First Impressions: Engaging First-Year Undergraduates in Chemical Engineering Design

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Abstract

Many first-year students arrive in undergraduate engineering programs eager to tackle problems with technical complexity and societal relevance. Chemical engineering provides a powerful set of tools to engage with pressing challenges in energy, health care, and environmental domains. Academics, industry professionals, and educators alike emphasize the problem-based approach of collaborative, creative, transdisciplinary teamwork as the driving force of a productive engineering education. Yet, professional success in engineering requires diligent training in applied science, often in a variety of academic departments, and not necessarily including the context of engineering design. Thus, first impressions of engineering design are a critical bridge between the motivations of incoming first-years and the rigors of a complete engineering education.

In this paper, we present a 60-minute *Desktop Reactor Design* workshop designed to introduce first-year chemical engineering students to their prospective field of study. In the workshop, participants brainstormed a comprehensive set of relevant parameters for engineering a chemical reactor, designed and tested several iterations of a hands-on desktop model to optimize mixing in such a reactor, and drew conclusions from their empirical observations. Then, the learners worked in a team to prototype a reactor vessel with 3D modelling software, justifying their design choices by considering reactor volume and geometry favorable for mixing. Throughout these activities, learners were curious and engaged, thoughtfully weighing and selecting design choices, offering and debating new ideas, and raising questions to be answered throughout the rest of their chemical engineering studies.

Designing this workshop, we aimed to activate the existing knowledge, skills, and motivations of these learners as resources for building knowledge about the chemical engineering discipline and for identifying and practicing skills for creative and productive engineering design. Moreover, these learning experiences followed a cycle of reflection and action to support collaboratively building knowledge without first having to introduce significant amounts of background content. This workshop affirms the problem-based motivations of engineering students while providing relevant connections to the chemical engineering discipline, forming an essential bridge for first-year undergraduates.

Introduction

The first year of undergraduate engineering education is a unique time of transition, opportunity, and expectation for learners. Therefore, it merits intentional design of learning experiences by engineering educators. Adopting a constructivist view of learning, where new knowledge is built as new experiences lead to the restructuring of previous knowledge [1], it is worthwhile to begin by considering plausible knowledge and skill backgrounds of first-years. While high school experiences vary appreciably, it is likely a first-year student interested in a chemical engineering program is exposed to general chemistry and physics with lab and introductory calculus or pre-calculus – either during high school or concurrently with other first-year coursework. Similarly, it is likely first-year students have some experience with group work or lab partners, less experience with open-ended brainstorming, and potentially little to no experience with engineering design challenges. It is also valuable to consider the motivations of prospective engineers, who may have enjoyed and/or been successful in previous math and physical science courses, and who likely received messages that engineers are problem solvers. Chemical engineering offers a plethora of application domains – such as energy, environment, and health – which present urgent challenges and opportunities for innovation.

With this perspective, in this paper we present the *Desktop Reactor Design* workshop, a first year chemical engineering learning experience that we designed to activate the experiences (existing knowledge and skills) and motivations of learners as resources for building disciplinary knowledge and practicing skills for engineering design. We aimed to support first-year students in beginning to build the skills needed by the "engineers of 2020," some of whom graduate from undergraduate engineering programs this year [2]. According to the 2004 National Academies report, such engineers embrace "creativity, invention, and crossdisciplinary fertilization." In a world of rapidly developing technology, communication, flexibility, and motivation for lifelong learning are essential attributes for success in creative problem solving. The current "student outcomes" criterion for the accreditation of engineering programs by ABET includes similar values, such as collaborative teamwork and the problem-based context for learning engineering [3]. More recent reporting from the National Academies provides design strategies for research-based instruction: learning is built from prior knowledge, peer interaction and collaboration facilitate the construction and retention of this knowledge, and discipline-relevant problem solving promotes both collaboration and a useful organization of concepts [4].

The many diverse and important applications of chemical engineering interact with problems that transcend the boundaries of academic disciplines. An appropriate introduction to this field includes an exposure to transdisciplinary work. In subtle contrast to *interdisciplinary* work, where specific individual disciplines are selected for synchronized application, a *transdisciplinary* frame foregrounds a problem and builds a system to design a solution that naturally blurs disciplinary boundaries. As written by Jean Piaget in a 1972 essay [5], transdisciplinary work "is problem-based and so concerned with the practical applications of knowledge in the real world where issues tend to be multifaceted and call for multiple analytical perspectives." A practicing engineer is likely to find familiarity in such a description.

