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Experiences with Prototyping and Making in Virtual Classes*

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The pandemic caused people to teach classes virtually that they never imagined could be taught virtually. Hands-on classes are among the most challenging to move from in-person to virtual. In this paper, we focus on how prototyping in engineering classes was handled when those classes were taught virtually during the COVID-19 pandemic. Four engineering educators from a diverse set of four schools were engaged on this topic through written reflections and two focus groups. Learning from this experience has implications for these classes as they remain virtual and shift to hybrid and back to in-person. The four educators each found ways to make prototyping work in virtual classes. Shifting closed-ended prototyping from in-person to virtual classes was found to require less change than shifting open-ended prototyping. Within open-ended prototyping, the instructors generally narrowed scopes and took on less ambitious projects, with students engaging in new ways that produced impressive prototypes that surprised some the educators. Access to materials and tools was handled through different approaches, with curated sets of materials that maintain design freedom being important for open-ended projects while a standard set of materials for all teams worked for closed-ended projects. Students expressed more interest in doing projects individually. For those that worked on teams, approaches included having the whole team produce one prototype and having each person produce a prototype. Having each person produce their own prototype opened up the possibility that students would not truly collaborate. Even though they were all virtual, teams of students who had to make a single prototype generally worked better than expected.

Keywords: prototyping; distance learning; virtual classes; design

1. Introduction: The Pandemic Caused Design Educators to Confront How Students Could Prototype in Virtual Classes

Educators had to suddenly shift their classes online in response to the COVID-19 pandemic in 2020. This provided particular challenges to design-oriented engineering classes with hands-on prototyping. Such prototyping is frequently done by teams of students (who were no longer co-located) in facilities designed for making (which students could no longer enter) and requires access to materials, hardware, and equipment (which students can only access when in-person).

A goal of this paper is to characterize the nature of prototyping in virtual and hybrid engineering classes experienced during the pandemic. To this end, this paper focuses on addressing the following questions:

- During pandemic-caused virtual classes, how did prototyping change and how did it not?
- How did these changes create challenges for prototyping and how were those challenges addressed?
- How did these changes create opportunities to improve prototyping experiences?
- How might prototyping change once in-person classes are possible again based on the learnings gained during the pandemic?

The findings in this paper are the result of four educators from a diverse set of institutions engaging in two focus group sessions where they reflected on how the move to virtual classes impacted prototyping.

2. Context and Literature: Prototyping in Engineering Design

While some definitions of prototyping focus only

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on physical designs ("the core of the Prototype for X framework is the act of building physical prototypes" [1]) or functionality [2], most lean towards broader definitions. Ulrich and Eppinger purposefully include concept sketches, mathematical models, and implementations of an idea in their definition [3]. Otto and Wood write that a prototype is an "artifact that approximates a feature (or multiple features) of a product, service, or system" [4]. Tim Brown describes prototypes with an eye towards implementation and building, calling prototyping "the willingness to go ahead and try something by building it" [5]. Tom and David Kelley in *Creative Confidence* describe a prototype simply as an "embodiment of your idea" [6]. Kelley and Kelley use examples that extend beyond physical, functional designs such as Post-It notes to simulate user interfaces. Lauff, et al., are similarly broad in defining a prototype as "a physical or digital embodiment of critical elements of the intended design" before narrowing a bit by adding "and an iterative tool to enhance communication, enable learning, and inform decision-making at any point in the design process" [7]. They specifically include examples such as hand sketches, role playing, storyboards, CAD models and renderings, and software in addition to realizations of a design such as physical, functional prototypes.

In this paper, we align with the broader definitions of prototyping such as those by Kelley and Kelly and Lauff, et al., using the world "realizing" instead of "building" to not imply that prototypes need physically built form. The focus of prototyping is embodying or realizing an idea. This realization could be physical (e.g., a works-like prototype of a utensil, a looks-like foam prototype of a mobile phone, a hand sketched UI wireframe), digital (e.g., a software program that calculates shortest paths for a delivery system, a virtual UI wireframe, a CAD model), experiential (e.g., a "wizard of oz" prototype with physical form but whose main purpose is to represent a user experience), or some combination of these.

The literature contains many taxonomies of purposes or roles of prototyping in a class. Lauff, et al., spent ten months following prototyping in design projects at three companies in a qualitative study using "ethnographically informed" methods to develop such a taxonomy [7]. Their methods led to a codebook with three major codes representing roles of prototyping: communication, learning, and decision-making. Within learning, subcodes include learning about technical elements, user interests, the product space, and business-related aspects. They further found that the communication and learning roles generally preceded decision-making.

Menold, et al., identified five reasons students prototyped in a junior-level mechanical engineering course in the United States through qualitatively coding survey responses [1]. In decreasing frequency, students used prototypes to link, to test, to communicate, to decide, and to interact. *Link* (98 responses out of 194 subjects) refers to "modeling or visualizing an idea(s) that links the idea(s) to the final product (turns concepts into concrete models)", *test* (61 responses) is any evaluation of the design and is not limited to formal verification testing, *communicate* (22 responses) is an early simple model that helps explain a product, *interact* (10 responses) is a prototype that enables interaction with end users, and *decide* (3 responses) prototypes inform decision-making by the team. Alignment with Lauff's codes is direct for decisions, communication, and user engagement. *Link* and *test* from Menold map to Lauff's *learn about technical elements*.

