Iterating Overnight: Using Cardboard to Teach Audio During a Pandemic

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1. Introduction

Prototyping is a key competency in engineering and technology disciplines, bridging abstract and often-technical design requirements and the realization of these requirements in the physical world. While many approaches have historically been used to encourage the development of prototyping competence in engineering education, rapid fabrication techniques are increasingly available both to students and the general public as part of the "maker movement" [1,2]. However, the development of prototyping competence has been considered to be understudied [3], particularly with regard to the appropriate levels of fidelity through which a prototype might be most beneficial to problematize the design situation, allow exploration of the problem space, and facilitate iteration [4,5]. In this paper, we will describe the tensions among technologically and pragmatically different approaches to prototyping. We focus our inquiry on a traditionally in-person multidisciplinary engineering/technology lab course which was confronted with two difficulties: a building construction project that caused the lab to be relocated off of the main campus with limited fabrication equipment availability and a mid-semester shift to online-only instruction due to the COVID-19 pandemic. In the context of these two instructional tensions, we describe the outcomes of a student project to design and fabricate a functioning loudspeaker in cardboard, providing an account of the design outcomes and prototyping approaches that resulted from this shift in fabrication approach.

2. Background

In this paper, we build upon literature that relates to the development of prototyping and representational competence, the role of increased availability of fabrication tools and resources, and the use of critique practices that encourage dialogue around design choices.

Representation and Materiality in Engineering and Technology Education

The ability to represent one's ideas is considered to be a key design strategy in engineering, design, and technology work. According to Crismond and Adams' [4] informed design framework, students should be able to "mess about" with prototypes, using rapid prototyping to "explore and investigate different design ideas." These authors draw a distinction between the capacity of beginning designers, who are able to "propose superficial ideas that do not support deep inquiry" and informed designers that "use multiple representations to explore and investigate design ideas." This competence in representation aligns with prior work from Lande and Leifer [3] and Dym et al. [6] that describes the prototyping efforts of students across a range of methods and fidelities as a means of design exploration. These material forms that manifest representations link directly to ways that engineers experience design [7], and we focus particularly on how the material qualities selected by students encourage directed creative exploration [7] and a capacity for reflective practice [8]. To engage with prototyping work more deeply and precisely, we rely upon the design theory-inspired vocabulary of Lim, Tenenberg, and Stolterman [5] in our analysis, which describes prototyping approaches selected by designers as mediated by prototypes as "filters" that are realized through "manifestations" to explore and better understand the design space. This perspective on the purpose and implementation of prototypes is outlined through these three key definitions:

> <u>*Fundamental prototyping principle:*</u> *Prototyping is an activity with the purpose of creating a manifestation that, in its simplest form, filters the qualities in which designers are interested, without distorting the understanding of the whole.*
>
> <u>*Economic principle of prototyping:*</u> *The best prototype is one that, in the simplest and the most efficient way, makes the possibilities and limitations of a design idea visible and measurable.*
>
> <u>*Anatomy of prototypes:*</u> *Prototypes are filters that traverse a design space and are manifestations of design ideas that concretize and externalize conceptual ideas.*
> [5]

Fabrication Critique and Feedback

The increasing interest in hackerspaces, makerspaces, FabLabs, and other technologically-driven environments that focus on prototyping over the past decade have become increasingly connected to engineering and technology education prototyping norms. Numerous scholars have leveraged the increasing interest in makerspaces, FabLabs, and other means of encouraging access to fabrication tools as an entry point into engineering professions or a means of deepening engagement in prototyping [1,9,10]. Other scholars have specifically focused on the capacity of these environments to encourage discussion around the (often social) processes of making [11], using critique practices to provide feedback on in-progress design artifacts [12,13] and engage in social forms of sensemaking as experienced through desk and group critiques [14,15]. In this paper, we seek to describe how fabrication choices and instructor feedback impact students' exploration of the design space and final outcomes.

3. Method

We use an artifact analysis approach to describe students' engagement in prototyping work across two different semesters that straddled portions of the COVID-19 pandemic. Through analysis of these prototypes, we seek to answer the following research question: **How did students use cardboard-focused prototyping methods to create working speakers during a pandemic?**

Research Context

We focus our analysis on student project outcomes from two semesters (Spring 2020; Spring 2021) of an interdisciplinary undergraduate audio engineering course at a large Midwestern US university. In this course offering, students are required to iteratively model and build a functional loudspeaker. During the Spring 2020 semester, a temporary change in program location necessitated a shift from traditional wood fabrication techniques to cardboard fabrication. In conjunction with the emergent issues relating to the COVID-19 pandemic, this fortuitous shift in material form allowed students to continue cardboard fabrication in their own homes after courses were moved online after spring break. We characterize the outcomes of the Spring 2020 semester (n=15) in relation to the Spring 2021 course offering (n=12), which intentionally built the early student experience around cardboard rather than other materials that require access to more substantial fabrication equipment or resources. Across these two semesters, we intend to describe how students shifted in their use of physical prototypes due to the pandemic, revealing the uptakes and opportunities of a more accessible prototyping medium to continuously iterate on design ideas and produce a working physical outcome.