In addition to social, creative, and analytical skills, problem solving draws on interconnected conceptual knowledge. The graduating chemical engineer equipped for professional success has studied physics, mathematics, chemistry and biology, with particular attention to thermodynamics, transport phenomena, reaction engineering, and process control, as well as detailed technical study in sub-fields of interest. Such an education includes coursework from multiple academic departments, and not necessarily in the context of engineering design. A common side effect of this rigorous training is that different skills and knowledge which count as engineering, defined as accountable disciplinary knowledge (ADK) [6], change over the course of an undergraduate education and entry into an engineering profession. In the first years of an undergraduate engineering degree program, introductory classes often focus on textbook problems, larger lectures, and individual written exams. The ability to produce specific numerical results to written problems is therefore ADK. In later years, ADK increasingly shifts towards teamwork, communication skills, research, and collection and analysis of data. Courses become more project-based and assignments have longer timelines with more open-ended solutions. For students this shift in ADK can be a source of frustration or anxiety, as they experience a misalignment between their understandings of problem solving and the work that was expected of them [6]. However, the open-ended problem solving required of students later in their studies is more reflective of the work of a professional engineer.

Workshop Design

Workshop Goals and Overview

The 60-minute *Desktop Reactor Design* workshop detailed in this paper was conceptualized with attention to the unique first-year engineering experience. First impressions of chemical engineering are a critical bridge between the incoming motivations, skills, and knowledge of first-year undergraduates and the training required for thoroughly equipped problem-solvers. Our workshop design provides a model for collaboratively building engineering skills and conceptual knowledge without first having to introduce students to significant amounts of background content. The workshop is intentionally accessible to learners who have not yet completed introductory college-level physical science and math (e.g. general chemistry). Therefore, it fits in the first-year education of a student interested in chemical engineering, who may or may not have declared the major, and who may not have taken (even concurrently) any courses in a chemical engineering department. Demonstrated in the Results and Discussion section of this paper, the workshop activities explicitly connect learners' actions to the conceptual knowledge and skills typically developed in courses spanning a chemical engineering curriculum. Therefore, the workshop is a broad and authentic introduction to this field. While the specific activities we present here comprise a single hour-long learning experience, the ideas used to create and arrange them are general, and thus may be extended to learning experiences of different scales, such as a series of workshops, a module within a course, or semester-long course curriculum.

The workshop has five sections (Table 1). First, for ten minutes of *design parameter ideation,* learners work together to brainstorm engineering parameters they consider relevant for chemical reactors, while facilitators record and represent ideas shared aloud on a visible whiteboard. During ideation, a learner might suggest the "shape" of the vessel, and a facilitator might write this down, ask learners what reactor geometries could be used, and then draw these geometries on the board. In the next phase, learners are faced with a 20-minute, team-based *desktop model design challenge.* As a model for optimizing mixing in a chemical reactor, learners are challenged to design a recipe and protocol for the best-mixed batch of chocolate milk, choosing from a variety of ingredients, ratios, mixing tools, containers, and other parameters (all materials described in the appendix). Through the desktop model, learners justify design decisions and draw conclusions from their empirical observations. Facilitators provide further context for these observations and conclusions by briefly presenting *textbook and industry examples* related to chemical reactor design. These schematic representations and photographs of chemical reactors from educational resources and industry build connections to chemical engineering education and practice. Then, a simple *3D modelling tutorial* (more details in Results and Discussion) prepares the learners to prototype a reactor vessel with 3D modelling software (SolidWorks). For the conclusion of the workshop, learners once again work in an engineering team to tackle this

3D modelling design challenge. Learners may draw upon observations and connections from throughout the workshop to consider reactor volume and geometry favorable for mixing, and to justify these decisions.