In their work centered on digital user interfaces, Houde and Hill's central thesis is how a prototype is made does not matter as much as its purpose. This sentiment is summed up with the quip "Is a brick a prototype? The answer depends on how it is used" [8]. They go on to define a 3-axis triangular model with Role, Look and Feel, and Implementation as the three dimensions of prototyping purposes. A Role prototype is used to explore how a prototype is useful to and used by a user (i.e., its "role" in a user's life). A Look and Feel prototype is used to explore the sensory experience of users with a prototype. An Implementation prototype is about how a design works or functions (akin to Lauff's prototypes focused on learning about technical elements). A single prototype is rarely used for just one of these three purposes.

Design as a social process [9] sets the context for social dimensions of prototyping. Studying prototyping in engineering requires consideration of "technical coordination" between people who initiated the work, executed the work, and checked the work [10]. This social coordination is integrally linked with the technical development of a prototype. Lauff, et al, speak to using heterogenous engineering to guide their work, where heterogenous engineering is a theory that views artifacts and prototypes as "arrangements of social and material elements." We view prototyping through this lens insomuch as the social, human element of prototyping cannot be separated from the technical, material elements [11].

In all the papers cited here, prototyping was assumed to happen in one location with everyone in-person. In this paper, we explore the nature of prototyping in a virtual classroom in the context of a broad definition of prototyping. We use elements of all three taxonomies of prototyping to characterize why prototypes are used in the classes under study. Further, we are particularly interested in how being virtual affects the social aspects of prototyping.

3. Methods: Four Engineering Educators Reflected on their Experiences with Prototyping in Virtual and Hybrid Environments through two Focus Group Sessions

This work is grounded in a constructivist framework in that we focus on the words of educators as representations of how they make meaning from their experiences [12]. This framework was used in contrast to a positivist framework to embrace that we are seeking to learn about prototyping in virtual classes from experiences and that the findings represent themes and insights related to the contexts under study. The goal is not to determine a universal absolute truth.

The methods centered on assembling a group of engineering educators that represent different institutions, classes, and roles of prototyping in their classes. The four engineering educators include a public high school engineering teacher, a professor at a private women's liberal arts college, a professor at a mid-sized private polytechnic institute, and a professor at a large state university. These educators adopted the role of participant-authors for the work. One of the four served as the lead participant-author. In that role, this person created the prompts for each stage, led the focus groups, and performed the coding and theme development.

The four educators shared their insights in three distinct stages. In Stage 1, each educator submitted a written description of how prototyping is used in their classes and how that changed during the pandemic. These writings were reviewed and compared to the literature on prototyping by the lead participant-author to develop prompts to guide the following two stages. For each of the following two stages, each educator answered a series of questions and then participated in a one-hour focus group (over Zoom). During the focus groups, participants observed the answers from all four educators, reflected on those answers, and shared their insights. A typical flow was 5 minutes to read the answers for one question in silence followed by about 10–15 minutes of discussion where each person could share their insights and build on what others were saying.

For the first round of focus groups (overall Stage 2), the prompts were:

Prompt 1. Why do students prototype in your virtual classes?

Prompt 2. How are prototypes made in your virtual classes?
  - ○ What "stuff" did students use to prototype and is this different than the stuff used prior to the classes being virtual? (materials, tools, either digital or physical).
  - ○ How did students access the stuff they used?
  - ○ What stuff are students not using in virtual classes that they did use when in-person?

Prompt 3. Were your students engaged in closed-ended work or open-ended work?
  - ○ Did you change or rescope the experience?
  - ○ If students were engaged in both, did moving to virtual classes impact closed-ended work vs open-ended work differently?

For Prompt 1, respondents were shown multiple categories of purposes for prototyping and asked to map how prototypes were used in their class to those purposes. The categories, drawn from the literature cited in the Literature Review section and Stage 1 written descriptions, were:

- Prototyping to learn . . .
  - ○ about **technical things and functionality**, including prototyping to obtain proof-of-concept base functionality, improve functionality through experimentation and iteration, evaluate functionality against requirements. and learn technical skills. This category is akin to the prototyping to learn technical aspects subcode from Lauff, et al, [7].and the implementation dimension from Houde and Hill [8].
  - ○ about **users / users' needs and non-functional goals**, including prototyping to identify and clarify users' needs directly (e.g., sacrificial prototypes), to represent the user experience (e.g., storyboards), and to explore what a design might look like (e.g., industrial design prototypes). This category maps to learning about user interests from Lauff, et al. [7], both role and look & feel prototypes from Houde and Hill [8], prototyping to interact from Menold [1], and using prototypes to engage stakeholders [13].
  - ○ about **the design space and ideation**, including prototyping to generate and flesh out ideas, which links to prototyping to learn about the product space form Lauff, et al. [7].
- Prototyping to communicate . . .
  - ○ including communicating both *to* people not on your design team (to explain an idea or persuade others) and *from* people not on your design team (to solicit feedback) and *within* a team (explain an idea or negotiate a decision within a team). This relates directly to both the Lauff, et al. [7], and Menold, et al. [1], taxonomies.

