International Journal *of* Designs for Learning
2024 | Volume 15, Issue 1 | Pages 38-55

DEVELOPING A "REVOLUTION": DESIGN CHALLENGES IN A CHEMICAL ENGINEERING DEPARTMENT

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Engineering is fundamentally about design, yet many undergraduate programs offer limited opportunities for students to learn to design. This design case reports on a grant-funded effort to revolutionize how chemical engineering is taught. Prior to this effort, our chemical engineering program was like many, offering core courses primarily taught through lectures and problem sets. While some faculty referenced examples, students had few opportunities to construct and apply what they were learning. Spearheaded by a team that included the department chair, a learning scientist, a teaching-intensive faculty member, and faculty heavily engaged with the undergraduate program, we developed and implemented design challenges in core chemical engineering courses. We began by co-designing with students and faculty, initially focusing on the first two chemical engineering courses students take. We then developed templates and strategies that supported other faculty-student teams to expand the approach into more courses. Across seven years of data collection and iterative refinements, we developed a framework that offers guidance as we continue to support new faculty in threading design challenges through core content-focused courses. We share insights from our process that supported us in navigating through challenging questions and concerns.

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https://doi.org/10.14434/ijdl.v15i1.34535

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INTRODUCTION

Answering the National Science Foundation's call for proposals to "revolutionize" engineering departments (National Science Foundation, 2014), our chemical engineering department set out to change the way undergraduate students learn and grow as engineers so that they can solve the world's most complex problems (https://facets.unm.edu/). Such changes require designing on two levels—for faculty and for students. In this design case, we focus on the development of design challenges integrated into the core curriculum. We share vignettes and artifacts from our seven-year, iterative process: our initial effort to develop design challenges for a first-year introductory course and for a content-heavy sophomore course; our shift to developing templates to scale the process to more courses; and our development of an educative framework that accompanies the templates, based on our experiences and iterative refinements. Across these efforts, we navigated challenges, including student buy-in, faculty concerns about coverage,

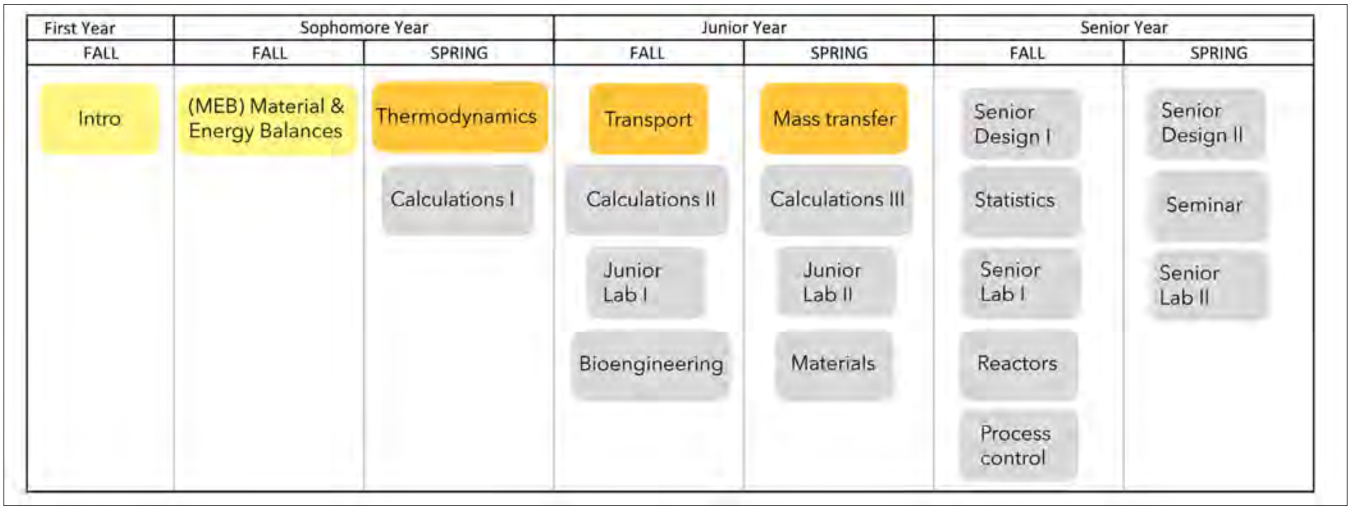


FIGURE 1. Course map representing the chemical engineering program at the beginning of the project, with focal courses highlighted. The first two courses were Introduction to Chemical Engineering and Materials & Energy Balances (MEB). We then focused on Thermodynamics, Transport, and Mass Transfer. Outside of the scope of this design case, we also made changes to other courses.

and limited experience teaching and learning through design.

We co-designed with a team of faculty and students. The first author is a graduate student (M, they/them) who came from chemical engineering into learning sciences to support the efforts of this project beginning in year five. The second author (Dr. S, they/them) is a faculty in the learning sciences and chemical engineering who co-wrote the initial grant and served as co-principal investigator with the third author, the department chair (Dr. D, he/him). Dr. S drew upon their extensive experience studying project-based learning and design education in guiding the project. The other three authors are faculty in chemical engineering who were co-principal investigators (Dr. C, she/her; Dr. H, he/him; Dr. G, she/her), were integral to the development of the design challenges from the outset, and who were the first to implement design challenges in their courses. The team also included various students (N, J, P), a social scientist, and an engineer with experience teaching and in accreditation (Dr. M, she/her).

CONTEXT

Our chemical engineering department is within the school of engineering at a Hispanic-serving research university in the American southwest. The department includes a mix of tenured and tenure-track faculty, as well as a teaching-intensive lecturer. Prior to the project, some of the faculty taught exclusively at the graduate level, interacting with just a few undergraduates in their research. Our chemical engineering degree includes a 1-credit first-year course, four core technical courses, as well as laboratory, seminar, and concentration-specific courses, culminating in a two-semester capstone design sequence (see Figure 1).

Some of the faculty were hesitant about the curricular changes (Ferris et al., 2022; Gallup et al., 2020; Svihla, Davis, et al., 2022). We viewed this as expected, in part because we recognized that in their educations, they had not experienced such approaches. And, as faculty at a research university, there are many incentives that direct focus onto research and away from teaching. Some faculty feared that making changes would leave less time for content, resulting in less "rigorous" courses that would fail to prepare students for industry or graduate school.

Some faculty viewed students in a deficit-oriented way, focusing on how students have shortcomings that need to be fixed rather than identifying the unique skills that students bring to their classes and to the profession. Deficit perspectives are common in STEM education and are exemplified by placing blame on students for opportunity gaps beyond their control (Valencia & Solórzano, 2012). This type of thinking disparately impacts minoritized students and communicates that they are not welcome (Castro, 2014). Further, the traditional instructional methods—lecturing, problem sets, and exams—many faculty used did not reveal much about students' strengths or prior experiences, instead focusing attention on their comprehension of course concepts. Such instruction, because it does not reveal students' strengths or build relationships between students and faculty can reinforce deficit views (Castro, 2014).

