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The Educative Design Problem Framework: Relevance, Sociotechnical Complexity, Accessibility, and Nondeterministic High Ceilings

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Abstract

Research suggests expert designers frame problems more broadly than novices, but authentic context may make a design problem too difficult. Yet decontextualized problems provide little opportunity for students to learn how to direct their framing and solving of problems. This paper considers characteristics of design problems that support students to develop design skills as they learn and apply concepts to the framing and solving of design problems. We selected and analyzed (un)successful design problems used over six years of iterations in an undergraduate chemical engineering program. We analyze salient features that made the design problems particularly educative and generalize an Educative Design Problem Framework, finding that such problems are relevant to students, have sociotechnical complexity, and are accessible yet require accurate application of technical content to solutions that are not deterministic—in other words, they are low-bar entry and high ceilinged. Faculty can use this framework to evaluate and improve design problems in their teaching.

Introduction and research purpose

While ABET students learning outcomes clarify the centrality of design in undergraduate engineering programs [1], teaching design courses and embedding design problems in core courses carries many practical issues for instructors. Researchers suggest that expert designers frame problems more broadly than novices, but authentic context may make a design problem too difficult. Further, authentic problems are not instructional designs; they may contain many details unrelated to course learning outcomes, and students may focus on aspects of a design problem that are familiar to them, missing key opportunities to learn both content and design practices. While highly technical problems seem promising as a way to focus students' attention on the content, decontextualized problems provide little opportunity for students to learn how to direct their problem framing and to develop solutions that feasibly meet worldly needs [2-4]. The purpose of this study was to synthesize characteristics of educative design problems—in other words, to identify characteristics of design problems that, when present, contribute to students' opportunities to learn about design and technical content. We see this as complementary to the body of research focused on the design methods used by experienced designers, the means to teach students such methods, and the various contextual factors that impact these.

Theoretical Framework

We anchor to a definition of authenticity proposed based on a review of engineering education research: "authentic problems are problems, which primary purpose and source of existence is not to teach or provide a learning situation; The primary purpose and source should be a need, a practice, a task, a quest and a thirst existing in a context outside of schooling and educational purposes" (p. 151)[5]. This definition foregrounds the world outside schooling, and that the problems in that world are not readily packaged and prepared for learners. We therefore view authentic engineering design problems in light of research on how people learn and constructionism [6]. Constructionism argues that learning should be personally relevant and meaningful, that learners should "construct" something—be it a model bridge, a derivation of the physics that accounts for a bridge's strength, or an evaluation of the tradeoffs present when situating a bridge in a way that displaces a neighborhood—and that there should be a public audience, allowing the learning to spill beyond the classroom walls. We intersect this with prior characterization of design problems as ill-structured, complex, and situated/discipline specific [7] to consider promising aspects of design problems for supporting learning.

Authentic engineering design problems are ill-structured [7]. This means they do not contain all the information required to solve them at the outset, and there are many solution paths and valid solutions [7-9]. In response, designers use various structured methods [10-13] to learn about and frame—and reframe—the problem they will solve [8]. Thus, learning is intrinsic to designing. Yet, learning to direct the process of problem framing, which is fraught with uncertainty, is difficult for students, in part because of a preponderance of prior experience solving well-structured problems [14]. And designers may work on aspects of design that are authentic yet not particularly educative, such as paperwork, matching clients' aesthetic preferences, and communicating well-understood information to non-technical clients. This complicates design instruction, where students may be distracted, for instance, by aesthetics at a cost to functionality.

Authentic engineering design problems are also complex. Complexity in this context is defined in terms of the number of variables or factors, the relationships between them, and the nature of the relationships between them [7]. Such problems are also situated and discipline specific [7], often requiring significant technical knowledge. In engineering design, problems are complex because variables commonly suggest an impractically large experimental space. For instance, consider a capstone design team trying to plan physical tests of a stent to determine conditions under which it would be effective. They might consider technical variables such as temperature, pressure, radial force, and particulate size. The number of possible variable combinations is too large to run every possible test, assuming each test takes 30 minutes. But beyond the technical considerations are social factors. If a stent is to be used in a living body, the team should also consider issues like long term biocompatibility, placement and removal, and short versus long term function, among others. From a purely technical focus, a stent could be optimized, yet could fail to meet one or more of these social needs.