One reason for prototyping emerged from Stage 1 that was not from the literature on prototyping: using prototypes to learn technical skills. For example, a student could learn about programming, kinematics, and making skills through building a prototype of a useless box that turns itself off each time a user turns it on. Or, more narrowly, some prototypes were used in a lab-like fashion to help students learn very specific topics (e.g., how to turn on an LED). While prototyping to inform decisions [7] was not part of Prompt 1, the topic surfaced during the focus group discussions in the context that students rarely use prototypes in this way. This lack of using prototypes to inform decisions aligns with the findings from Menold, et al. [1].

The second round of focus groups (overall Stage 3) used the following prompts:

Prompt 4. What do you think the role(s) are (and should be) of the physical design / maker spaces provided to students at schools?

Prompt 5. How did social interactions at a distance affect prototyping? How did prototyping affect social interactions at a distance?

- ○ How did you handle work that required more than one student to collaborate to make a single prototype (where social and technical processes were inseparable) in a virtual environment?
- ○ With respect to prototyping on teams in a virtual environment, what worked well and why? What did not work well and how do you know?
- ○ Outside of the pragmatic challenges of how multiple students can prototype together when not physically together, what other differences did you or your students notice about teamwork in a completely virtual team?

Prompt 6. Overall, what were the top three things that got better for prototyping when classes switched to virtual? What were the top three thing that got worse?

Prompt 7. What data sources did you use when responding to these prompts?

During the focus groups, the lead participant-author served as the facilitator to guide the conversation and take notes. The focus groups were recording using Zoom.

3.1 Coding and Theme Development

The lead participant-author identified themes from the of answers to the seven prompts using holistic coding in several stages. First, the audio recordings were reviewed to identify an initial list of themes and insights. This initial list was then reviewed against the notes taken at the time of the meeting. A third round of iteration involved re-reading the verbatim answers to the seven prompts to look for new themes and refine the existing list. An initial list of themes was read multiple times to identify ways to consolidate themes into the final list.

3.2 Lead Participant-Author Positionality

The lead participant-author is a male faculty member in engineering, facilitated the focus groups, led the theme development, and taught one of the classes. He has been an engineering design educator who integrates prototyping into courses for over twenty years, considering himself a proponent of active, hands-on, authentic design learning. This positions him as an "insider" as defined by Merton [14]. His view on virtual classes prior to the pandemic was negative due in large part to the sense that virtual classes lacked deep engagement between instructors and learners. Though shifting to virtual classes caused real and intense challenges for him, his overall experience with virtual classes in the pandemic was surprisingly positive. That led him to reach out to colleagues and initiate the work in this paper.

He had no prior experience with the courses from two of the other educator-authors and limited knowledge of the course from the third. Most of the other educator-authors were not familiar with each other's courses. The only exception is that one educator had previously co-taught the course currently taught by lead participant-author. The lead participant-author has worked with all three other educators previously; only one pair of educators had not met previously. While the lead participant-author constructed the themes from the data, the other three educators all reviewed the themes. Taken together, the central role of the lead participant-author in the work and his position as an "insider" to the world of engineering design education introduces drawbacks and bias into the work while also providing benefits [15].

4. Sample: The Four Educators' Classes were Diverse in Many Dimensions including how they Engaged Students with Prototyping

The educators include a public high school engineering teacher, a professor at a private women's liberal arts college, a professor at a mid-sized private polytechnic institute, and a professor at a large state university.

4.1 A Sequence of Hands-On Electromechanical Engineering Classes at a Public High School

Project-based learning and hands-on prototyping have been central to the Engineering program at this high school since its inception seven years ago. On day one of Engineering 1, students are handed LEDs, wires, resistors, and an Arduino microcontroller and tasked with making the LEDs blink. By Thanksgiving of their first year, students are taking home electromechanical projects designed in CAD and manufactured on the school's laser cutter and 3D printers. When it became clear that the school building would remain closed for at least the start of the 2020-2021 school year, the Engineering team determined that the students would still use physical hardware to create projects of their own design. To do this, students needed computer aided design software, physical electronics hardware, and access to tools such as laser cutters and 3D printers for manufacturing of mechanical hardware. Over two hundred students were enrolled in these engineering classes.

OnShape replaced Solidworks for CAD so that students could do their work at home on school-issued Chromebooks. Kits full of electronics hardware – wires, resistors, microcontrollers, sensors, LEDs, servos, LCD screens, etc. – were hand-packed for each student and either delivered to their door or picked up at the school. For manufacturing, the instructional team developed a semi-automated system where students could submit files for manufacturing which would be placed in an online queue. Teachers took turns in the CHS Engineering lab manufacturing parts and then, as soon as the parts were ready, the system generated an email to the students and their parts were placed in a lock box outside the high school for pickup.

Most classes in the engineering program consist of a series of closed-ended lab-like prototyping activities that last several weeks. The classes then transition to an open-ended project where students apply several of the specific skills they have just learned. Students can choose to work individually or with a partner on the project. If working with a partner, the pair develop a single prototype together.

4.2 An Undergraduate Sequence in Robotics Engineering at a Private Polytechnic Institute

The Robotics Engineering program is known for its project-centered curriculum. In all five core courses in the program, students work in teams to build or embody a robot with the ability to accomplish a set of prescribed tasks. Students are typically presented with theory in lectures and apply that theory in a series of labs, culminating in a final demonstration that requires application of the material from the lectures.