One aspect that makes our project distinctive is its focus on developing learning experiences—in particular, design challenges—that make students' everyday experiences salient as engineering *assets*. Others have argued that students' everyday and cultural experiences are valuable as *funds of knowledge* that can serve as a foundation for formal education—a successful approach that is commonly studied in K-12 settings (McGowan & Bell, 2020; Moll et al.,

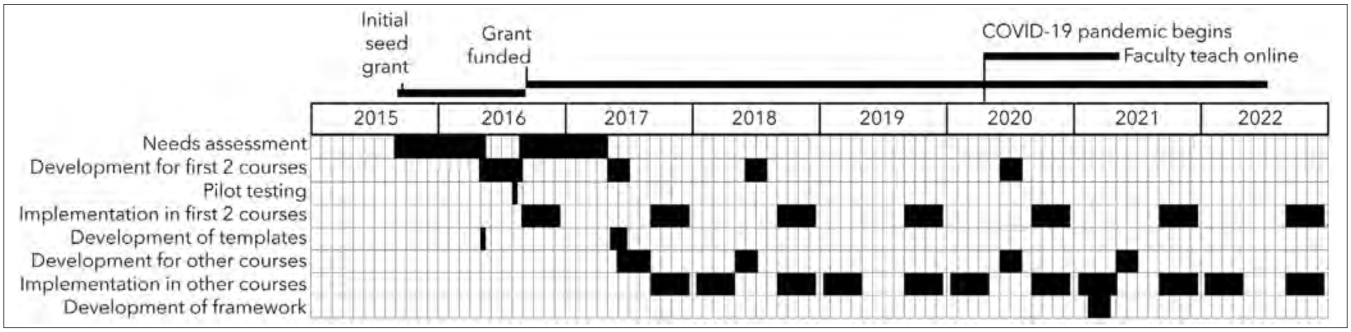


FIGURE 2. Timeline of design process and implementations.

DESIGN IDEA	SETTING	RATIONALE FOR CHANGING THIS IDEA
Hands-on, fun, team activities, without socio-technical context	First-year course, pre 2016	Students considered the original design challenges to be unrelated to both chemical engineering and their interests
Community-, industry-, research-, or entrepreneurial-based design challenges using authentic chemical engineering concepts, made relevant through student co-designers	First-year and sophomore courses, Fall 2016	Some design challenges were deterministic, evidenced by students coalescing on highly similar solutions; students may have received the message that design problems have a single right answer. Some design challenges offered generic, open scenarios that made it difficult for students to draw from their experiences, when we expected those experiences to be useful, such as rural students sharing their knowledge of rural needs related to water use.
Design challenges should include constraints that direct students toward their experiences; design activities should emphasize generativity / ill-structuredness	First-year and sophomore courses, Fall 2017	When expanding to other courses, the faculty who taught these courses had many of the same questions and concerns that faculty who taught the first-year and sophomore courses had raised.
Design challenge templates and the Educative Design Problem Framework provide guidance for faculty as they develop a design challenge	2018-2020	We continued to refine these design elements over these years but didn't make substantive change.

TABLE 1. Summary of the iterative design ideas present in the effort to develop design challenges embedded in core courses.

1992; Verdín et al., 2021; Wilson-Lopez et al., 2016). In these studies, a teacher or team uses ethnographic methods to understand and relate experiences in a community to school topics. Challenges for translating this approach to higher education include larger class sizes and often highly diverse and far-flung communities that university students come from. To overcome this issue, we sought to identify various kinds of everyday experiences students might have that could be valuable to them in learning to frame and solve engineering design problems (Chen et al., 2022; Svihla, Chen, et al., 2022).

This type of asset-oriented thinking is particularly key at our institution. Our students are diverse, with most of them from groups that are minoritized in engineering in some way. While the profession reflects inequities—more than 85% of engineers are white or Asian, and 85% are men (National Science Foundation & National Center for Science and Engineering Statistics, 2021; U.S. Census Bureau, 2016)—43% of our chemical engineering undergraduates are women, 45% are Latinx and 5% are Native American. One-third speak a language other than English at home, 52% work more than ten hours a week during the semester, and 27% come from low-income households. However, prior to our redesign efforts, we identified gaps in persistence to graduation; while our first-year course was consistently diverse, our graduating class was much less so (37% women, 35% from minoritized racial and ethnic groups).

We focused initially on the first-year course and first core course, both of which had the highest rates of students leaving the program (48% and 25% leaving, respectively). Minoritized students (including low-income and rural students) leave engineering programs at much higher rates, despite entering with the same level of interest in engineering as their peers (National Academies of Sciences Engineering and Medicine, 2016). We hoped that by supporting early courses to focus on the strengths of minoritized students, we could narrow the gap.

DESIGN PROCESS

Over a seven-year period, we developed, implemented, evaluated, and refined design challenges for a set of core chemical engineering courses (see Figure 2). To illustrate this process, we share punctuated vignettes that we consider to be key moments in our process: First, we detail how we began with lower division courses, collecting information about existing courses, generating ideas about possible design problems, then developing several of these for the first two courses in the sequence. We share a few insights and refinements to these. Second, as we considered ways to expand into other courses, we shifted strategies, developing templates and guidance for faculty. Over time, we also developed an educative framework to guide faculty. We summarize the iterative development of key design ideas across courses (see Table 1).

Assessing Need

In the process of developing a proposal for the project, we engaged various stakeholder groups—students, faculty, and industry—to better understand the strengths and weaknesses of our program in preparing diverse students for industry and graduate school. As is common, our program participated in cycles of program review for our university and for accreditation. In particular, the accreditation process foregrounds many professional skills (ABET Inc., 2020) that are challenging to assess. We, therefore, developed performance-based assessments to track the development of design problem-framing ability and identified surveys to measure students' beliefs about design and design self-efficacy (Carberry et al., 2010; Mosborg et al., 2005). In collecting baseline data, we sought to identify strengths our diverse students brought from their everyday experiences that were salient for engineering. Broadly, we sought to understand student and faculty perceptions about teaching, designing, and their roles.

We found that while faculty believed that students sought chemical engineering degrees because it is one of the highest paying fields, most of our first-year students expressed a desire to be innovators or make a difference in their communities and the world.

Interviews revealed that individually, most faculty valued teaching, but they did not believe their colleagues held similar beliefs. Most also recognized that they had never had opportunities to learn to teach and acknowledged that replicating the ways they were taught—lecture, problem sets, exams—were not the only or even best options. Some faculty brought examples into their lectures or problem sets, but seldom in ways that allowed students to develop the professional skills that engineers need, as outlined by accreditors (ABET Inc., 2020).

In designing *with* faculty, we sought to acknowledge their hesitance as a legitimate expression of care about teaching, rather than treating it as "resistance to change," a contrast to how many have positioned faculty in change projects like these (Reeping & McNair, 2020; Tagg, 2012). Given our aims to develop asset-based learning experiences, we recognized that we needed to take a similar stance with faculty, finding and building on their strengths, while coaching and re-interpreting situations with them. For instance, a faculty member shared that they had walked around to tables, asking "Do you have any questions," and then complaining that the students had none, yet on the assessment, it was clear they had not understood the activity. We responded by first acknowledging the frustration as well as the good intent, then suggested that they had inadvertently been asking students "Are you stupid?" as admitting to having questions at that point might have revealed that they were not as smart as their peers or as smart as the instructor expected them to be. The faculty member took up our suggestion of instead asking students "Can you fill me on your conversation?"

We also found that most faculty were accepting of the idea that our diverse students might have hidden strengths, and we found two root causes for this belief: First, most faculty had the experience of working with diverse undergraduate students in their research projects, where they noticed a great deal of growth in students. Second, many of the faculty held a belief that fixing, making, and tinkering activities as children can provide a solid foundation for future engineers. Given that many of our first-generation and low-income students had abundant opportunities having to "make do" and "make it work," our faculty readily agreed that these kinds of experiences were valuable. We share more detailed examples of how we collaborated with faculty elsewhere (Davis et al., 2021; Gallup et al., 2020; Kang et al., 2022; Svihla, Chi, et al., 2022).