In an effort to reduce complications and ensure students have opportunities to learn critical content, faculty sometimes use "toy" problems or highly technical problems, stripped of their context and decoupled from the world. This can show up as fanciful design problems that emphasize popular culture or science fiction, such as designing for fictional characters, or as designing familiar objects optimized for their technical properties, like bridges in the absence of a specific location or purpose. We argue that when such design problems fall short, it not because they are not authentic, but because they may be missing other elements. Perhaps surprisingly, even in the popular culture design problems, this missing element may be meaningfulness or relevance [15], a central tenant of constructionist learning [6].

Engineering courses tend to privilege the technical aspects of engineering [16], though analysis of authentic engineering design practice characterizes this work as *sociotechnical* [17, 18], and research has increasingly suggested reflecting this in engineering programs is valuable [19, 20], providing students with opportunities to grapple with complex factors and ethics [21, 22]. Such problems create opportunities to connect with the world outside the classroom [6] and develop critical agency [23]. Yet, we are brought back to the issue of authenticity. How can such complex, ill-structured problems become available to students and focus their efforts on learning engineering content and design practices? While we note that there have been many efforts to identify instructional moves that answer this question [24], we approach it with a focus on the design problem itself. Specifically, we argue for low-bar entry, high ceilinged problems, an approach recently advocated for in computer science for all programs [25].

Collectively, the research and theory above carve a space for considering the nature of the engineering design problems that students might encounter, and the educational opportunities such problems afford. We detail the dimensions of this space below in our methods.

Methodology

We first developed a framework detailing the potential space engineering design problems, from highly authentic to inauthentic, using the insights synthesized in our theoretical framework (Table 1); specifically, problems may or may not be relevant to students, may be strictly technical or have sociotechnical complexity, may present inaccessible or accessible entry points, and may or may not require accurate application of technical content to nondeterministic solutions.

Table 1. Framework for evaluating educative potential of design problems

Dimension	***Definition and range***	***Justification and backing***
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	Relevant and meaningful problems help students make connections between content and the world [6]
Sociotechnical complexity	The problem includes complex (multiple interrelated variables/factors) sociotechnical context. Social factors intersect in consequential ways with technical factors/variables.	Design problems are complex [7]. Sociotechnical problems reflect authentic practice and can support student learning when social factors are well integrated to technical ones [21, 22], providing a means to connect to the outside world [6]
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.	If students cannot understand the problem, they cannot engage with it. It only becomes a problem when it is accessible to them. Design problems, while presented, must be framed by the designers [8].
Nondeterministic 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.	Design problems are ill-structured and require disciplinary knowledge to be framed and solved [7], providing an opportunity for students to construct both problem frames and solutions [6]

We used this framework to qualitatively analyze a set of design problems that have been developed and used over six years in a chemical engineering undergraduate program in a Hispanic-serving research university. The program was able to provide many examples of design problems, along with data about their use and student reactions to and learning from the problems because they have been engaged in a process of threading design as a spine through core courses. A majority of the faculty lacked significant industry experience. Some of the design challenges were co-designed with graduate students who worked in industry, vetted by the department's industry advisory board, or developed with significant input from industry sponsors. Along with shifting to design-focused courses, the faculty collaborated with a learning scientist and attended workshops to develop learner-centered teaching strategies, results of which are reported elsewhere [26-31]. Over this timespan, several faculty discarded prior challenges or significantly revised their design challenges, before being pleased with the student outcomes. This set of design problems, therefore, provided a range perceived of by faculty as (in)effective. We sought to categorize these design problems using this framework as a means to provide initial validation of the framework.

We approached this work as qualitative research [32], treating the proposed framework as an analytical lens. Following a constructivist/interpretivist stance, the credibility of our work rests on our efforts to (dis)confirm our interpretations across multiple sources of data (e.g., the design brief and related assignments, student and instructor comments from field notes, audio/video recordings, student work and surveys); on our six years of collaborative engagement with the department faculty; and on our ability to provide sufficient description that readers can follow our interpretations [33]. Each researcher independently reviewed data, then we discussed and merged interpretations.