Approaches for moving away from fully in-person classes differed for different classes in this program. In the introductory course, roughly 45 students/term traditionally had significant design freedom to design and build a robot with many options available for the mechanical design and for which sensors to use. During the pandemic, students purchased a more limited robot kit which kept costs down but also reduced the solution space. As a result, the course focused more on technical aspects than design flexibility through a parametric design project. Intermediate courses (roughly 65 students each) were less affected by the switch as they focus more narrowly on specific technical topics. Students purchased kits that were not substantially different in functionality from the standard kit. In the final course, a ROS-based course focusing on navigation, students performed all the labs in simulation. Using robot kits and simulation, it was possible to cover the technical topics of the courses. With teamwork, students could not work side-by-side during the pandemic as they normally would, so each student on a team had their own robot on which they worked in parallel.

4.3 A Sophomore-Level Client-Based Design Course at a Private Women's Liberal Arts College

Students of all backgrounds (not just engineering) work in teams to develop a solution to a problem for an external client in the Engineering Design in the Community class. Thirteen students were enrolled in the class. Between the pandemic shifting the focus of the preselected clients and students being spread all over the country, we selected all new projects and students completed an inventory of space, equipment, and tools they had access to at home. The school also sent electronics (e.g., microcontrollers) and placed orders to local hardware stores for other materials and tools. At the end of the course, finished products were mailed to the clients and able to be used. Multiple students worked on the same project but they each made their own prototype in parallel. The projects ran smoothly although construction was limited by available space and tools. Product testing required some creativity but was possible; for example, a dog-walking assistive device was tested with a student's own dogs.

4.4 A Design-Integration Course with Real-World Projects at a State University

This junior-level design course integrates systems architecture, prototyping, design of experiments, testing, and design team collaboration. Nine engineering students from different disciplines were enrolled in the class. The goal is to get students' heads out of just designing components to see how these parts fit into whole systems. The pandemic hit at a critical juncture in class – at the start of the 6-

week final project. All projects focused specifically on systems that (1) collect data, (2) send that data to a database on a server, (3) process the data on the server, and then (4) display data online. We redesigned the project format, with students choosing from either a "Systems Realization" project that led to functional systems designed by a team of three or a "Paper Design" project where individual students could work alone as a systems architect generating detailed, but not built, designs. Critical on the Systems Realization projects were the clearly defined team roles of Hardware Designer (to whom we mailed an electronics kit), Information Engineer (using an AWS Lightsail server), and User Interaction Designer (using Figma, Tableau, and similar front-end design tools); these roles allowed teams to work remotely from each other as the interfaces between roles all occurred via the internet and/or on a remote server. Regardless of option, the challenge of the projects was in systems integration; each part alone was not intended to be difficult to design.

5. Findings and Discussion

The four educators indicated in their responses to Prompt 7 that they used a variety of data sources to inform their responses. More formal sources were documents like syllabi, project documents, student work, course evaluations, and CATME survey results. One instructor relied upon contemporaneous interviews of the students while another reviewed a recording of the final day of class where students participated in a class de-brief. Additionally, all four educators relied upon their own memories. The focus groups occurred in March 2021. Classes occurred in spring 2020, fall 2020, and some were ongoing in spring 2021.

5.1 Context

Several comparative dimensions emerged from the answers to the prompts discussed in the focus groups. Shown in Table 1, these set the context for the themes found regarding prototyping in virtual classes.

All four schools have one or more physical spaces typically used for prototyping activities when students are in-person. The spaces and their contents at the four schools vary, but all four contain relevant tools, equipment, and materials for prototyping in the classes focused on in this paper.

A key distinction in how students access materials for virtual classes was if the prototyping was for a closed-ended or open-ended project. For closed-ended projects, students were frequently using prototyping to learn new skills and every student needed the exact same materials. Thus, a standard kit of materials was prepared (or purchased) for each student who received that kit either via mail or by picking it up from school. For open-ended projects, two directions were taken. In the Robotics Program, the project was made less open-ended such that a standard set of materials could be sent to each student. At the other three schools, each student or team was working on a unique project and thus a custom kit of supplies was curated for each team.

Prototyping as a team was handled one of three ways. First, some students could work alone. At the High School, students can always choose to work on a team or alone; more students chose to work alone when classes were virtual than before (from

Table 1. Comparing the Context for Prototyping at the Four Schools

		High School	**Robotics @ Private Institute**	**Private Women's College**	**State University**
Facilities at school	**Maker/ Innovation space at school?**	Yes	Yes	Yes	Yes
Virtual Physical Material Access	**Closed-ended projects**	Unified supply kit	Unified supply kit	N/A	N/A
	Open-ended projects	Curated kit for each team, relied on things at home	Unified supply kit (and made project less open-ended)	Curated kit for each team, relied on things at home	Curated kit for each team
Handling teamwork	**Teams**	Team made one prototype together	Each student made complete prototype in parallel	Each student made complete prototype in parallel (mostly)	Team made one prototype together
	Individuals	More students took this option than in a normal year	N/A	N/A	Added this as an option
User engagement on projects	**Work with users?**	Not required. In some cases, student had an external user (e.g., a parent, friend, or pet)	Not in the first- and second-year courses	Required to have actual users involved at three points, two of those points included prototypes	Required to have users in mind; Engaged external users at start. instructor and peers acted as users to review prototypes

roughly 5% to roughly 30% of students). At the State University, students were given the choice to work alone specifically in response to the pandemic and three out of nine students took that option. Second, for those students at these two schools that worked on teams, each team was expected to collaborate on a single prototype. The third way schools handled teamwork occurred at the other two schools, where each student was expected to make a complete design in parallel.