Indeed, traditional teaching provides few opportunities for students to develop teamwork, project management, communication, and design capacities. Further, such methods disproportionately do not support minoritized students, who bring a more varied skill set that is not captured on typical exams.

In this design case, we focus on the information collected from our first-year introductory course, which included two design challenges prior to the project. In the first design challenge, instructors tasked students with determining why cheap coffee pots fail to brew strong coffee and proposing ways to redesign them to remedy this. Chemical engineering faculty appreciate the general topic of coffee because any

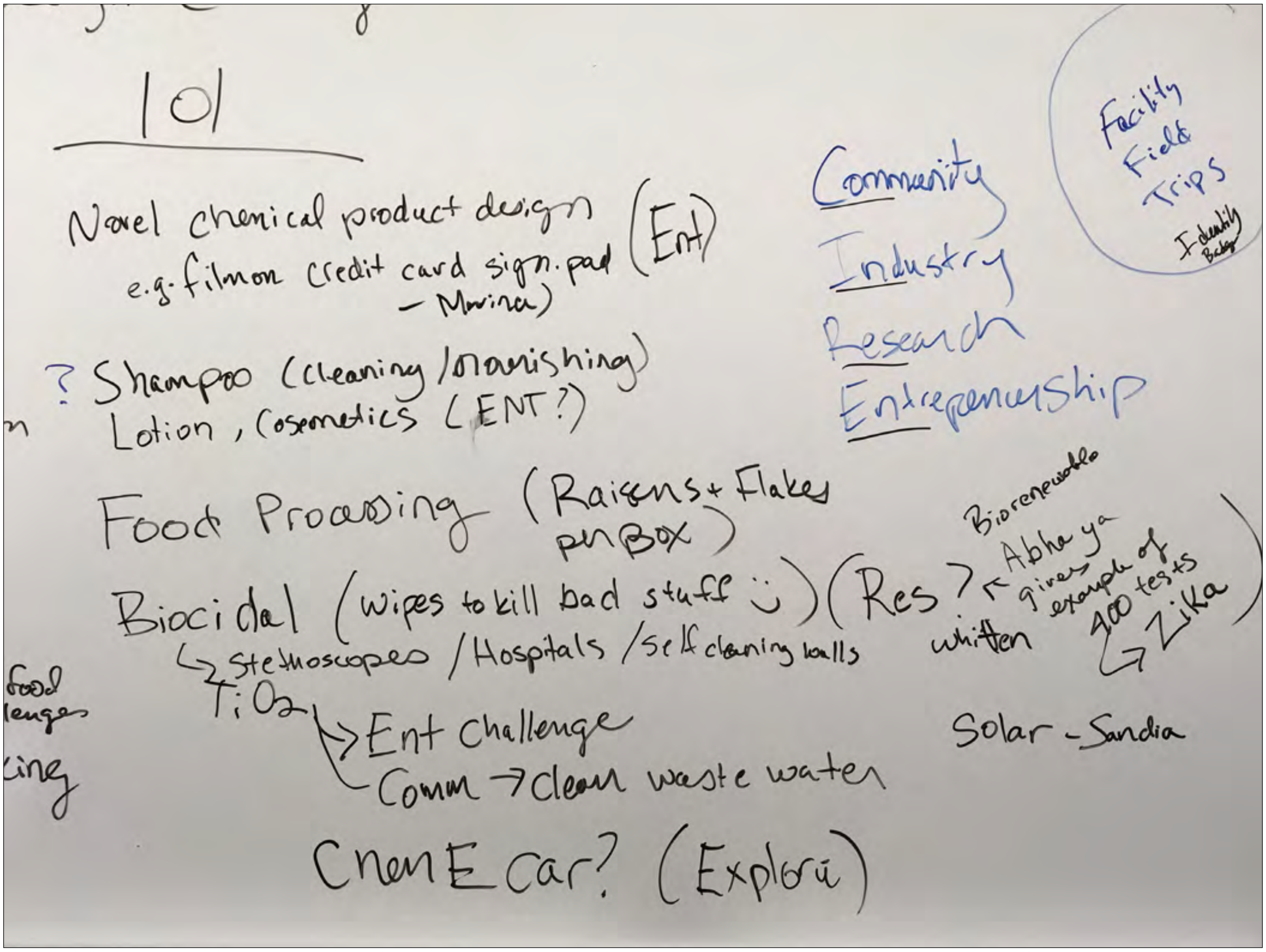


FIGURE 3. 2016 ideation with faculty about potential design challenges for the introductory course.

aspect of chemical engineering can be investigated. Indeed, a wildly popular chemical engineering elective course at the University of California-Davis (https://engineering.ucdavis.edu/engineering-research/coffee-science) illustrates this. In our introductory course, the coffee design challenge incorporated concepts central to chemical engineering, like heat transfer, and it provided an opportunity for students to test existing designs in a laboratory experiment. While this problem can clearly be open-ended, the instructors provided a set of resources that inadvertently directed students' attention to the issue of elevation—our high altitude allows water to boil at a lower temperature, producing weaker coffee. Resources also hinted at a solution—pressurization— and the lack of variety in students' solutions suggested they did not treat the problem as ill-structured. We considered simply modifying the resources and activity, but we also discovered that making coffee stronger was of little interest to most of our first-year students who had not developed a taste for it.

The second design challenge was an edible car. Students had to design a vehicle for a small toy passenger out of only food. None of it could be frozen and the design culminated in a competition to see which team's car traveled the furthest after rolling down a steep ramp. Students enjoyed the project but reported not understanding what it related to or why they were doing it. For students who were looking to impact the world through chemical engineering, the challenge seemed whimsical and not relevant. For students who had faced scarcity, the challenge also seemed wasteful. In this way, we can understand how the instructor's privilege shaped this learning design into one that reflected systematic inequities.

Uncovering these issues with the existing design challenges provided direction for us. We knew we wanted the design challenges to be authentic problems related to core chemical engineering concepts, and we decided the challenges should be community-, industry-, research-, or entrepreneurial-based, with a "design challenge originator" (DCO) acting as an authentic representative of the problem. By authentic, we referenced a definition from engineering education research; authentic problems have a "primary purpose and source [...] existing in a context outside of schooling and educational purposes" (Strobel et al., 2013, p. 151)—a definition that also highlights why it is important to scaffold or otherwise make such problems educative. We realized that the authentic problems faculty might propose could be overly technical or uninteresting for students. To mitigate this issue and balance authenticity with relevance, we invited student co-designers to join the team.

Ideation

We invited faculty and a few student co-designers to generate ideas for possible design challenges (see Figure 3). In this three-hour session, we first reviewed the existing program, the aims of the grant, plans for studying the impact of changes, and course-specific learning objectives. A few faculty raised concerns about the openness of design problems and students' potential to solve problems accurately. Student N noted the importance of designing something realistic, and Dr. D emphasized that it should be creative and feasible. We documented ideas on a whiteboard, including a new antimicrobial material developed by departmental faculty, cleaning wastewater, a local company that developed an evaporative cooling technique to keep biosamples cool, airplane de-icing, a spacesuit, chocolate making, algal biofuels, etc.