Results

We summarize design problems presented to students enrolled in first year through junior core chemical engineering courses, along with the instructors' assessment of its impacts, based on student engagement and performance. We evaluate each design problem using the proposed framework. We note if the design problem was discarded or significantly revised.

Edible Car (Discarded)

The edible car problem, according to the instructor, served as an opportunity for first year students to participate as a team on a fun design project, but it did not connect to disciplinary content. The design brief highlighted technical constraints, and no context was provided:

> …design an edible vehicle using the following constraints: No more than <u>8 inches</u> in length and no more than <u>3 kg</u> in total weight, Capable of traveling down a ramp and then along the floor as <u>far as possible</u> from the starting point (extra points, if distance is greater than <u>1.5M</u>). The vehicle must have been stored at <u>room temperature for 24 hours</u> before its demonstration. The vehicle must be capable of carrying a passenger (and maintaining him/her in an upright position throughout the travel) whose dimensions will be no larger than <u>1.5 cm radius and 8 cm in height</u>. The ramp will be about <u>5 feet</u> above the floor and situated at an angle of around <u>41</u> degrees.

While "fun," this design problem lacked meaningful connections to the students' lives [34]. The prospect of designing an edible car is accessible, requiring no advanced education to understand, and nondeterministic, demonstrated by the great variability of materials incorporated in students' designs (rice crispy treats, watermelons, uncooked pasta, gingerbread structured, etc.). Because no technical content is needed to produce a solution, we would not categorize it as reaching a high ceiling. Student learning was not assessed. While the instructor reported students appeared to enjoy the project, students complained on end-of-course surveys that it was "frivolous," "meaningless" and "silly."

Coffee maker redesign (Discarded)

This problem tasked first year students with redesigning a coffee maker. The instructor appreciated the problem because they saw connections to all aspects of chemical engineering:

> Drip coffee makers are simple and inexpensive, but the coffee that is produced is of variable quality. The purpose of this lab is to analyze a common home coffee maker as a prototypical chemical process. You will investigate optimum conditions for making coffee and find out what where your coffee maker falls short, leading to poor coffee quality. You will suggest new designs that could help overcome some of the limitations you see in the current generation of drip coffee makers.

Students tested budget coffee makers in a rushed (establish through video recordings), well-structured cookbook-style lab [34]. Students' recommendations for improvements to coffee makers were highly linked to the resources provided to students, meaning almost all students suggested pressurization, suggesting that even though such a problem could be ill-structured, the experience was highly deterministic. While a coffee pot is a familiar device, making it accessible, the instructional team reported—and video recording of the lab confirmed—many first year students found coffee unappetizing, and therefore found the problem of improving a coffee maker to be irrelevant. Although coffee may seem like a highly social product, the changes students proposed were strictly technical, as were the learning outcomes.

Antimicrobial products

The antimicrobial products problem asks students to propose an entrepreneurial application of a recently developed antimicrobial material that is highly effective:

> Prior to the 20th century, infections that we think of as being easily treatable today, such as pneumonia and dysentery, were often fatal to those infected. It is in large part due to the use of antibiotic drugs that these infections have become so little a threat to human life. In addition to drug treatment, we've also discovered the importance of surrounding ourselves with clean and disinfected surfaces to stop the spread of infectious pathogens. Paul Ehrlich, in the late 19th century was one of the first scientists to postulate that compounds might be developed that could target certain bacteria without harming other cells [1]. This idea was essential to the development of antimicrobial treatments. There are many chemicals that are effective at killing infectious cells like bacteria, but most would also damage our own cells. Today, scientists and engineers are investigating and developing a variety of materials with antimicrobial properties that are effective at killing bacteria, and that are safe to our cells. Many of these materials are polymers that can be molded and formed in numerous ways. These polymers could be incorporated into items and surfaces with which we come into contact every day, thereby reducing our contact with infectious pathogens.
>
> For this challenge, you are joining a research team that has just developed a material that is an oligomer falling into the category of oligo-phenylene ethylynenes (OPEs). This particular OPE has remarkable antimicrobial properties, has proven safe for human contact, is highly durable, and can be molded into a variety of shapes and sizes or integrated into a variety of materials. Your task is to design a product that can be made from or can utilize OPE and that can be marketed and sold by a major company.