The four schools fell at different points along a continuum regarding user engagement in the open-ended projects. User engagement was highest at the Women's College where each team had external users, they met with three times during their project: once to define needs, once to show initial ideas, and once with a final design. User testing was only possible by constraining projects to those where users were accessible by the team. User engagement was integrated slightly less into all the projects at the State University: students engaged with users to identify needs in Week 1 and, in later weeks, students made prototypes on which other students in the class gave feedback as if they were users. At the High School, students could, but did not have to, choose a project topic with a user other than themselves. Finally, in the Robotics Program, the projects did not focus on designing for an external user.

The reasons for prototyping in these classes mostly centered around technical functionality of a design: learning new technical skills, exploring if an idea can be made functional, and iterating to improve functionality. Prototyping specifically to engage or learn about users followed the continuum described in the prior paragraph, with non-functional user interface wireframes and "looks-like prototype" sketches being used heavily at the State University for this purpose. The Robotics Program traditionally uses prototyping for ideation and exploring many ideas in its first-year class. Instructors generally did not see communication as a primary purpose of prototyping in their classes outside of the already cited user engagement.

5.2 Themes

Across all four schools, instructors were able to make prototyping work in virtual classes in some cases even better than when in-person. The following themes characterize their experiences with prototyping in virtual classes. Quoted sections are from the focus groups or written responses by the four educator-authors.

Prototyping for closed-ended work was affected less by the shift to virtual classes than for open-ended projects. Closed-ended prototyping remained largely unchanged. As the High School teacher said, "I basically [read through] the closed ended assignments and said okay they're going to need this many wires, this many etc., put that in a box and that didn't really change." For the second year Robotics Program courses which were largely closed-ended, students bought kits with a pre-designed robot ("they're not starting from scratch"). In both cases, students could send CAD files for manufacturing (3D printing and/or laser cutting) and then pick up or be mailed finished parts. With all the necessary parts in hand and remote manufacturing facilitated, the closed-ended activities did not need to be changed much and prototyping could proceed much as it did for in-person classes.

All instructors agreed that their open-ended projects were affected by shifting to virtual classes. Modern making technologies have made prototyping for open-ended projects in virtual classes more possible than ever before. Multiple instructors wondered if prototyping in virtual classes would have even been possible without modern tools. The High School teacher characterized this well:

> "If this was 1980, I'm not sure how that would have worked. But there are enough online tools – Zoom, Onshape, Repl.it, Google Docs, Slack, GitHub – that I feel like it went okay. More specifically, students would meet and collaborate and brainstorm over Zoom. They would model using online CAD (Onshape) and Zoom. Then, I would make the stuff in the lab and one student would do the actual assembly. But even that usually happened over Zoom. I even had students testing hardware while distant. Both students would collaborate on code using Repl.it. One student would upload it to the physical hardware on their desk, and then hold up the result to the Zoom screen."

And the State University instructor added the role that internet-connected devices played in facilitating virtual prototyping:

> "Teams could collaborate remotely as each role interfaced with other roles primarily through a database on an AWS cloud server that they could all connect to remotely. The microcontroller connected to the internet through Wi-Fi and the Particle platform while the frontend connected directly to the server."

The instructors reported open-ended projects being affected in several ways by going virtual. More limited material/part choices and reduced scopes were shared by all four schools, each in their own unique way.

Sending a unified set (same for all teams) supply kit approach constrained projects or even narrowed the purpose of prototyping. Unified supply kits were used with closed-ended projects because they were already highly constrained. The one instance where unified kits were used for open-ended projects was the first-year course in the Robotics Program. When in-person, students were given a big range of parts to choose from and used prototyping to explore the design space and for proof-of-concept purposes. For the virtual class, every student built the same physical design and used analysis and prototyping to optimize parameters of that design. The purpose of prototyping shifted to performance improvement/optimization and was more tightly connected to analytical design. This narrower purpose of prototyping and the unified, set supply kit for all students, driven in part by an inability to send as diverse of range of materials to virtual students, worked together to change the experience students had with prototyping to be more closed-ended than when in-person.

Curated kits matched to a specific project helped maintain open-endedness but still left students with fewer options and limited-the fidelity of prototypes. The kits were curated by the instructors to match a particular project; thus, the ability to curate a kit was linked to project topics and scope. Compared to resources typically available to students during in-person classes, the curated kits did constrain and limit the options available to teams, but not minimally compared to unified kits. In most cases, the curated kits still gave the students multiple ways to achieve the functions necessary for their project. While 3D printing and laser cutting was facilitated during virtual classes at some schools, it was more common to see even lower fidelity materials like cardboard and plastic storage containers in final prototypes during virtual classes when compared to in-person classes.

Instructors scoped open-ended projects to be less ambitious and match available materials. Project scopes were designed to fit materials that could be sent or found at home. In many cases, these project scopes were narrower and less ambitious than when classes were in-person. As one instructor said, "expectations were scaled down." Highlighting reasons for narrower scopes beyond just the materials, another instructor said:

> "being virtual caused me as the instructor to say, well, I better like hem things a little bit, I better make things a little . . . fewer options, less crazy. I just want to get some work out of these kids while we are virtual . . . let's just kind of reduce the options a little bit."