Table 1: *Desktop Reactor Design* workshop summary with ICAP taxa and active/reflective roles

Workshop Component	ICAP Taxa	Active/Reflective Role
Design Parameter Ideation *(10 minutes)*	**Interactive:** Learners use each other's ideas as a starting place for their own suggestions. **Constructive:** Learners build on their own ideas or drawings of their ideas on the board.	**Reflective:** Learners activate past experiences in chemistry labs or draw on general background knowledge.
Desktop Model Design Challenge *(20 minutes)*	**Interactive:** Learners discuss ideas, consider the merit of one other's ideas, and test them out with the desktop model.	**Active:** Learners carry out experiments and draw conclusions based on direct observation.
Textbook and Industry Examples *(5 minutes)*	**Constructive:** Learners generate connections between their observations from the desktop model and the example reactors. **Passive:** Learners look at pictures without generating connections.	**Reflective:** These examples contextualize the hands-on experience from the design challenge.
3D Modelling Tutorial *(10 minutes)*	**Constructive:** Learners generate questions about how to perform useful operations in the software. **Active:** Learners repeat/rehearse certain useful operations. **Passive:** Learners watch and listen to the tutorial.	**Reflective:** Learners consider how the 3D modelling software could be useful to them designing a reactor vessel.
3D Modelling Design Challenge *(15 minutes)*	**Interactive:** Learners contribute to a shared product (reactor vessel) by asking questions, making suggestions, and taking turns operating the modelling software.	**Active:** Learners work together to create a 3D model.

Theoretical Frameworks for Workshop Design

Productive disciplinary engagement. The design criterion for these activities is simply stated but challenging to achieve: workshop participants gain direct experience *doing* chemical engineering design themselves. To understand when learners are "doing chemical engineering," we use the lens of productive disciplinary engagement [7]. Learners are engaged when they seek to make contributions during a task, which may be expressed by collaborating with a team, physical manipulation of materials, or eye/body alignment with the task, for example. This engagement is disciplinary when there is contact between what the engaged learners are doing and the practices of a discipline, such as engineering. For the purposes of this workshop, disciplinary engagement in engineering can include applying the practices of engineering design to transdisciplinary work. This engagement is productive when it leads to intellectual progress in a discipline's norms, such as ideation, building prototypes, collecting and assessing data, and iteration during engineering design.

ICAP. We refer to the ICAP taxonomy to inform the design of activities, components of the workshop, which promote cognitive engagement [8]. ICAP establishes a hierarchy of activity types with respect to levels of this engagement, with *interactive* activities involving dialogue the most engaging, followed by *constructive* generation of knowledge through individual reflection on or revoicing of content, *active* repetition of information verbally or through physical manipulation or verbatim notes, and *passive* receiving of information. The second column of Table 1 assigns ICAP taxa to the components of this workshop. Multiple taxa may be assigned to a given component because a given activity may include significant instances of different levels of cognitive engagement. For example, while learners brainstorm parameters for engineering a chemical reactor, they may dialogue with each other in order to ideate on specifics based on each other's suggestions. In the same activity, the same learners may also internally build on their own ideas to generate new ones, and while the former case is interactive, the latter is constructive.

Fidelity and complexity. To promote disciplinary engagement, engineering activities in the workshop follow guiding principles of fidelity and complexity [9]. Fidelity is the similarity of the training to working conditions in the field of engineering. Meanwhile, complexity is useful to promote teamwork, as a more complex activity has multiple interdependent tasks that require significant cognitive effort, so individuals must pool skills and resources to complete them. Focusing the subject matter of the workshop on chemical rector design (more granularly on mixing in chemical reactors) utilizes the synergistic character of fidelity and complexity. Reactor design synthesizes conceptual knowledge from throughout a chemical engineering education, from basic chemistry to heat and fluid transport to control systems, and a design challenge such as specifying a reactor vessel to support homogeneous mixing is a realistic task in the chemical engineering practice. Moreover, such a complex task, further complicated by the introduction of unfamiliar 3D modelling software, encourages a team of three workshop participants to work together.