In part because of the entrepreneurial nature, this design problem is relevant to students' lived experiences [34]. The instructors reported—and student work confirmed—a wide variety of proposed applications (e.g., toys for children's hospitals, money counters, cell phone covers, condoms, etc.), even prior to the COVID-19 pandemic, which enhanced the relevance of antimicrobial products. This also highlights the sociotechnical complexity of the problem, as students framed the problem in light of both social needs and considerations, as well as in light of technical requirements (such as biocompatibility). The problem is accessible to students, as despite the inclusion of a few technical terms, field notes over multiple years document that students were able to immediately begin brainstorming possible applications. The diversity of products proposed suggests they do not experience it as deterministic. The instructors reported—and student work confirms—a high ceiling that is not consistently reached, as some students delved deeply into the material itself, while others do not.

Acid Mine Drainage

The acid mine drainage design problem presents a case study of a disaster involving acid mine drainage and tasks first-year students with proposing prevention or emergency response water treatment systems for a specific rural community, paired with a community engagement plan. The design brief details the importance of clean water and regional challenges:

> Water is the most important resource to sustain life. Communities have relied on their local sources of water since the beginning of time. When these sources become threatened, communities can lose their sense of identity in addition to losing their way of life. Water sources in the American Southwest—already an arid environment with limited rainfall—face additional challenges.
>
> In New Mexico alone, there are 15,000 abandoned mines and only a small percent have been remediated. Water flowing through abandoned mines or tailings from mining can mix with sulfide minerals to produce acid mine drainage, polluting the already limited water in the Southwest. In August of 2015, over 3 million gallons of acid mine water from the Gold King Mine in Colorado were accidentally released into the Animas river by the Environmental Protection Agency during routine remediation activities. This river feeds into the San Juan River Basin which is one of the sole sources of water for many rural communities and the Navajo Nation [35]. The response to the incident left many who call the watershed their home feeling neglected and distrustful [36]. The Navajo Nation claimed the EPA misled the community about the extent to which the mine water was toxic [36]. They also claimed that the EPA did not accurately assess the cleanup procedures and whether or not they were successful. According to a report by the US Department of the Interior, the Gold King Mine spill was caused in part because of a lack of understanding of the "engineering complexity" of abandoned mines [35]. They warn that if teams don't include this expertise, we should expect more such disasters in the future.
>
> As chemical engineers, you can help protect one of our most valuable resources: water. Your challenge is 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.

This problem is relevant to students because it involves an incident that occurred recently (2015, with recurring issues), and affected the water supply of a population they are likely familiar with (those living in Navajo Nation) [34, 37-39]. It is accessible, yet solutions require dealing with sociotechnical complexity. Instructor comments and student work reveals that as students consider the varied stakeholders' needs, from households and farming to religious and recreational uses of water, they also evaluate the costs and effectiveness of possible solutions. The instructors report—and student work confirms—varied solution approaches, suggesting students do not experience this as a deterministic problem.

Algal biofuels

The algal biofuels design problem presents concerns about fossil fuels and tasks sophomore students with developing a proposal, including socioeconomic modeling, for growing and harvesting algae and extracting biofuel, scaled to a rural county and using available resources efficiently. The design brief reviews some of the challenges in producing biofuel:

> Biofuels represent a preferred alternative to traditional fossil fuels. Unlike fossil fuels which are net emitters of carbon, biofuels ultimately pull carbon from the atmosphere creating a carbon neutral energy source. In fact, most of the fossil fuel deposits we mine from the earth today began as algae in various water systems, so the process of deriving biofuels from algae simply allows a much more rapid jump from the carbon source to energy [40]. The process of growing, harvesting, and converting algae to fuel is also something that can be done domestically, which is strategically preferred to foreign dependence on fossil fuels. Still, with so many potential sources for biofuel, why algae? For example, corn is currently the largest source of biofuel in the US and is used to produce ethanol. But where each acre of corn can be harvested only once a year, portions of the algae grown in an acre-sized pond can be harvested every day [40].
>
> Certain species of algae can be composed of 50-70 percent oil by mass which makes it an ideal source for producing biodiesel [41]. One of the major challenges facing biofuel production from algae is being able to grow algae at a quick enough rate to make the process profitable [42]. While algae may seem to grow rapidly in a natural environment, such as a pond, the rate isn't actually sufficient enough for fuel production and is limited by the amount of nutrients that are accessible to the algae from the natural environment. A small rural community in New Mexico relies on the local dairy farms to support its economy. One of the problems with these dairy farms is they produce a large amount of wastewater. One of the ways that we can mitigate the amount of wastewater is to use it to support a large scale algal biofuel production facility, with added benefit of increased economic stability.

This problem is relevant to students because it encourages them to consider local and regional resources (e.g., local dairy farmers) and because many students are interested in sustainable fuel sources (based on surveys, video recordings, and field notes) [43-45]. The instructors report—and video data confirms—some students find the problem compelling because of the innovation potential in other commercial applications of algae. While the problem is relatively accessible, producing answers requires careful integration of sociotechnical factors, including through socioeconomic modeling, to reach a high ceiling. Students learn about many algae strains, as well as varied growth, harvest, and extraction techniques and apply what they learn to make design decisions. The sociotechnical context enhances the nondeterministic nature of the problem, as each team works with a different county and must scale and customize their ideas for the community.

Evaporative Cooling (Significantly revised)

The evaporative cooling design problem began as an unconstrained opportunity for sophomores to apply thermodynamic principles. When students struggled because of the inaccessibility of such a broad problem, instructors mentioned that evaporative cooling could be used to keep medicines cool in situations without electricity. This led to a deterministic high-ceilinged problem as almost all students used this example as their project. The initial grading rubric emphasized technical aspects, and most students did not integrate sociotechnical context into their designs. With the COVID-19 pandemic, the need to keep vaccines cool under varied situations became suddenly relevant. The instructor revised the design challenge, first providing background information on the pandemic:

> Scientists from the government, academia, and industry have combined efforts and raced to produce safe and effective vaccines to combat this pandemic. The Pfizer-BioNTech and Moderna COVID-19 vaccines are currently being distributed all over the United States. However, without a national plan for distribution, the states have been left to figure out many of the logistics individually. One challenge with the distribution of these vaccines is maintaining the thermal integrity of the vaccine. To maintain effectiveness, the vaccines must be kept within a strict temperature range during transport. Your challenge will be to design a thermodynamic system that will aid the state of New Mexico in their vaccine distribution efforts.
>
> You will need to apply the concepts of thermodynamics such as extraction of work from a system and cycles (carnot, rankine etc) in order to aid our community in a plan for vaccine transportation. You may choose **either** of the vaccines that are currently available (Pfizer-BioNTech or Moderna). In addition, you will choose one of the following scenarios for distribution: transportation from a central storage facility to hospitals throughout the state; transportation from hospitals to nearby clinics; transportation from hospitals to rural areas in New Mexico.
>
> **Note:** This design challenge is based on a current real-world problem and you are encouraged to make your design as innovative as possible. There is a potential for your work to contribute to New Mexico's current vaccine distribution efforts.

Because the idea of maintaining vaccine temperatures was a current event, the notion of applying thermodynamics to cooling became highly relevant. In this iteration, the problem is accessible, yet presents a high bar. Students must contend with both social and technical factors in proposing a solution.