While instructors were narrowing the projects, some instructors noted that for their students "it's almost the opposite." Instructors from the High School and the Women's College reported students being less constrained/more creative with prototyping. Compared to in-person classes, instructors noted that students had to "scrounge" for parts instead of being given everything, were not primed by seeing the work of prior students in the maker/innovation spaces and may have felt more empowered and welcome at home instead of in maker/innovation spaces. Something about being at home increased the creativity that students brought to projects. For the State University, the instructor saw similar levels of creativity but higher levels of functionality when classes went virtual. This could be an example of "less is more" with prototyping. While the instructors generally lamented the reduced set of materials for each student, simpler prototypes made from fewer parts have been show to lead to better designs [16].

"A lab itself has built-in biases." Some of the most robust discussion during the focus groups was about how maker/innovation spaces may unintentionally limit students . . . limits from which the students were freed with virtual classes.

> "A lab itself kind of has some like built in biases or at least kind of predetermined directions that come out of them. When you walk in my lab you go 'oh I'll be building a robot that looks like that, or like that'. When kids are home with you know nothing but like cardboard tubes and duct tape or they're looking around at like their potential customers are their cat and their fish. . . It actually opened things up in a way I didn't expect. I was trying to close things in and then I'm getting more."

Lower fidelity yet more creative prototypes from virtual classes can be compared to higher fidelity, more routine prototypes generated in maker/innovation spaces. The spaces themselves may inhibit creativity. The fact that prior work is on display in most maker/innovation spaces creates an opportunity for design fixation [17]. The instructors agree that their spaces are wonderful resources full of useful materials and equipment. Students put them to good use to make things they might never be able to without them. The flip side of that benefit was characterized well during the focus group by one of the instructors:

> "By having a maker space or an innovation space are we confining our idea of creativity to only happening in those spaces, which are sponsored by large corporations and the university?"

Which then extended to discussions about equity of inclusion and true access to those spaces among the instructors.

> "If you take a young unconfident freshman girl and show her like the maker space and there's all these machines and, honestly, there's a bunch of white upperclassmen males sitting there working, she is going to feel intimidated. [She may think] that maybe her cool idea for a slime robot isn't worthy. And that's true for a young freshman guy too."
>
> "[If students perceive that] making, creativity, engineering can only occur in this defined space, which is usually perceived as male, there might be less female interaction, or less people of color interaction there."
>
> "[If the institution is saying that maker/innovation

> spaces are] the only place you can be creative and if you don't feel welcome there, then that means you can't do [engineering]."

The instructors considered that maker/innovation spaces may limit who is even in these classes in the first place. Equitable access to university maker spaces has been identified as a potential problem in prior work. Roldan, et al., assert that "university makerspaces often fail to create an environment supportive of women" [18]. Studies have shown that fewer women use university maker spaces [19, 20] and that women use makerspaces differently than men [21, 22]. While makerspaces frequently aim to empower everyone through democratizing prototyping and innovation, seeing students in virtual classes (without access to a makerspace) generate more creative prototypes made the instructors question the nature (i.e., could makerspaces implicitly only encourage certain kinds of prototypes) and equity (i.e., could makerspaces put up barriers to certain students?) of that empowerment.

Beyond materials, tools, and spaces being different for virtual versus in-person classes, the instructors reported using prescriptive processes and more defined expectations to keep remote students progressing. This is another dimension of constraining the students – not by limited kits of materials but by process. The State University instructor spoke to prototyping becoming more prescriptive. Whereas the in-person 6-week projects used to have a one early deliverables and then only informal check-ins during class leading up to their final deliverables. the virtual class had clear weekly deliverables shared by all teams, e.g., "develop an ERD for the database and two hand drawn wireframes by Week 2 and have the database built and receiving data with a second iteration wireframe in Figma by Week 3." Further, who would do what (i.e., team roles) were more prescribed for the virtual version of the class:

> "The individuals on the teams had very specific roles. the Hardware Designer (electronics), the Information Engineer (database backend), and the Interaction Designer (front-end software). [These roles meant that each] person would work on different parts that had to be integrated . . . and could be integrated remotely."

The High School instructor has always required students to form a project plan at the start of their projects. But the in-person project plans might just be "we're gonna make a robot" and the instructor would work with the teams to define the project more along the way. When classes went virtual, he expected clearer project definition in the planning document. He was not prescribing the process more, but he was expecting the process to be more prescribed by the students. The projects at the Women's College already used a prescriptive process even when in-person.

The move towards projects with more detailed plans and clear milestones along the away aligns with practices that generally increase the quality of final designs. As Yang and Epstein reported in a study of prototyping in an advanced mechanical engineering course, "designers who meet a threshold level of time commitment (as a percentage of their overall time) and maintain that commitment are somehow linked to doing better. A participant who 'slacks off' for the first half of the project is unlikely to catch up later on" [16]. Virtual classes pose challenges to communication between students and instructors and among students; hence creating a structure that encourages students to regularly maintain their time commitment should lead to more productive prototyping.

Virtual prototypes became used more heavily and for longer in the virtual classes. Not only are virtual prototypes easier to change and iterate, but they are also easier for teams to collaborate on remotely. The High School instructor highlighted this role of virtual prototypes when he talked about how multiple students working on one prototype adapted to virtual classes: "they just kept [prototypes] virtual as long as possible, so I think a little longer [than when in-person]." Virtual prototypes came in many forms: CAD drawings for the High School projects, analytical "prototypes" of parametric design options at the Robotics Program, and wiring diagrams for microcontrollers, ERDs for databases, and wireframes for user interfaces at the State University.