Dr. S drew upon their experience working in a project-based high school to list key tasks and next steps as: "Descrip. of problem; Provocative to students; Design Brief; Videos of External Client/DCO; Design thinking supports." They gathered everyone's summer schedules and planned the next meetings, including a visit to meet with a local entrepreneur who developed an evaporative cooling technique to keep biosamples cool. Dr. S sent a follow-up email of the ideas that they thought seemed most promising for the introductory course and listed only the algal biofuel idea for the sophomore class as Dr. G, who taught the course, seemed excited and ready to integrate that topic into her class.

Research and Development

Drs S, D, and G worked with the students to develop drafts of a few of the ideas. Because of the newness of the collaboration, Dr. S did not feel empowered to make large-scale changes to the first-year course, until Dr. D, the course instructor, approved them. Dr. S provided an example design brief template with sections: introduction, constraints, student learning outcomes, project roles, and timeline and deliverables. They worked with students N and J, who drafted four design briefs in as many weeks:

1. an entrepreneurial challenge of proposing applications of an antimicrobial material developed by department faculty
2. a community-based challenge focused on a local disaster in which acid mine drainage was released into rivers
3. a bioshipping challenge using evaporative cooling to precisely chill samples in transit
4. a revised edible car challenge with a focus on sustainability

The students named project roles as timekeeper, project manager, and designer. Concerned that some of these roles would not distribute responsibility effectively and knowing that women are often placed in less technical roles, we revised the roles as research scientist, market & financial analyst, community coordinator, systems engineer, and requirements engineer. In each case, we included a specific description of the role. We agreed that the design briefs should be generally accessible, but that they should also introduce a few key technical terms and include a couple of citations, formatted in the specific numbered style students would need to use throughout their coursework.

In the versions, the student co-designers developed, the introductions to the first two design briefs presented ill-structured problems that reflected authentic, external issues with socio-technical context (Strobel et al., 2013). For instance, the antimicrobial material was situated with a discussion of history, antibiotics, antibiotic resistance, and biocompatibility. In the acid mine drainage challenge, the introduction hinted that while some solutions may be straightforward, rural and tribal communities have legitimate reasons to mistrust outside solutions. In contrast, the bioshipping challenge was somewhat deterministic, suggesting a particular solution might be ideal. Finally, the edible car challenge—even with its positioning as a sustainable product marketed for children—still felt inauthentic and disconnected from chemical engineering concepts. We decided to proceed with the first three for the first-year course.

Dr. S reflected on the varied forms of design education they had experience with when deciding how to support students in these design challenges. First, they realized that the year-long capstone model common in engineering programs was not a good fit, because Dr. S wanted the approach and materials to be relevant for the core courses, in which most of the focus would be on learning technical content. Dr. S also worried that students and faculty alike were more comfortable with *solving* problems that, while difficult, had correct answers. Based on this, Dr. S decided to incorporate scaffolding for problem *framing* activities, like generating ideas, considering stakeholder perspectives, and researching the problem and failures of existing solutions. Dr. S drew inspiration from their prior experience working on a project that developed Legacy Cycles (Giorgio & Brophy, 2001). This research-based problem-solving cycle poses a challenge that students generate ideas about; they then explore multiple perspectives, research, and apply their understanding, before making their solution public. Inspired by Legacy Cycles, Dr. S guided the student co-designers to develop a sequence of worksheets that scaffolded students through similar steps: (a) generate possible design ideas based on what they already knew; (b) conduct research using library resources, internet searches of existing solutions, and news stories about issues; (c) develop and evaluate possible solutions; and (d) present their ideas. We share examples of these in later sections (e.g., *First version of the antimicrobial design challenge*).

In parallel, Dr. G worked with a student and Dr. S to develop the algal biofuel challenge for her sophomore-level core course. In contrast to the first-year course, this Materials & Energy Balances (MEB) course included significant technical content, much of which was unfamiliar to Dr. S. Dr. G planned to replace a couple of homework with design challenge assignments and use a few recitation sessions to support students to negotiate and make collective choices. Together, they developed worksheets to scaffold students to use decision matrices and to conduct research. A decision matrix is a commonly used tool in professional design work, enabling designers to identify and rank options and criteria (Pugh & Clausing, 1996). Seldom used in lower-division engineering courses, we designed an activity for students to identify various strains of algae as options and to propose criteria, like lipid production, growth rate, and growing conditions to help them make their decision (Gomez & Svihla, 2018); Gomez et al. (2017). In our version, we provided spaces for them to fill in their choices and criteria, and we included spaces for them to provide weight and rating, which they could use to calculate scores, and ultimately, select the best option (see Figure 4).

To orient students to the design challenges, we also developed launch videos, helping the students gain a situated understanding of the problem and surrounding context. These were inspired by lessons from anchored instruction (Cognition and Technology Group at Vanderbilt, 1992). Specifically, Dr. S recalled the project launch videos from the *Jasper Project* and the *Mission to Mars* Challenges, which offered context for a problem, broadening rather than narrowing its scope, suggesting many possible ways forward (Cognition and Technology Group at Vanderbilt, 1997; Hickey et al., 1994). We hired an undergraduate film student to develop our storyboards and descriptions into 3-5 minute videos. In contrast to the high production quality that the videos had, we prioritized a compelling storyline and relatability and assumed that revisions might be needed. In Dr. S's prior experience, students can ignore lower quality production value if the video is otherwise engaging. For the antimicrobial materials challenge, our launch video offers a short and vivid history of bacteria, antibiotics, and antibiotic resistance, laced with humor (the high cost of textbooks) and culture (showing videos of local cultural events), before introducing Dr. W., one of the researchers developing new antimicrobial materials, to explain briefly what the materials are and how they work (see Table 2).

The video ends with a challenge: "In which specific ways can you see [these antimicrobials] applied and where?" paired with a quick succession of images to highlight the varied potential applications, such as hospitals, schools, workplaces, and gyms.

With your team, assemble a decision matrix to come to a consensus on your final choice. Scale: 0-3 where 3 is Best and 0 is Poor

		Choice 1: Nannochloropsis		**Choice 2:** Chlorella		**Choice 3:** Thalassiosira		**Choice 4:** Spirulina	
Criteria	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Cost	.2	1	.2	1	.2	2	.4	1	.2
CO_2	.2	2	.4	2	.4	2	.4	2	.4
Yield	.2	2	.4	2	.4	3	.6	2	.4
Growth Rate	.2	2.5	.5	3	.6	2	.4	1	.2
Temperature	.2	3	.6	3	.6	3	.6	3	.6
Total			2.1		2.2		2.4		1.8
				Best Option:		Thalassiosira Weissflogi			

FIGURE 4. Sample decision matrix; non-bolded text in table is student work, reflecting algal strains the students chose, the criteria the students chose, and the weights, ratings, and scores they assigned each choice.

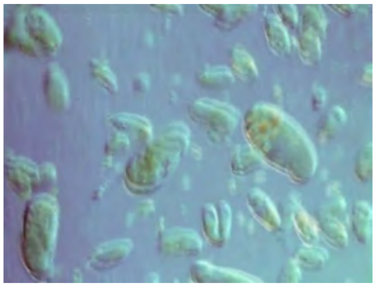
Bacteria play an important role in the function of human bodies. We use bacteria to aid digestion, help respiratory function, and bolster immune support. Without bacteria, we cannot survive. But just as there are good bacteria, there are bad bacteria that cause diseases. 	Thanks to the work of Alexander Fleming and other scientists, the age of antibiotics began. You can read everything you need to know in this textbook I have right here. You can have yours at the university bookstore for only $900 today. This is not a paid advertisement. 
Hi, I'm a guy in a lab coat who is not a paid actor. Anyway, let's get started. What happens when bad bacteria enter our body? At some point, you might've had an infected cut, a sinus infection or food poisoning. Many times, this is caused by bacteria. Thanks to modern medicine, you don't have to worry about these seemingly minor issues having serious complications, but what happened before modern medicine? 	One of the problems, however, was much like animals can adapt to their environment, bacteria can do the same. 