Divergent and convergent thinking. An additional frame for engineering design is as a decision-making process, the interplay of divergent and convergent modes of thinking [10]. Divergent thinking involves expanding from facts into a multitude of possibilities, and convergent thinking leads to convergence of questions arising from these possibilities into new facts. Decision making in the engineering design process involves divergent thinking for ideation of potential relevant parameters and solutions, as well as convergent thinking to narrow this solution space and plan and implement a design. Convergent thinking in the classroom setting may be more familiar to first-years, as it can solve the quantitative written problems associated with the ADK at the start of an undergraduate engineering education. The beginning of this workshop, where learners are invited to generate their own ideas for parameters relevant to chemical reactor design, is an opportunity to practice divergent thinking. During the mixing desktop model, divergent thinking meets concrete examples of parameters to vary, and through experimentation with the model system, design decisions are made. Similarly, learners work in teams to use 3D modelling software to design a reactor vessel, converging design possibilities into a product to print.

Multiple cycles of reflection and action. While individual workshop components are designed to elicit productive disciplinary engagement in engineering design, these components are intentionally ordered to activate background knowledge and new experiences as the building blocks of new knowledge and skills. To this end, each component is identified with a role as either an *active* or *reflective* task, as shown in the third column of Table 1, where these roles are irrespective of ICAP taxa. In an active task, learners engage with a problem through a hands-on, concrete experience, while in a reflective task, they consider observations from experiences (such as an experiment) and existing knowledge to make predictions, draw conclusions, and build new knowledge and ideas. The first activity of the workshop is reflective, intended as a bridge between previous knowledge and experiences (such as reacting chemicals in a beaker during chemistry lab) and the content of the workshop. The desktop model design challenge is active, both an opportunity to apply the knowledge activated in the previous reflective task and a chance to generate new ideas to consider in the next reflective task. We propose this cycle of reflective and active tasks enables learners to collaboratively build knowledge and limits the need for significant technical background despite the complexity of engineering design. From this understanding, this strategy is well aligned with the goal of introducing first-year undergraduates to the chemical engineering field.

Results and Discussion

After carefully designing the workshop according to the goals and frameworks discussed above, we piloted it with three volunteer participants. In this section of the paper, we provide a narrative report on this initial workshop enactment. The facilitators were the first and second authors, and the participants were three female first-year undergraduates who had recently declared intended majors in chemical engineering at the same small private university.

Design Parameter Ideation

To begin the *Desktop Reactor Design* workshop, we prompted the learners to share what they envisioned when they heard the words "chemical reactor." The goal was to brainstorm key parameters for reactor engineering. This exercise in divergent thinking was unfamiliar for the participants, an evident mismatch with the ADK of their concurrent first-year courses, such as general chemistry. In a bid to activate past experiences, we encouraged the learners to think about reacting chemicals in a beaker during lab – essentially a scaled-down chemical reactor. Lauren volunteered that she imagined cylindrical tanks, and we invited the other learners to further describe what the tanks looked like as they all nodded in agreement. Another learner mentioned controls and valves, opening a discussion of what the valves were measuring and what was being controlled, which led to answers such as temperature, pressure, and humidity. The interactive character of this activity created a sustained period of ideation. Eventually, mixing was discussed after a facilitator's invitation to think back to what the learners did when a reaction wasn't happening as expected in chemistry lab (they usually shook the beaker a bit to mix). We recorded key words and drew representations of what the learners discussed on a whiteboard, and as they did, the learners became emboldened and more vocal in sharing ideas. In addition, we emphasized how parameters the learners introduced would become recurrent topics in future chemical engineering coursework. Figure 1 includes the whiteboard from this *design parameter ideation* section of the workshop, as well as a schematic representation of what we drew as the learners ideated. Components of the schematic in Figure 1 are labelled with important chemical engineering topics to emphasize the contact between this activity and chemical engineering education and practice.