Kirtland Air Force Base jet fuel spill

The Kirtland Air Force Base jet fuel spill design problem concerns a jet fuel leak that occurred over the span of several decades in the students' community. Junior students are tasked with designing solutions to mitigate the spread of the fuel to prevent it from contaminating the drinking water of the surrounding communities:

> The jet fuel spill in Albuquerque, New Mexico at Kirtland Air Force Base (KAFB) occurred in the Bulk Fuels Facility located in the northwestern part of the base. The facility operated between 1953 and 1999. Within this period, the fueling area was separated into two areas: one designated to be a tank holding area where bulk shipments of fuel were received and the other area was a fuel loading area where fuel trucks would be refilled. The Bulk Fuels Facility was no longer in service when an underground leakage of residual jet fuel was identified in 1999 due to corrosion of the underground delivery pipes [46].
>
> Research conducted between 2004 and 2007 revealed that the leaked fuel had reached the groundwater table. The leak has a tremendous effect on the surrounding community. If the groundwater were to be left untreated, ethylene dibromide (EDB), a suspected carcinogen in the jet fuel would be ingested and lead to depression, reproductive malfunctions, and fetal death. This incident is immediate and easy to connect with as a community-based problem [47].
>
> The goal of this problem is to design a way to contain, monitor, and treat the contaminated soil and water. This challenge will apply principal concepts in chemical engineering, including diffusion, fluid mechanics, advection, chemical kinetics, and separations to a real-world problem. This design problems requires the engineer's adherence to multiple constraints including legal, community, and design constraints. The engineer will have to consider specific types of permits and certifications required to build pipeline and monitoring wells throughout the city, how to design devices that will allow for water collection and sampling throughout the city without disturbing the community, and how to design a fuel delivery and storage setup that follows set parameter constraints.

Guest speakers provide an opportunity for students to understand the problem as unresolved. Students understand that clean water is a vital resource to any community, but because of the proximity of the base, the water potentially affected by the spill could be the very water feeding the drinking fountain in the hallway that students might have sipped from before class. This design problem is accessible to students, yet proposing solutions requires significant learning, both about the technical aspects of the problem as well as the social and legal issues that shape the problem [48].

Cancer detection (Discarded)

The cancer detection design problem provided an opportunity for sophomores and juniors to learn about existing technologies used in detecting cancer, including circulating tumor cells, molecular detection of cancer related DNA signatures, and metabolic imaging technology. Students were tasked with designing a system to detect atypical cells, such as lung cancer cells, using molecular diagnostics and flow cytometry. The design project involved students selecting the best detection technology from a set of potential technologies. Their goal was to detect a type of cancer using the most effective technology. The students had to report why they chose the technology they used and also why the other technologies would not be as effective.

This design problem, though relevant for many students, was not accessible for most students. It was indeed a high ceilinged problem due to its highly technical nature. Students viewed the problem as deterministic, even though the instructors considered it ill-structured. Although the problem could have been treated as sociotechnical, the difficulty of the content meant that most students had little time to consider issues that intersected with the technical concerns, even though the context might suggest a focus on social aspects of cancer detection could be critical in their success. The instructors described the course as a "train wreck" as students floundered with the highly technical information.

Discussion

We proposed that considering design problems in light of their relevance, sociotechnical complexity, and accessibility (as low-bar entry) paired with nondeterministic high ceilinged-ness could shed light on whether particular problems afforded educative experiences. We developed and applied the *educative design problem framework* to a set of design problems that have been classroom tested and evaluated to be successful or not by instructors (Table 2). That the framework differentiated these two groups suggests that it is a valid approach for characterizing prospective design problems across a range of levels. A commonplace approach for first year design courses is to include toy problems that require little technical knowledge. Our framework highlights that such problems may fail to be relevant or to engage sociotechnical complexity. Perhaps pressured by the challenges of managing instruction and grading, faculty may set deterministic outcomes. Our analysis highlights alternatives that retain the accessibility that is ideal for first year courses, while offering a relatively high and nondeterministic ceiling for students' sociotechnical explorations of problems they encounter in the world.

Table 2. Summary of design problems evaluated in terms of their success, relevance, sociotechnical complexity, low-bar entry, and nondeterministic high ceilings.