TABLE 2. Screenshots of the antimicrobial design challenge launch video with summarized transcript. (Continued on next page).

In the process of developing the video for the acid mine drainage challenge, we interviewed a faculty member with expertise on the topic. He discouraged us from including sociotechnical context, explaining that it would be too complicated for students to understand. Because our work was meant to be "revolutionary" we chose to retain this aspect. Ultimately, we were glad we did, but at the time, it prompted concerns from the faculty responsible for the course.

Pilot Testing

Once developed, we pilot-tested the antimicrobial and acid mine drainage design challenges with students who were participating in summer research experiences on campus. We documented their participation through artifacts and followed up with a focus group to gather their perceptions. The students were enthusiastic. They found the problems easy to get started on. The few technical terms prompted them to search for information. While these upper-division students were quite different from our first-year students, we found the pilot testing reassuring and made only minor edits before using them in our courses.

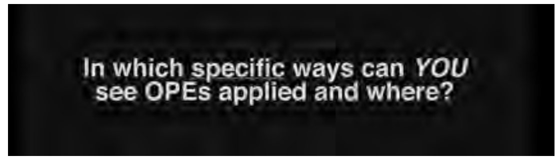
Bacteria can become resistant to the materials we use to fight it. This was foreseen by Fleming. We have to keep one step ahead. Luckily, there are people who are fighting for a future, the World Health Organization, the Centers for Disease Control, and even our university are leading the fight against bacteria. Dr. W developed a new compound that targets bacteria.	 Video ends with rapid succession of images of hospitals, gyms, workplaces, schools
	

TABLE 2 (CONTINUED). Screenshots of the antimicrobial design challenge launch video with summarized transcript.

First Version of the Antimicrobial Design Challenge

First, we launched the antimicrobial challenge, sharing the video and design brief. The first worksheet was completed individually, an approach that gave the instructors an extra week to form teams. This worksheet prompted students to define terms—antibiotic product, antibacterial product, antimicrobial product—provide examples of each, explain the types of organisms each could kill, how they work, and identify problems with each. Next, they were asked to distinguish between bacteria and fungi cells and explain which kind of infection is easier to treat. The last step of the first worksheet asked students to generate ideas: "Review the design brief and begin coming up with possible ideas for products that [antimicrobials] could be added to. List at least five surfaces people come into contact with that support the spread of pathogenic microbes. Consider people of all ages and of various occupations. You'll bring these ideas to your team to choose a product, so be ready to defend your ideas."

The second worksheet was completed as a team, with each member identifying their role, as defined by the design brief. This worksheet prompted them to list all the ideas each member generated and then to come to "consensus as a team and choose one surface that your team feels represents a need for an innovative product. State your reasons for choosing this one over others discussed." The worksheet then guided them through making a product proposal ("Describe your idea for a product. Who uses the product? Why and how do they use it?"), conducting market research ("List and describe at least two products currently on the market that are similar to yours. Who is currently buying those products? For what purpose and at what retail price? Existing products may or may not include antimicrobial properties.") and estimating the cost of their proposed product ("based on the approximate dimensions of your product and the volume of [antimicrobial] material to be used. You'll need to factor in the cost of the product itself as well as the cost of the [antimicrobial] material. Decide as a team what the retail price will be for your product."). We provided an estimate for the cost of the antimicrobial material. Knowing that the added material would significantly affect the cost, we also prompted them to deal with this issue ("How could you change your design to minimize this difference? Alternatively, how could you intuitively communicate how much safer your product is?").

Students had an opportunity to meet Dr. W., one of the faculty involved in studying the antimicrobial material. Because they had already begun their idea generation, they had questions for him about its safety and applications. We also invited a guest speaker who presented on how to pitch a product. We provided guidelines on their pitches and created an evaluation sheet that asked judges to score students and offer comments about the following:

1. The students presented confidently or worked to overcome any nervousness.
2. The students concisely explained the problem and needs addressed by their design.
3. The pitch helps clarify how the product would be used, how it could change customers' lives, and what makes their product better than existing products.
4. The idea presented is creative.
5. The pitch conveys the market potential of their product.

Following the pitch, Dr. W offered feedback about some of the ideas he found particularly exciting and shared with students some of the steps in bringing an idea through development and testing, with federal regulations in mind.

First Version of the Bioshipping Challenge

The bioshipping challenge situated the problem as transporting samples from rural clinics to urban laboratory facilities, tasking students with designing a shipping container capable of maintaining the temperature for a 24 hours. Students conducted a laboratory experiment with different materials to inform their designs. The laboratory experiment was very cookbook; students followed the steps listed in a handout to collect their data. They were scaffolded to characterize the thermal properties of the materials they were given. This project culminated in a short technical report, followed by a meeting with the inventor of an innovative bioshipping container that was the inspiration for the project. We saw little variety in students' designs, suggesting that, like the original coffee pot experiment, the challenge was rather deterministic.

First Version of the Acid Mine Drainage Challenge

The acid mine drainage challenge engaged students in researching the 2015 Gold King Mine Spill which impacted communities in Colorado, New Mexico, Utah, and Arizona, turning rivers a vivid orange color. The design brief introduced some of the issues and challenged the students to "design a comprehensive response plan, including community engagement strategies and choosing a treatment system that could filter water for an entire community in the event of pollution from abandoned mines." With guidance from a librarian, they learned about citation software, ways to avoid plagiarism, and conducted library research on acid mine drainage, methods of water treatment, and community engagement strategies. This challenge also culminated in a pitch. We noticed that a few teams included a rural student who could offer a firsthand account or explanation of the needs of such communities and that these teams tended to select water treatment systems that were more economically feasible to implement.

First Version of the Algal Biofuel Challenge

In contrast to the first-year course, the MEB course design challenge needed to connect to specific course content. We threaded the design challenge throughout the course, introducing it in the first weeks of the semester, and revisiting it every two to three weeks. The algal biofuel challenge tasked students with designing a plan for an algal biofuel facility scaled for a non-specific rural community. We divided students into three large groups focused on three phases: growing algae, harvesting algae, and extracting lipids for biofuel. Within these foci, students worked in teams to make decisions about how to grow the algae (using an open pond or a closed system called a bioreactor), about what type of algae to grow, how to harvest it, and how to extract it. Students completed research individually and brought their ideas together in sessions designed to support them to comparing and using decision matrices to arrive at a decision. Teams then negotiated to come to a consensus within foci and then across the whole class. This approach eventually resulted in a single class-wide solution, which inadvertently communicated to the students that designing was rather deterministic. Because students made decisions sequentially, this did not allow them to consider the implications of the first decision on the following decisions. This approach communicated to students that individual decisions could be made in a vacuum rather than iteratively and interconnectedly. Students complained that they wanted to consider the problem from all points of view, not just from a single focus.