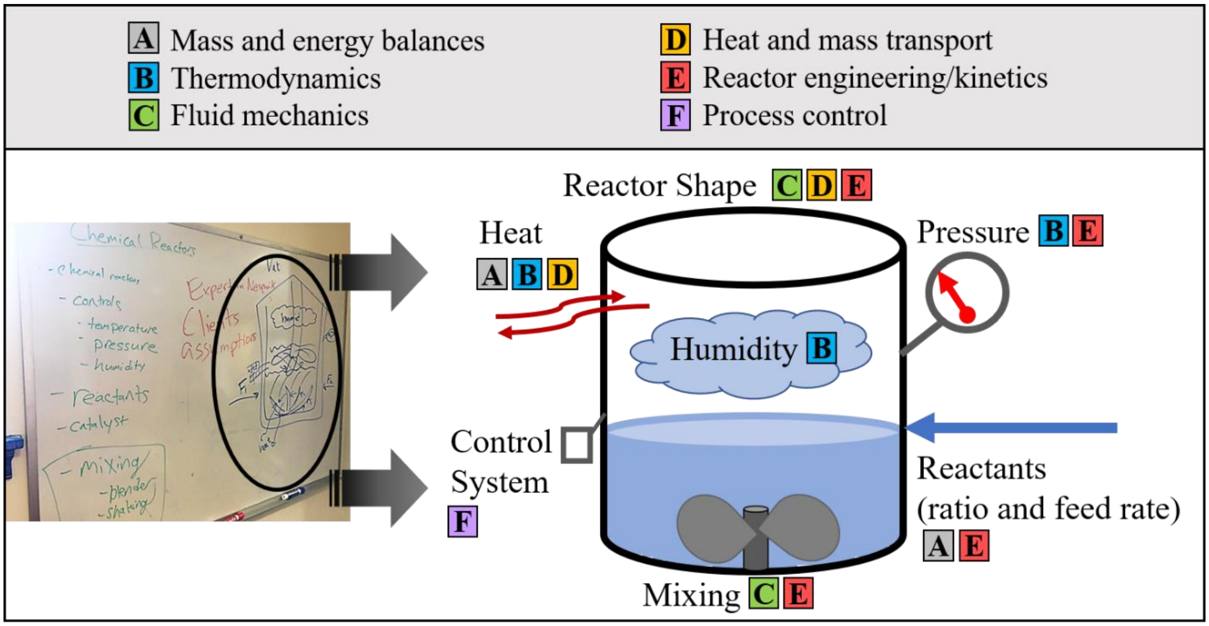

Figure 1: Schematic representation, components labeled with relevance to typical chemical engineering coursework, of the whiteboard diagram created during the *design parameter ideation* stage of the workshop

Desktop Model Design Challenge

Next, we provided the participants with a series of containers, mixing implements, milks, and chocolate flavorings and challenged to design a well-mixed, delicious cup of chocolate milk as a team (materials listed in the appendix). They were challenged to justify all design decisions and invited to experiment without immediately creating a final design. After the reflective *design parameter ideation*, the workshop was grounded in engineering practice and the participants had called their relevant background knowledge and experiences to mind. Engaging with the new active task, the participants methodically discussed how the various attributes of each parameter (vessel, milk fat content, chocolate properties, stirring tool) would impact mixing. First sustaining a divergent mode of thinking, the participants planned and carried out some simple experiments, and then observed how a tall, narrow vessel led to more difficult mixing than a wide, round bottomed container. Clara questioned precisely how to assess homogenous mixing and generated some ideas: checking the sides of the container for residue after emptying the liquid and using color to qualitatively detect chocolate concentration. Her suggestions, coupled with additional experiment, led the team to choose chocolate syrup for their design after a direct comparison with powder across different vessels.

The learners were consistently dialoguing with one another during this design challenge. They introduced ideas to consider, shared tasks such as performing experiments, and assessed results to make decisions, which are all characteristic of an interactive activity in the ICAP taxonomy. Alternating between ideating, experimenting, and making evidence-based choices, the learners demonstrated facility with convergent and divergent thinking to make engineering decisions. The multitude of parameters to vary made the activity complex despite the apparent simplicity of making a drink, and the facilitators described how the actions of the learners were connected to engineering practice as they navigated a design process. Table 2 catalogues instances of engineering decision making, providing the learners' actions and the relevant connections to chemical engineering conceptual knowledge and skills. The sum of these instances is sustained productive disciplinary engagement during the *desktop model design challenge*.