Design problem	***Considered successful by instructor***	***Relevance***	***Sociotechnical complexity***	***Low-bar entry***	***Nondeterministic high ceiling***
Edible car	No	No	No	Yes	No
Coffee maker	No	No	No	Yes	No
Antimicrobial products	Yes	Yes	Yes	Yes	Yes
Acid mine drainage	Yes	Yes	Yes	Yes	Yes
Algal biofuels	Yes	Yes	Yes	Yes	Yes
Jet fuel spill	Yes	Yes	Yes	Yes	Yes
Evaporative cooling, 1st version	No	No	No	Yes	Yes
Evaporative cooling, 2nd version	Yes	Yes	Yes	Yes	Yes
Cancer detection	No	Yes	No	No	Yes

We revisit each factor of the *educative design problem framework*. First, rather than authentic, design problems should be relevant to students' experiences. Authentic problems sometimes fall flat because they are not relevant to students. Relevance was sometimes challenging for instructors to anticipate, such as when they did not realize many first year students had little interest in coffee, and even less in making it stronger. By including undergraduate students as codevelopers of design challenges, faculty can get quicker feedback about what students find relevant.

We also note that relevance is not static, but can shift with changing current events. For instance, in a first-year introduction to chemical engineering course, one of the design problems centered on designing antimicrobial products. However, due to the shifting relationship to concepts like disease spread and high-contact areas, students in Fall 2020 saw the problem as even more relevant than those in prior semesters did. Students proposed highly practical ideas informed by their own concerns and experiences and showed a more grounded understanding of what products would be valuable. While previous cohorts were able to understand and connect with this problem, students in the most recent cohort showed a deeper understanding that led to more sophisticated products.

Second, sociotechnical context aids students in decision making as they frame problems because the constraints are endemic and understandable. Sociotechnical context, rather than a distraction, helps them understand the impact of abstract concepts. For instance, whereas prior iterations of keeping medicines cool fell flat, the pandemic version of this challenge—clearly contextualized by the sociotechnical challenge of vaccine distribution—engaged students because, in addition to being more relevant—required the integration of social and technical factors.

Third, problems that could be characterized as low-bar entry, yet high ceiling are particularly educative. Such problems meet students where they are, allow students to understand the problem and connect it to their varying interests and strengths, but also offer the opportunity for significant learning and growth.

Limitations and future directions

While our approach appears to be a valid means to evaluate the educative potential of design problems, it is important to note some key limitations of this work. First, while some of the design problems are in usage by other programs, all problems were used in the same chemical engineering program. We see no reason to expect the framework to fail to account for variability in prospective design problems in many other areas of engineering. For instance, many mechanical engineering programs engage students in SAE International's Collegiate Design Series, where students may design, for instance, a snowmobile or an all-terrain vehicle. Using the framework, we might assess such challenges as relevant because of their options (a snowmobile challenge might not be terribly relevant to our students in the desert, but the all-terrain vehicle is); as accessible because of the common experience students have with vehicles; as offering technical, but not much sociotechnical complexity, as several challenges depend heavily on technical performance; and as somewhat deterministically high-ceilinged (due to the emphasis on technical optimization). However, we acknowledge that more work in needed to establish the utility and extensibility of this framework. In particular, we anticipate that the framework may not suffice for systems design and may be of less value for fields that treat design as highly constrained.

Second, problems viewed by faculty as most successful were developed by teams of collaborating instructors, including engineering education researchers, students, and chemical engineering faculty. This certainly shaped the problems to fit the framework as the team was already steeped in research on these elements. Thus, we invite amendments and revisions to the proposed educative design problem framework to ensure it more broadly fits the range of promising design problems. We therefore encourage faculty to use this framework to evaluate and improve design problems in their teaching.

Third, our framework is mute on the topic of design instruction, which is tremendously impactful in shaping students' engagement and outcomes. We see the framework as a complementary tool in the toolbelt of faculty who teach design, and who already have many resources on design methods [10-13, 49, 50], design teaching methods [24, 51-55] and a host of contextual factors (e.g., team formation, learning contexts/modalities such as a learning studio versus lecture hall, face-to-face versus online, structural oppression/racism & poverty, pandemics) that can enhance or diminish student learning [56-63]. Future research that evaluates (un)successful design education efforts, including previously published studies, could establish a link between design problem dimensions included in our framework and student behaviors (e.g., engagement), as well as opportunities for learning content versus design methods/practices.

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