REFINEMENTS AND INSIGHTS

In the first iteration, the faculty encountered some challenges. For instance, faculty expressed concerns about how students would learn to design if we were not offering lectures on *how to design*, they were uncertain how to monitor and manage student engagement during class sessions, which could be noisy, and when a student happened to ask a more advanced question, faculty sometimes launched into lecture in response. They also expressed concerns about whether the design challenges were taking away from important conceptual learning opportunities. However, faculty also perceived encouraging benefits. For instance, they were surprised by how passionate many of the students were about chemical engineering. Several faculty members shared that, compared to lecturing and problem sets, the design challenges allowed them to get a better understanding of their student's interests and that students were willing to work hard to learn.

Initially, students also complained about the effort needed to work in teams and navigate the ambiguity the design challenges offered. We found this diminished when we began using CatMe software to form teams that had common availability—a challenge given the high percentage of students who worked more than 10 hours/week and/or had caregiving responsibilities (Layton et al., 2007), and as students became accustomed to having design challenges every semester.

We made many refinements over iterations and draw attention to just a few here. In the first-year course, we made refinements to design challenges and eventually removed one.

In the antimicrobial challenge, we added an additional activity to support team formation, in which students completed a simple team charter assignment that aimed to foster a sense of responsibility for their contributions to their team. We shifted from having them generate initial ideas individually to doing this as a team. We also shifted from encouraging students to look up terms of the first assignment to asking them simply to draw upon what they already knew.

Although this made some students uncomfortable, we realized that focusing the first assignment on the accuracy of their definitions sent the wrong message about the nature of design. We wanted to signal instead that they needed to draw upon their prior precedent, doing research when needed. To prompt them to do research when needed, we found inspiration in the project-based learning strategy of using a KWL (Know, Want to know, Learn). Dr. S had observed project-based teachers using KWL to pace and track progress, revisiting and updating the same board weekly. Because of challenges maintaining such a board (e.g., it would be erased by other instructors who used the room, or sticky notes might fall off if it was transported back and forth), we decided to emphasize student agency in planning their work. The worksheet we developed guided students to take greater responsibility for diagnosing what they knew and did not know: "As a team, you should begin by figuring out what you already know, and what you need to do research on. Just write down your best ideas and what you know. Do not do any research now. You'll have time to do research later. What are antibiotic, antibacterial, and antimicrobial products? How are they different from one another? What organisms do they kill? How do they work?" We included boxes for their responses:

- What do you know about these questions?
- What do you need to research? What gaps in understanding do you have? What tools/resources will you use to find information?
- What questions do you have about [antimicrobial materials]? What do you need to know about them?

We also added a specific constraint: students could not propose a cell phone cover. This was a popular idea in the first set of presentations; as such, students appeared awkwardly in competition with one another. By encouraging them to come up with uncommon ideas, their pitches were enjoyable to watch.

To deal with the overly constrained biosample shipping problem, we took the same fundamental ideas and developed a new challenge of designing a self-cooling water bottle using evaporative cooling. In the lab, students first tested a water bottle wrapped in simple muslin dipped in water. We provided students with craft supplies to develop their designs, which were highly varied. Students tested their designs and uploaded their data using a Google Form, which then granted them access to everyone's data. We were pleased that they could explain their reasoning behind their designs. However, it took significant time to coordinate, leaving the course feeling rushed. Ultimately, we decided to

FIGURE 5. Simulated acid mine drainage sample.

remove this design challenge in favor of offering a deeper experience with the Acid Mine Drainage challenge.

Specifically, we expanded the acid mine challenge to include a laboratory experiment and required students to select a particular rural county in our state. We reviewed students past designs to determine which chemicals were commonly selected and that could be feasibly included in a laboratory experiment. We simulated samples of contaminated water using a weak acid and turmeric; students were very cautious with the samples, which suggested to us that they found our simulation quite convincing (see Figure 5).

As we had done with the prior laboratory experiment, students submitted their designs—in this case, the volume or mass of each of the four chemicals they could select—as well as their pH over time using a GoogleForm, which granted them access to all students' data. They could then compare their results to others who used different designs. This approach also enabled us to offer students data with which to work during the COVID-19 pandemic, when they could not be on campus to test their designs. We have since also taken this approach to other laboratory courses because it makes it easier for students to have enough data to learn to conduct statistical comparisons.

In the sophomore MEB course, we also made refinements over time. First, like with the acid mine drainage challenge, we shifted from a generic rural community to requiring students to select a specific community in our state. In this algal biofuel challenge, this decision was consequential, as it provided an opportunity for students to survey community resources and make more sustainable choices, like using wastewater from a dairy, which in turn limited which algae could grow. This helped students see the iterative and interconnected nature of their decisions.

One change to the design challenge was not successful in the second iteration. In response to student's frustration at not getting to cover everything in the first version, instead of placing students into focal areas (growth, harvest, and extraction), we introduced these sequentially in the second version, with every student responsible for every focus. However, we found that students engaged more shallowly; they seemed spread too thin. They focused on efficiently getting the "right" answer. In our third iteration, we shifted the team structure such that each team included one or two students who specialized in each focal area. We also drew inspiration from the classic jigsaw approach by having students across teams with others in their focal area to review and discuss criteria prior to negotiating decisions within their teams and across focal areas (Aronson, 1978). This worked well, prompting much deeper and more specific conversations.

Across these changes, we also found it valuable to contextualize a few more typical homework problems using the design challenge. This helped students make connections between the core content and the design challenge.

DESIGN CHALLENGE TEMPLATES

As we aimed to expand our approach to all the core courses, we recognized that we could be more efficient in transferring lessons learned if we created educative templates that offered guidance. We developed a series of templates to support the process of developing a design challenge. Additional templates focused on doing research, generating ideas, evaluating ideas, and supporting teamwork. The design challenge templates have been a powerful scaffold for our faculty and student co-design teams, making the process less intimidating than generating all the materials from scratch. Using templates also supported student buy-in, as students became more accustomed to seeing these kinds of activities in their core courses.

The design brief template includes sections for the introduction, student learning outcomes, project roles, references, and deliverables. It is educative in that it offers guidance to faculty about each section. We offer the design brief template in full (see Table 3).

Cover Sheet Template

We also shifted from simply asking students to select roles, to having them plan and report on their contributions to each assignment as a cover sheet. In the first-year course, when team issues arose, this allowed us to modify the grade only of the individual who did not complete their work, as teams could turn in a deliverable missing that person's contribution. In other courses, when a missing piece was more consequential, instructors could decide how to handle the situation, sometimes even reconfiguring teams.

Student Learning Outcomes Describe the observable outcomes that students should be able to accomplish after completing the design challenge. Identify just 2-4 for a short design challenge, and 4-8 for more involved design challenges. Avoid the words "understand, appreciate, and learn." Use words like: identify, present, analyze, propose, conduct research, estimate, define, and explain. For a more comprehensive list: https://www.missouristate.edu/assets/fctl/Blooms_Taxonomy_Action_Verbs.pdf After completing this design challenge, students will be able to: • identify … • explain …
Project Roles In most design challenges, students will work in teams. Provide authentic roles for them to take on. Avoid roles like "scribe, note taker, researcher, time keeper, recorder, organizer." Provide a description of each role, and a statement that makes clear that everyone is accountable for all information. Make sure there are at least 3 roles, and generally not more than 4, allowing two members to take on roles that might require more significant effort. Consider the project deliverables and write the project descriptions with this in mind. Mimic the examples below. All members of the team are responsible for all information, and every member should participate in making design decisions. Team members should specialize as follows: Project Manager: Responsible for developing group action plan and keeping group on task. Organizes and submits deliverables. Monitors team shared understanding of project. Environmental engineer(s): Oversees research on the problem, including the impact on natural and human resources. Coordinates with team members to ensure they have the information they need to be effective in their roles. Community coordinator: Oversees research on community engagement strategies, including understanding all relevant engineering content and developing a communication strategy aimed at broader audiences. Coordinates and advocates community interests to team members to ensure effective design.
References Provide a list of references cited in the introduction. The following are sample references that you may use to supplement your research. They are cited using a numbered style, so use them as a reference when citing your documents.
Deliverables Provide a list of deliverables and estimates for points for each deliverable. Note that you will need to make all worksheets/ assignments.