While more students opted away from teams to prototype individually, the social dimension of prototyping could be maintained in a virtual class. As stated in Section 5.1, team prototyping in virtual classes was handled three different ways: (1) students could work alone, (2) students on teams each made their own prototypes in parallel, and (3) students on teams collaborated on a single prototype.

There was more demand to work alone at the two schools where this was allowed. Not only did the perceived challenges of working with a partner drive people to work alone at the high school, but it was also hard to get to know potential teammates when every class was over Zoom. Even though students were not allowed to work alone at the Robotics Program, many students were able to try to do the projects alone given that each student had the same kit.

> "[We told the students they had to] meet with the with the student assistant as a team to get sign offs. And the next day, superstar kid is there trying to get

> all of his sign offs. [I tell them] no, no, [you must] work with people."

Students gravitated to working alone despite being told messages like "this is how the real-world works." The State University instructor re-listened to the recorded final class discussion and heard the three students who chose to work alone speaking to unanticipated challenges of working alone remotely. They felt that working alone led to limited ideas and made it more difficult to get unstuck. The students also reported feeling less safe taking risks since they bore all the responsibility to execute on those riskier choices.

When each team member worked on a parallel prototype, instructors had differing experiences. In the Robotics Program, we have already established that students erred towards working alone. The instructor went on to say:

> "In general, for many groups, the collaboration was minimal or 'trivial' at best. Each student had to produce a result, but often individuals worked on things by themselves in parallel, asking only clarification questions, or one person did the work and essentially shared the solution with others. Neither represent the ideal of a team collaboration."

This contrasts with the Women's College where teammates making prototypes in parallel acted as partners. The instructor wrote "I was surprised by the initiative that the students took to meet outside of class and help each other."

Several approaches were taken to get students to all work together on the same prototype. At the High School, the quote at the top of this section that starts "If this was 1980 . . ." characterizes the collaboration well. Meetings over Zoom to do initial brainstorming and planning followed by virtual CAD prototyping (using OnShape) and coding on Repl.it. Then one student wires up the electronics and holds it up to Zoom for everyone to see if it worked or not. While the instructor said this approach worked "better than expected," he also admitted that it struggled during troubleshooting. Troubleshooting, be it between students or by an instructor, was a challenge reported by many instructors in the virtual environment. "It is easier to turn to a fellow student or ask a question of the teacher when they are in the lab. That part of the open-ended project work was diminished [in virtual classes]."

At the State University, the projects were decomposed by the instructor along interfaces that were online. The hardware engineer worked with an internet-connected microcontroller that sent data to an AWS cloud server on which the information engineer built a database that the front-end engineer connected to with visualization software. This structure did limit the range of projects that could be run, but it helped the teams focus on the main learning objective of the class: designing a system composed of integrated subsystems. The instructor, who had taught this class six times in-person, reported that

> "Decomposition of roles worked extremely well. Better than when in person. Integration became more of the highlight/focus for the 3-person teams – by having to make projects simpler and more focused around the three roles, it helped teams focus on what mattered for this class."

6. Implications and Limitations

While prototyping in in-person classes and virtual classes is fundamentally different, both can work. Instead of in-person or virtual being "better," each has trade-offs. More specifically:

For in-person classes: fully open-ended experiences are possible and can take full advantage of maker/innovation spaces' materials and tools. Students can have more opportunities for ideation (with more parts, materials, tools), have a greater chance to self-manage a less prescriptive process, make higher fidelity prototypes, and more fully embrace the messiness of design. For all their benefit, attention also needs to be paid to mitigate the drawbacks of maker/innovation spaces, with the two highlighted by the educators in this paper being that (1) such spaces may inadvertently create dependence which leads to less creativity and (2) that it takes work to make such spaces welcoming for all students.

For virtual classes: experiences benefit from fewer materials/tools and more limited, but still open-ended scopes, they provide an experience more like the real world and are freed from implicit biases of the classrooms and maker/innovation spaces. Simplifying project scopes and making processes more prescribed helps support students who never meet each other or an instructor in-person. The inability to use maker/innovation spaces at schools, while a limitation in many ways, also had unexpected benefits. Teamwork was more realistic to industry where everyone designing a product is not co-located and CAD files are sent out for manufacturing. Investing less time in making can benefit classes where the connection between manufacturing and design is a less central learning objective.

6.1 Implications for Integrating Prototyping into Virtual Classes

After being forced to teach remotely by the pandemic, we expect that prototyping in virtual classes will be more common than before the pandemic. A common message from all four educators in this paper is that prototyping in virtual classes can be effective. As with all classes, one needs to clarify the learning objectives associated with prototyping and craft experiences that support student learning in those areas. Learning specific technical skills, general familiarity with the design process, demonstrating an ability to generate ideas, integrating analysis into design, and to designing integrated systems were among the goals in the different classes in this paper. Part of this process is identifying what type of prototyping students are learning about. For example, moving to virtual for an experience focused on creating prototypes for verification testing will be different than for an experience where students create non-functional user experience prototypes aimed at immersing a user into a new system.

Within the context of a given set of learning objectives, this work highlights some key trade-offs faced by educators when designing virtual classes with prototyping.

