day of the course.

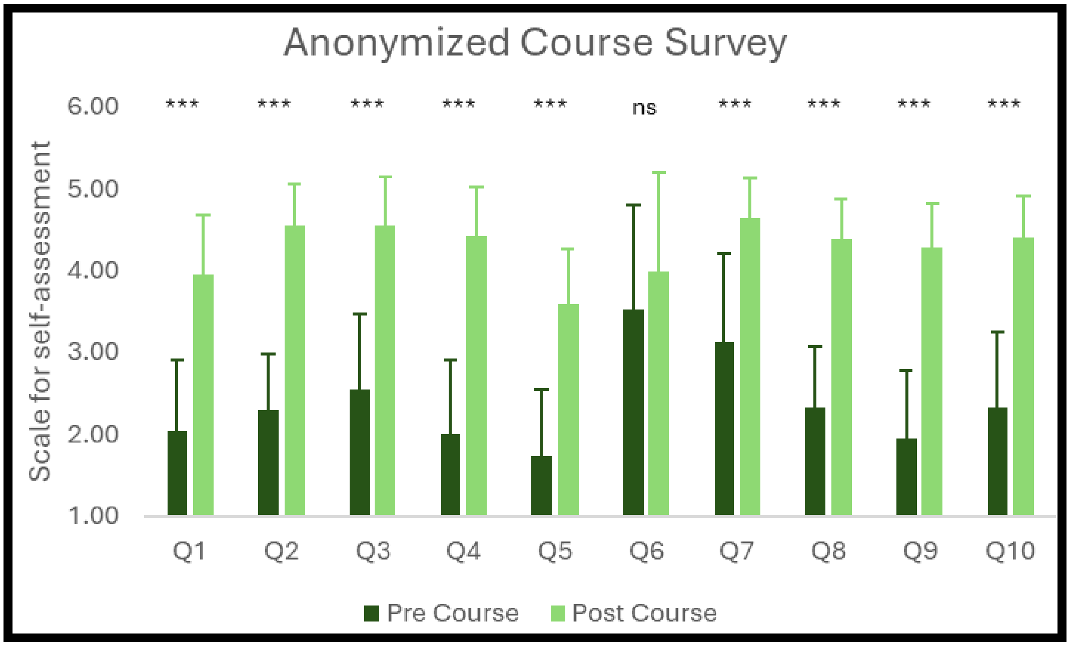

Figure 4. Self-evaluation results from survey taken on the first day of class ("Pre Course") and on the last day of class ("Post Course"). Error bars indicate the standard deviation. *** indicates a p-value < 0.001 and ns indicates a p-value > 0.05.

Closing Remarks

This course provides a framework for a chemical engineering elective course in synthetic biology, a rapidly growing field where cells are engineered to produce chemicals, medicines, foods, and other entities. This course is inspired by the rising prevalence of chemical engineering graduates entering biotechnology-related fields [17]. Introducing chemical engineering students to the synthetic biology design-build-test-learn framework for upstream engineering of cells should complement traditional engineering curriculums that largely focus on downstream engineering production principles. The course is a mix of lectures and lab and is structured to i) teach the fundamentals of synthetic biology, ii) provide a broad range of applications of synthetic biology for chemical engineers, and iii) use a semester-long project as a case study to immerse students in a typical synthetic biology project. Lab activities are designed to provide practical wet-lab and computational skills to prepare students for roles within biotechnology, and a range of summative and formative assessments are incorporated to stimulate an effective introduction to the way synthetic biologists solve problems. The framework of this course should help others design courses introducing students to synthetic biology as well as other chemical engineering-adjacent fields including systems biology [18], downstream bioprocessing [19], climate technology [20], and nanotechnology [21].

The project for the course contained three modules to illustrate three iterations of the design-build-test-learn (DBTL) cycle for continuous improvement of novel biological systems. While this DBTL iteration serves as an effective and comprehensive means to teach synthetic biology, individual modules can be utilized for more general bioengineering elective courses to provide a brief introduction into synthetic biology. Executing a single DBTL cycle can be completed in 2-3 lab sessions effectively in this case if the proper materials are in place. Courses that are strictly lecture based could also adapt computational synthetic biology projects, although teaching a full course in synthetic biology would be difficult without a computational or wet-lab component. Indeed, many students mentioned that their favorite part of the course was being able to accumulate relevant wet-lab and computational skills that are otherwise only obtained through internships or undergraduate research experiences. While core chemical engineering courses largely equip students with the skills to pursue downstream process engineering jobs, this type of elective course should help students decide if they want to pursue careers in research and development, particularly within biotechnology.