Table 2: Summary of engineering decisions made by learners during the *desktop model design challenge*

Decisions	What Learners Did	Engineering Connection
Container geometry	Hypothesized and observed a rounded bottom improved mixing; larger batches are harder to mix but create more product	Geometry impacts reactor **dead volume (E)**; batch size impacts **process time (F)**
Syrup or powder?	Observed that powder floats and clumps while syrup sinks; selected syrup	Material properties impact **transport (C, D)**
Type of milk	Kept milk constant while comparing syrup and powder; hypothesized fattier milk dissolves chocolate ("like dissolves like")	Experimental design and solubility properties from **general lab chemistry**
Mixing tool	Supposed that different mixers were best suited to different containers, selected smaller tools for smaller containers, and compared several batches	Selecting **process equipment (E, F)**
When/how to add ingredients	Questioned whether to add milk or chocolate first, and observed adding syrup gradually while mixing was effective	**Fed-batch reactor (E)**
How to measure results	Identified that color indicates chocolate concentration and residue after container emptying suggests incomplete mixing	**General lab chemistry, reactor engineering (E), engineering design:** defining and measuring success criteria
Human factors	Asked: "Who are we designing for?"	**User/client-centered design**
Team roles	Savannah identified as a chocolate powder expert; divided tasks to test different containers simultaneously; initiated discussions to make collective decisions	Teamwork is important in **capstone projects** and **professional engineering** settings
A Mass and energy balances; B Thermodynamics; C Fluid mechanics	D Heat and mass transport; E Reactor engineering/kinetics; F Process control	

Textbook and Industry Examples

The new experience of the *desktop model design challenge* opened opportunity for the construction of new knowledge, which was further realized through the next reflective task: building connections to *textbook and industry examples.* Participants were shown the images reproduced in Figure 2 and prompted to point out features relating to their ideas and observations during the workshop thus far, as well as to ask questions. All the images matched the learners' expectations and design choices related to vessels with rounded bottoms, and some also matched the expected cylindrical shape. We emphasized that not all real reactors matched the examples, but for reasons the learners identified earlier, minimizing edges in a reactor vessel is a common design choice. Learners were particularly interested in the scale of real reactors, which was an earlier point of discussion when the team considered how much chocolate milk was reasonable to make in a batch. We discussed how the impeller in Figure 2b was designed for homogenous mixing at all levels of the liquid, which had proved difficult in taller containers with the implements provided in the *desktop model design challenge.* In addition, the first-year undergraduate participants were equipped to recognize the mixing phenomena shown schematically in Figure 2d, making connections to observations from the desktop model. While this schematic is used in an upper-level undergraduate reactor design course, stagnant areas in the desktop model presented themselves when the participants used Clara's method of checking for chocolate residue on the sides and bottoms of their mixing containers.

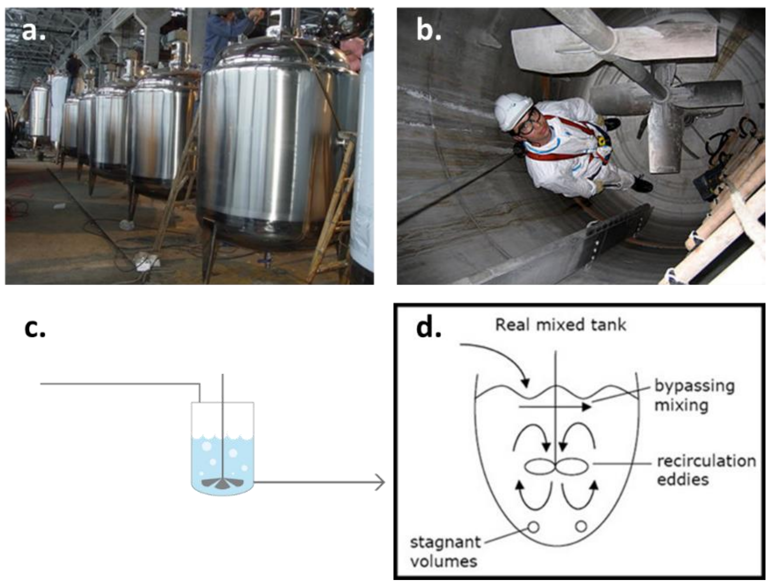

Figure 2: Images shown as *textbook and industry examples* to provide context for the first two stages of the workshop [11]

3D Modelling Tutorial and Design Challenge

The rest of the *Desktop Reactor Design* workshop utilized 3D modelling software, central to mechanical engineering curricula but rarely taught to undergraduates interested in chemical engineering. Its inclusion in the workshop has application-based motivation: workshop participants are challenged to design a reactor vessel for mixing, and the software provides the opportunity to create a 3D-printable prototype. A hypothetical follow-up workshop could use the printed prototype as a starting point for further experiment, as the next stage in an iterative design process. The application-motivated use of 3D modelling software is a consequence of the transdisciplinary perspective on engineering practice that informs the design of this workshop.