Getting Materials to Students and Providing Access to Tools

Students will likely have a smaller set of materials and more limited access to tools for virtual classes. Curating a set of materials that maintains design freedom is important for open-ended projects while a standard set of materials or even a pre-made kit can be provided for closed-ended projects.

Open-ended vs Closed-ended Projects

Prototyping in closed-ended work were mainly used in classes where the purpose of prototyping was to learn technical skills or improve a base design (e.g., through parametric analytical or experimental design). While not seen in this paper, reverse engineering/product dissection is another example of prototyping that is largely closed-ended. Learning about prototyping for most other purposes benefits from open-ended projects. Prototyping to engage users, to immerse users in the experience of using a new design, to embody what a design might look like, and to develop proof-of-concept functionality are all examples of areas where open-ended projects are useful.

Scoping of Open-ended Projects

The educators in this paper rescoped projects for virtual classes to be more constrained and less ambitious. That said, students surprised them with more creativity and novel ideas and a scrappiness borne of having to find their own materials.

Level of Process Prescription

Connected to scoping, educators also found that giving students the guardrails of a more prescriptive process was helpful for a virtual class that involved prototyping. This ranged from requiring students themselves to prepare a detailed project plan to instructors taking the responsibility to play the role of Product Manager by defining clear and regular deliverables. There is a trade-off an educator must balance: if one goes too far with tightening the level of prescription, an open-ended project could become closed-ended; in the other direction, if one is as flexible and adaptable as in-person, students may struggle to make progress.

Social Aspects of Prototyping

While students showed more desire to work alone when prototyping in virtual classes, they also reported challenges associated with taking on projects alone. The social aspects of prototyping written about in prior literature cannot be explored without teams. For teams, the educators found different ways to support teamwork. Some had everyone on the team working on one prototype while others had each person working on their own prototype. For the former, students in one class maintained virtual prototypes longer and then collaborated on the physical design over Zoom (with only one person having the design). In another class, roles were defined along Internet interfaces such that the team members could each design a part of the system and integrate them remotely. When each person on a team made their own prototype, one educator reported challenges with students just working individually and not truly collaborating while another was surprised by how much students took initiative to help their teammates. Regardless, troubleshooting in a virtual environment was more challenging than in-person.

6.2 Implications for Prototyping in In-Person Classes

What can we learn about prototyping in virtual classes that might affect how we think about prototyping in in-person learning experiences? The educators in this paper were just beginning to think about this question and thus the implications are less well-developed. Considering the themes identified in the Findings and Discussion section, the following can be said.

Maker/innovation Spaces Come With Benefits and Liabilities

More than one educator in this paper was surprised by how shifting students out of the maker/innovation spaces to home freed them from hidden constraints of the maker/innovation spaces. Some liabilities are easy to fix (e.g., if you want students to not be limited by the work of prior students, do not display prior work in the space). Others are more complex, such as building recognition that innovation, prototyping, creativity, and design can happen in other places too and continually working to make maker/innovation spaces welcome to all.

Prototyping in maker/innovation spaces is not the right fit for every class

The State University course is a good example of where 3D printing and physical making was so time intensive when held in-person that it interfered with the core learning objective around design integration. The pandemic has given educators the opportunity to critically evaluate the learning objectives for specific classes and the possible role maker/ innovation spaces could play.

Less can be more

Depending on the learning objectives related to prototyping, giving students fewer supplies can lead to simpler prototypes and better designs for open-ended projects.

Certain classes may "return to normal" while others should hold onto some changes

Many of the classes focused on in this paper will largely return to how they were prior to the pandemic. But, for some, that is not the case. For example, the State University class would keep running projects around the three team roles. There is not a one-sized fits all for what to keep from virtual classes.

6.3 Limitations

Methodologically, the work in this paper focuses on virtual classes during Spring 2020, Fall 2020, and Spring 2021. Is what we are seeing about prototyping in a virtual class or prototyping in a pandemic? Leading virtual classes during a pandemic could be different than virtual classes during "normal" times and we have no way to isolate findings about "virtual classes" from "virtual classes in a pandemic." This work is based on using participant-authors. The four authors are the four educators in the focus group. This has benefits of the authors being deeply familiar with the experiences and classes. It also has drawbacks related to not having an external perspective to review the data and findings.

7. Conclusions

The educational experiment caused by the pandemic provided an opportunity to explore how prototyping could be integrated into virtual classes. The four educators-authors of this work each had unique experiences with this challenge. We accessed those experiences through writing reflections and discussing in two focus groups. Shifting closed-ended prototyping from in-person to virtual classes was found to require less change than shifting open-ended prototyping. Within open-ended prototyping, the instructors generally narrowed scopes and took on less ambitious projects; students went the opposite direction, showing more creativity for two classes and better functioning designs in another. In addition to general resourcefulness through needing to "scrounge" for materials, the instructors attribute some of this to limitations and biases inherent in using maker/innovation spaces at their schools. Students expressed more interest in doing projects individually in virtual classes. Perhaps the most interesting related to teamwork is that students on teams that had to make a single shared prototype worked better not only than expected but, in some cases, better than in-person. At one school, teams adapted by keeping their prototypes virtual longer and creatively used online collaboration tools. At the school where virtual teamwork worked better than in-person, the project and team roles were decomposed by the instructor along interfaces connected by the Internet; this allowed each individual to design a subsystem that could be integrated at a distance.

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