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References

[1] C. A. Voigt, "Synthetic biology 2020–2030: six commercially-available products that are changing our world," 2020. doi: 10.1038/s41467-020-20122-2.

[2] S. Shi, Z. Wang, L. Shen, and H. Xiao, "Synthetic biology: a new frontier in food production," 2022. doi: 10.1016/j.tibtech.2022.01.002.

[3] X. Yan, X. Liu, C. Zhao, and G. Q. Chen, "Applications of synthetic biology in medical and pharmaceutical fields," 2023. doi: 10.1038/s41392-023-01440-5.

[4] V. L. Colin, A. Rodríguez, and H. A. Cristbal, "The role of synthetic biology in the design of microbial cell factories for biofuel production," 2011. doi: 10.1155/2011/601834.

[5] Y. Luo, J. K. Lee, and H. Zhao, "Challenges and opportunities in synthetic biology for chemical engineers," *Chem Eng Sci*, vol. 103, 2013, doi: 10.1016/j.ces.2012.06.013.

[6] A. S. Karim *et al.*, "Deconstructing synthetic biology across scales: a conceptual approach for training synthetic biologists," *Nat Commun*, vol. 15, no. 1, Dec. 2024, doi: 10.1038/s41467-024-49626-x.

[7] K. L. Garner, "Principles of synthetic biology," 2021. doi: 10.1042/EBC20200059.

[8] Q. Guo *et al.*, "Advances in the metabolic engineering of Saccharomyces cerevisiae and Yarrowia lipolytica for the production of β-carotene," 2024. doi: 10.1080/07388551.2023.2166809.

[9] D. Durmusoglu *et al.*, "In Situ Biomanufacturing of Small Molecules in the Mammalian Gut by Probiotic Saccharomyces boulardii," *ACS Synth Biol*, vol. 10, no. 5, 2021, doi: 10.1021/acssynbio.0c00562.

[10] "The Benchling Enterprise Implementation Methodology."

[11] D. Burman *et al.*, “Bioproduction of Aromatic Molecules: Engineering Biology Towards Economic Viability,” 2023.

[12] J. Qadir *et al.*, “Leveraging the force of formative assessment & feedback for effective engineering education,” in *ASEE Annual Conference and Exposition, Conference Proceedings*, 2020. doi: 10.18260/1-2--34923.

[13] L. K. Alford, H. Rypkema, H. M. Jhaveri, R. Hosseini, and M. Beemer, “Turns Out Our Exams Were Pointless, So We Changed Our Assessment Strategy,” in *ASEE Annual Conference and Exposition, Conference Proceedings*, 2022. doi: 10.18260/1-2--41301.

[14] T. Paloposki, V. Virtanen, and M. Clavert, “From a final exam to continuous assessment on a large Bachelor level engineering course,” *European Journal of Engineering Education*, 2024, doi: 10.1080/03043797.2024.2334728.

[15] T. S. Hattingh and L. Dison, “How assessment shapes learning: A perspective from engineering students,” 2021.

[16] J. Hattie and S. Clarke, *Visible learning: Feedback*. 2018. doi: 10.4324/9780429485480.

[17] I. CPS, “Top 2024 Trends for Chemical Engineers.”

[18] K. A. Janes *et al.*, “An engineering design approach to systems biology,” 2017. doi: 10.1039/c7ib00014f.

[19] V. Beschkov and D. Yankov, “Chemical engineering methods in downstream processing in biotechnology,” *Physical Sciences Reviews*, vol. 6, no. 4, 2021, doi: 10.1515/psr-2018-0064.

[20] G. Centi, G. Iaquaniello, and S. Perathoner, “Chemical engineering role in the use of renewable energy and alternative carbon sources in chemical production,” *BMC Chemical Engineering*, vol. 1, no. 1, 2019, doi: 10.1186/s42480-019-0006-8.

[21] A. Henslee, “Citation: Henslee A. Nanotechnology in chemical engineering: Applications and future trends,” *Arch Ind Biot*, vol. 8, no. 1, p. 188, 2024, doi: 10.35841/aaaib-8.1.188.