TABLE 3. The Design Brief Template.

Self and Peer Evaluation Template

To support better team interactions and promote students to reflect on their contributions, we designed a self- and peer-evaluation template/tool. Dr. S had studied senior design teams previously and realized that students would typically give themselves and their teammates equal, perfect scores unless something was going very poorly. To encourage students to reflect both on their team overall and their contributions, they created a convoluted scoring system (see Figure 6). The form prompted students to "remember, everyone has strengths and weaknesses. Your scores should reflect this," and to be honest: "You will receive full credit for this assignment if you complete it. Individual project grades may be adjusted based on triangulation of information, not based solely on these scores."

The form asked students to select a team score, and then distribute the points on multiple dimensions:

1. Completed quality work
2. Quantity of participation—was willing to do a fair share of the work
3. Was prepared in a timely fashion
4. Dealt with difficulties effectively
5. Open-minded and respectful when disagreeing
6. Encouraged everyone to contribute
7. Made sure we understood each other
8. Contributed creative ideas
9. Gave constructive feedback

Self & Peer Evaluation		2) Fill in your name and your teamma across members—including yourself- Remember, everyone has strengths anc should reflect this.		
1) You can allocate 42 to 367 points for each criterion below, labeled 1 through 15. See the example in blue below, where the person gave 302 points to #1 and 110 points to #2. The flag TRUE or FALSE indicates whether you distributed all the points among the team mates, based on the total you allocated to this criterion. First evaluate how well your team performed on each criterion, on a range of 42 to 367 points: 350-367: Truly exceptional! You are likely paid to give talks on this! 293-349: Accomplished. You could mentor other teams on how to do this well. 147-292: Okay. Maybe you had a minor issue or still have room for growth. 98-146: You faced lots of challenges and made some mistakes in this area. 42-97: Utter failure (rare)		Your name:	Team member name:	Team member name:
Example 1: Completed quality work	***302***	*40*	*45*	*58*
Example 2: Quantity of participation—was willing to do a fair share of the work	***110***	*25*	*30*	*22*
1. Completed **quality** work				
2. **Quantity** of participation—was willing to do a fair share of the work				
3. Was prepared in a **timely** fashion				

FIGURE 6. Sample of self and peer evaluation template.

Finally, the form asks if they would want to work with each person again, to share ways in which the team worked well together, and to explain how they dealt with issues or challenges they faced as a team.

FROM TEMPLATE TO IMPLEMENTATION

In integrating design challenges into other core courses, we continued to use faculty-student co-design teams. In most cases, the students had firsthand experiences as learners in a prior course that included a design challenge and had also completed the course they were helping to create a design challenge for. While the template offered guidance on what should be included, we did not always provide enough support on the first attempt. For instance, in reflecting on the first versus second version of a design challenge in the spring sophomore course, the instructor noted that too much open-endedness was challenging. Inspired in part by examples from another university, he tasked students with proposing an application of evaporative cooling.

Students found the possibilities daunting, and so he shared an example of using evaporative cooling to keep medicine cool without electricity. Almost every team then proposed using evaporative cooling to keep medicine cool without electricity, resulting in rather monotonous presentations. Once contextualized and partially constrained, as suggested by the template, students' designs were more varied and creative.

In developing design challenges for the junior courses, the template supported the co-design teams to create socio-technical problems that were fruitful topics for students to work on. For instance, in the fall course, students were tasked with designing a solution to help remediate a local, complicated underground jet fuel spill that had been going on for decades. In the spring course, the design challenge focused on making nonalcoholic beverages through separation methods (removing the alcohol while retaining the flavor).

Yet, we recognized that the templates were limited in their capacity to share ways to thread the design challenge through other course activities, like homework and lectures. In the first version of the fall course, Transport, the design challenge provided insufficient scaffolding and students struggled to see the connection between course content and the design work, which made that work seem like an add-on. As we refined the design challenge, we focused on providing additional connections. The instructor added problems in the homework, much as Dr. G did in the sophomore course. This helped students make the connection to specific course concepts.

By adding smaller assignments distributed across the semester, students were prompted to think about their design challenge many times before it was due and to consider how the things that they were learning could be leveraged in their designing. This prompted students to have more creativity in their designs (as they had less tendency to just use concepts that had been introduced most recently) and to have a greater understanding of how and why they could use the transport principles they were learning.

We took the idea of smaller assignments to support students in another junior course, Mass transfer. Here, instead of only focusing on ways to integrate the design challenge into homework, the instructor also created in-class activities and demonstrations to better visualize the forces at work. Smaller assignments allowed students to keep on track and receive ongoing opportunities for feedback and revision.

THE COVID-19 PANDEMIC AS CONTEXT

On March 13, 2020, our governor shut down public schools and universities, initially for two weeks. Our university directed faculty to use the two-week window to transition all courses online, with the expectation that following a longer spring break, students would complete the semester online. During this time, faculty mostly worked individually, rushing to develop online materials. Some faculty, overwhelmed by this transition, as well as the other challenges related to the pandemic (such as suddenly teaching their children, etc.) abandoned design challenge plans. One faculty member, Dr. C, heard students' desire to be able to do something to help. She adapted her design challenge to enhance its relevance given the pandemic context. She shifted the challenge from designing nonalcoholic beverages to distilling hand sanitizer. She later brought this design challenge into the laboratory course that students took in the Fall of 2020, where students designed ways to produce and distribute hand sanitizer, working with local distilleries to scale their systems (Wilson-Fetrow et al., 2021).

In late spring, a few faculty elected to complete a 6-week online teaching course offered by the university (and nearly all faculty completed it by the end of the summer); while they found many helpful tips and tricks, they were unsure how relevant some ideas were in teaching engineering. During this time, teaching was a common topic during faculty meetings. With no argument from faculty and no break, we continued faculty meetings the week after the semester ended. Most faculty attended and seemed both resigned and committed, expressing concern about their students, their capacity to teach online and their interest in approaching the fall semester better prepared. The meetings were engaged and responsive to questions and concerns, and Dr. S offered research-based guidance, such as using shorter video lectures interspersed with guiding questions, organizing modules, supporting online collaborative learning, assessing learning in ways that were fair and useful, and understanding students' experiences and responding with care. Faculty took these ideas seriously; for instance, as others adopted surveillance software for exams, our faculty rejected it as intrusive, as potentially enhancing students' anxiety and therefore producing sources of measurement error, and with concerns about internet bandwidth (Davis et al., 2021; Ferris et al., 2022).

As we approached the fall 2020 semester, inspired by how Dr. C brought her design challenge into the pandemic context, several faculty also planned changes. First, in the sophomore MEB course, the instructor, who newly rotated into the course, pivoted the challenge, fearing that it would be too complex to orchestrate the complex, collaborative peer interactions via Zoom. Instead, Dr. H replaced the algae biofuel challenge with one centered on the manufacture of face masks. Students pitched their mask designs in videos, rather than in live sessions.