3D modelling tutorial. First, a simple tutorial provided the reflective task of connecting operations in the software with design objectives uncovered during the *desktop model design challenge*, the last active task. The format of this tutorial was an interactive demonstration. During the *3D modelling tutorial,* one facilitator invited the learners to watch what happened to a model on a computer screen as he manipulated it and described conceptually the steps he was taking to make the changes he wanted. Then, he carried out the same operations more slowly, inviting the learners to watch specific buttons and tabs in the software interface so they could operate it themselves. Instances of the tutorial were active (ICAP taxon) as learners rehearsed how to carry out individual operations with the software. Other instances were constructive, as learners generated questions about different operations related to carrying out their intentions for designing a prototype vessel. The "container" modelled for the demonstration was a very poor option to facilitate mixing, in order to not influence learner design decisions, and the tutorial did not exceed ten minutes in duration.

3D modelling design challenge. After the tutorial, the team of undergraduates took control of the software to prototype a reactor vessel in the workshop's final active task, the *3D modelling design challenge*. Learners began by discussing their desired geometry, and quickly agreed on a cylinder based on their prior observations and discussions. The three learners took turns operating the keyboard and mouse, though all three were cognitively engaged with the design process, weighing decisions as a team before making any moves in the software. With the screen at the center of the table and all three learners circling it, the computer and the 3D reactor vessel it displayed was a shared product and catalyst for interactive dialogue. Although they had become familiar with important considerations in reactor design by this point in the workshop, this design challenge maintained complexity by introducing the new software, which allowed for the quantitative specification of the prototype geometry. Moreover, the team naturally adopted the engineering decision making practices honed throughout the first active task. They debated radius to height ratios appropriate for hypothetical mixing tools, wall thicknesses required for mechanical sturdiness and temperature insulation, and how best to reduce unmixed dead volume. At the participants' request, a facilitator gave a brief additional demonstration of how to round edges, after the team decided a rounded bottom was the best option for reducing stagnant areas in the prototype vessel.

While modelling the prototype, Lauren would occasionally appear impatient with the group discussion and encourage her fellow learners to move faster to approach a finished product, a value situated in engineering school world. When she did, Maggie would offer a justification for continuing the discussion to its conclusion, such as by connecting choices about the cylinder height and radius in the software to their effects on batch size and the efficacy of different mixing tools. The theory of *figured worlds* helps to explain this tension between Lauren and Maggie: accurate and efficient completion of assignments is paramount in "engineering school world," while the design of useful products is prioritized within "engineering practice world" [12], [13]. Maggie was making bids to remain in engineering practice world, and when the other members of the team re-engaged her in discussion of parameters grounded in engineering design considerations, her bids were accepted. That the team members consistently accepted bids into engineering practice world is partially a reflection of the activity's fidelity, and evidence of sustained productive disciplinary engagement.

Learner perspectives. At the workshop's conclusion, the team had a completed, 3D-printable model for a reactor vessel they collaboratively designed. Asked to identify when they felt like they were doing engineering during the workshop, Clara and Maggie were quick to identify the *3D modelling design challenge*. Clara elaborated that the activity matched her expectations about engineering work, and Maggie described how she felt the activity was relevant to engineering practice, attesting to its fidelity. The participants were also asked what impressions of chemical engineering the *Desktop Reactor Design* workshop provided overall. Maggie emphasized the skills the workshop enabled her to use, making a connection to the skills she might use later in her studies and as a professional engineer. In referencing these skills, Maggie was thinking about the accountable disciplinary knowledge of chemical engineering, and predicting that the engineering decision making practices she used in the workshop were going to be central to her skillset as she advanced in her engineering education. Maggie, interested in getting involved in chemical engineering research as an undergraduate, also connected skills from the workshop to the disciplinary practices of engineering faculty. She recognized that engineering research is highly collaborative.