Likewise, in the thermodynamics course, the previously overly broad evaporative cooling refrigeration challenge became suddenly relevant as communities struggled with distributing vaccines that needed to be maintained at extremely cold temperatures. Here, students could choose which vaccine they wanted to transport, which community they wanted to transport it to, and how they wanted to keep the vaccines at their requisite temperatures.

Other design challenges needed no changes to be relevant. For instance, in the antimicrobial design challenge, the need for antimicrobial materials sharpened. While students had commonly proposed high-touch surfaces like doorknobs, many more teams did so during the pandemic. The spread of COVID-19 situated the problem as far more salient and relevant to students.

These pandemic pivots collectively foregrounded the importance of providing a way for students to impact things that were going on in their lives as well as the lives of those around them, supporting student engagement and passion

CRITERION	DESCRIPTION
Relevance	The problem is relevant to students' lives or experiences, such as by connecting to their prior every day or cultural experiences, by connecting to a current or regional event
Socio- technical complexity	The problem includes complex (multiple interrelated variables/factors) sociotechnical context. Social factors intersect in consequential ways with technical factors/variables.
Low-bar entry	The problem is accessible and understandable to students. With little to no additional work, they can identify key issues and stakeholders related to the problem and explain why the problem matters.
Non- deterministic high ceiling	The problem requires accurate application of technical content, but lacks a single deterministic solution, and even the particular technical content may be dependent on how students frame the problem.

TABLE 4. The Educative Design Problem Framework.

for their designs. That faculty made these changes exemplified their commitment to relevance and care (Davis et al., 2021).

THE EDUCATIVE DESIGN PROBLEM FRAMEWORK

Given the various iterations and attendant research studies, we conducted a retrospective review to synthesize a framework to guide future efforts to develop design challenges (Svihla et al., 2021). Although we had developed challenges for every semester, the pandemic foregrounded the value of problems that were relevant to students. In addition, as new faculty are hired or rotate into new courses, we realized that having a framework, in addition to the templates, could offer better guidance (see Table 4). We linked each dimension to research on how people learn because we knew that faculty might be curious, or might find the backing reassuring, especially when trying something new.

CHALLENGES AND WHAT WE LEARNED

Across this seven-year project, we had many opportunities to refine our approach, from how we collaborated, and how we developed individual design challenges, to how we supported faculty to develop and implement design. Elsewhere, we report on research into how faculty developed and how the learning opportunities supported our students. Here, we focus on our experiences as designers—both of design challenges and of supports for those developing design challenges.

First, we certainly encountered faculty who were hesitant, and understandably so. Just as we sought to create learning experiences that were asset-based, we aimed to treat our co-design teams with the same approach, meeting them where they were and with understanding about why this effort was difficult. Traditional teaching and assessment, as our faculty had experienced both firsthand as learners and replicated as instructors, tends to reinforce deficit narratives. In engineering, we have heard about "rigor" (Riley, 2017), and have seen the ways it can shape faculty beliefs. In developing and implementing design challenges, we were asking even the enthusiastic faculty to make a leap of faith; we took them out of their comfort zones. Dr. S acknowledges feeling spread thin in this process, as they were sometimes unable to provide as much collaborative support as would have been helpful.

Second, while the templates and framework were helpful, on their, we suspect they would be insufficient. We aimed to strike a balance in providing the right amount of information in the template. However, we recognize that we had resources and time to invest and that these contributed to many opportunities for faculty to learn with and from one another. From Dr. W visiting the first-year course and being impressed by students' enthusiasm, to faculty sharing at meetings, and adding each other to their courses, our faculty gained many opportunities to peek into peers' courses and even to troubleshoot when things did not go as expected.

Third, we faced challenges related to student buy-in, and these challenges shifted over time. Initially, some students were frustrated because they were familiar with traditional schooling and knew their places in lectures, worksheets, and exams, but had much less experience in these open-ended problems. They struggled with the concept that there was no singular right answer; it felt uncomfortable to many. Students in the first iteration of the sophomore MEB course wanted to experience all the foci (growth, harvest, extraction). In making this change for the second iteration, we fed into students' mile-wide, inch-deep, accurate-and-efficient expectations of what education should be like rather than having them work together to build a design and think deeply about specific topics. Over time, we have gotten better at framing expectations for students and have shifted more of their grades from exams to performance assessments and project work to aid in reinforcing to students that we are interested in the learning process much more than achieving the "right" answer. And, Dr. S has infused their explanations of student requests, complaints, and preferences with research on how people learn, helping faculty differentiate between what students want, and what will benefit their learning. Striking a balance between listening to student concerns and recognizing that not all student wants are best for learning is a difficult and ever-shifting line to walk.

Fourth, we found bringing students into co-design teams to be critical and sometimes surprising. For instance, the undergraduate student hired to develop project launch videos brought his experiences into the videos he created. As faculty, we were unsure about the humor he had introduced into them, but every time we have played these, we have witnessed how students connect to them. We recognize that having students helps us bridge connections between our expectations and students' experiences. Initially, some faculty sought to hire the highest-achieving students to aid in co-designing and implementing the design challenges. Over time, we came to realize that students who have struggled a bit more in some way—be it in balancing family, work, and school responsibilities, or in making sense of abstract content—can provide valuable insight in making design challenges relevant to students. This also helps to provide a check on faculty centering their perspectives in their teaching by adding students who can both connect to students in a different way and talk about their experiences with struggle and outside commitments.

CONCLUDING THOUGHTS

In this design case, we shared highlights from an iterative effort to develop a "revolutionary" approach to teaching chemical engineering. With grant funding, we supported a new collaboration between faculty in chemical engineering and learning sciences. Over seven years of design work, we found certain approaches to collaborative design to be particularly productive:

We designed *with* faculty, seeking their strengths (e.g., embracing their hesitance as a sign of care) and coaching them through difficulties. As more faculty engaged, those who were hesitant turned to their peers as they implemented design challenges.

We engaged students as co-designers to develop learning experiences that were jointly authentic and relevant. Engaging students this way helped faculty understand student perspectives and experiences, and avoid some inadvertent biases about what they (the comparatively privileged faculty) thought students liked.

We developed educative templates and a framework to aid faculty in planning and implementing a form of pedagogy that was previously unfamiliar to them.

We note that the grant funding (approximately $2 million over six years, or around $65,000 per year, after indirect costs were removed) certainly made many aspects of the project feasible, including hiring an undergraduate film student to develop launch videos, hiring student co-designers, attending conferences, and providing faculty with summer salary as an enticement to participate. Perhaps surprisingly, developing the launch videos was one of the more affordable undertakings, costing around $100 to produce each video, a cost not as out of reach as readers might have imagined. We cannot overstate the value of having sustained funding and focus over time for this kind of collaborative undertaking, which carried, as its central aim, cultural change in the department, realized in part through pedagogical innovations.

As the project has also entailed research studies to understand the impacts of changes on departmental culture and student learning and development, we were able to feed lessons from studies into refinements. And rather than treating the design challenges as perfect, we have encouraged faculty to continue to make changes, in response to societal changes, new research developments, and their insights and interests, while staying focused on supporting student engagement and learning, especially of the complex professional skills. Students grapple with the same issues that professional engineers face, including framing problems in ways that render them solvable, working with team members, and dealing with ambiguity, all while learning the core content needed to become chemical engineers.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. EEC 1623105 and 1751369. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. We would also like to acknowledge the many students, faculty, advisory board members, industry partners, and other collaborators who have supported this process.

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