Discussion

Throughout this workshop, the team of participants worked through reflective tasks to connect previous knowledge and experiences to new ideas in chemical engineering, as well as active design challenges to directly engage with the skills of the chemical engineering practice. Meanwhile, we identified and described how the learners' actions had meaning and value in a chemical engineering context [13]. While navigating the workshop, the participants learned and used chemical engineering knowledge and skills, and as they did, their actions were affirmed as meaningful in order to welcome them into the chemical engineering community of practice [14]. While the workshop is designed to introduce participants to chemical engineering, it relies on the facilitators to help participants find belongingness in the chemical engineering discipline. Chemical engineering provides a powerful toolkit to engage with urgent and complex challenges facing humanity and the planet. Chemical engineering – and engineering broadly – also glaringly underrepresents identities other than the most privileged, in universities and professional practice, due to historic and systemic structures of power [15]. Educators are positioned to make the engineering field more inclusive by inspiring enthusiasm and confidence in students as they participate in engineering design and develop unique engineering identities. From this viewpoint of social justice, it is essential that first impressions of chemical engineering are welcoming.

We have presented this workshop model as a proof-of-concept demonstrating activity design and pedagogical strategies for introducing first-year undergraduates to chemical engineering. Since the workshop was tested with three volunteer participants (one engineering team) and two facilitators, there are limitations to this demonstration and thus, compelling research questions which remain. We identify general ideas for discipline-based, research-informed activity design with the intention that the types of activities in this workshop are scalable, both for expanding a workshop such as this for a larger group of learners, and for creating a series of workshops or sessions of an undergraduate course. Increasing the number of learners for very interactive activities could eventually cause difficulty for facilitators' tracking the progress of individuals, but a classroom with dozens of students (in engineering teams of three) could likely be managed with one facilitator per about five teams. Facilitators' identification and affirmation of learners' engineering practices is critical for creating a welcoming and informative introduction to chemical engineering, so the facilitator-to-learner ratio must allow for this. In scaling activities like those we present here, we could learn more about how learners with varied identities and backgrounds interact with engineering design and one another within the first-year chemical engineering context. While inclusion is a priority in this workshop, the volunteers for its pilot enactment consisted of a single all-female engineering team. The role of gender and other identities in first-year undergraduate engineering spaces – especially in the dynamics of engineering teams – must be the focus of ongoing work for engineering educators designing learning experiences.

Conclusion

We present an introductory chemical engineering workshop designed to activate the motivations, knowledge, and skills of first-year undergraduates as resources for constructing new disciplinary knowledge and for productively engaging in engineering design. Activities in the workshop cycle between reflective and active tasks to promote this construction of knowledge and skills.

The *Desktop Reactor Design* workshop was tested with a group of three volunteer participants, all female first-year undergraduates who recently declared intended majors in chemical engineering. First, the team of learners generated parameters relevant to reactor design in a group brainstorming activity, while we encouraged them and provided context to their ideas by drawing representations and making connections to chemical engineering practice. Then, the learners experimented with a desktop model of mixing in a reactor to make evidence-based design decisions and create a homogenous solution of chocolate milk. In a reflective task, the learners made connections between their observations from the desktop model and example images of reactors from educational resources and the engineering industry. Next, we provided a brief tutorial on 3D modelling software, outside common disciplinary boundaries of chemical engineering, but very useful for the task of creating a 3D-printable reactor vessel prototype. To conclude the workshop, the learners engaged in transdisciplinary engineering work to operate the software and specify a collaborative, quantitative reactor design.

A combination of intentional activity design, workshop structure, and affirmations of engineering practices throughout can create a compelling, rigorous, and welcoming introduction to chemical engineering. Undergraduates in the first year of their engineering education, faced with transition and opportunity, are equipped and excited to do productive engineering work. Educators who recognize and celebrate this are positioned to prepare new engineering learners to be curious problems solvers, meticulous decision makers, and confident chemical engineers.

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Appendix: Materials for the *Desktop Model Design Challenge*

Vessels: shallow bowl, large round-bottomed mug, regular cylindrical mug, kitchen measuring cup (1 cup), 8 ounce water glass, tall and narrow shot glass, rectangular plastic bin

Mixing Tools: teaspoon, tablespoon, salad fork, butter knife, chopsticks, small plastic ice cream shop tasting spoon

Milk: Half and half (dairy), 2 % milk (dairy), skim milk (dairy), almond milk

Chocolate: chocolate milk powder, chocolate syrup