Data Sources and Analysis

We used a content analysis [16] approach to evaluate in-progress design artifacts from both semesters. From the Spring 2020 semester, we analyzed project reports (n=15) that included details of iterations and other design decisions alongside videos of the final loudspeaker outcomes. These reports ranged from 4 to 18 pages in length, and included a range of design process artifacts that we consider as *prototypes*, including: CAD drawings, frequency response plots, "hot glue-aggeddon" cardboard prototypes, and photos of the interior and exterior of the speakers. From the Spring 2021 semester, we analyzed Miro virtual whiteboards (n=12) that included in-progress student work from the first two months of the course. These whiteboard frames included design process artifacts that we consider as prototypes, including CAD drawings and photos of cardboard prototypes. By the conclusion of the Spring 2021 semester, these students will have fabricated their speaker in wood, and we plan to include a portion of these final artifacts in our analysis of a revision of this paper.

Table 1: Filtering Dimensions Codebook (adapted from [5])

Filtering Dimension	**Example Speaker Variables**
Appearance	sound; size; shape; form; texture; hardness; haptic; finishes
Data	data sheets: electro-acoustic variables; frequency response plots and ranges; electrical power needs; aesthetic data: geometry, proportions; surface treatments
Functionality	aesthetic appropriateness (e.g., finishes, type of room); performance parameters
Interactivity	acoustic measurement methodology; critical listening; placement in end-environment; customizability (physical or electrical)
Spatial structure	physical/3D: placement of two or more drivers within a single box + boxes in relation to each other; data + data/physical: plots in relation to each other or a physical manifestation; environmental: relation to the environment

To analyze these data, we began by operationalizing the prototyping language of Lim, Tenenberg, and Stolterman [5] as a research team to describe prototyping vocabulary in ways that were particular to speaker design. This vocabulary served as an *a priori* frame for further content analysis work. These definitions are described further in Table 1 and 2, and acted as our codebook for further content analysis. To begin the content analysis process, as a research team, we assessed five diverse examples of the 2020 reports together, identifying each distinct example of a process artifact that could be considered as a "prototype." We then collaboratively evaluated which manifestations and filters were present in each prototype in this portion of the dataset. After building full consensus through this process, one researcher coded the remaining artifacts from the 2020 reports, seeking to identify other outliers or confirm the initial analysis outcomes. This conclusive coding was then reviewed by all researchers until we researched full agreement.

4. Findings

We organize our findings by semester, describing the kinds of prototypes students used in each course section to support their final speaker outcomes. In the Spring 2020 semester, cardboard was used exclusively for physical prototyping, providing opportunities for engagement during the pandemic; in the Spring 2021 semester, cardboard was more intentionally used as part of the prototyping process in the first half of the semester, leading to iteration and modeling in wood in the latter half of the semester. We focus our attention primarily on the use of cardboard in both semesters.

Table 2: Manifestation Dimensions Codebook (adapted from [5])

Manifestation Dimension	**Definition (from** [5])	**Example Speaker Variables**
Material	Medium (either visible or invisible) used to format prototype	cardboard, wood, plastic, data sheets; tools: scissors, box cutters, saw/chisel, laser cutter, hot glue, duct tape, soldering irons, electrical test equipment, sound level meters, wood glue, CAD software, measurement software, microphones, reference loudspeakers/sources, design guides
Resolution	Level of detail or sophistication of what is manifested (corresponding to fidelity)	data-driven alignment with frequency plots; real world versus data/guide comparison; felt experience; comparing acoustic data to auditory input/experience
Scope	Range of what is covered to be manifested	System blocks/number of components: speaker + enclosure + other things; staged process of measuring speaker without anything else, leading to other components being added

Spring 2020: Cardboard and Remote Prototyping

In the 2020 semester, a shift in lab availability forced the students to engage in prototyping work without access to a woodshop. Thus, the activities in the first half of the semester were focused on a combination of cardboard prototyping and CAD modeling, alongside other forms of prototyping to assess sound quality in relation to the physical manifestation of the speaker. This use of cardboard turned out to be fortuitous given the shift to completely online instruction after spring break in the wake of the pandemic. By the week before spring break, when students were still present on campus, every student had at least had one in-person listening test with the class, but not all students had been able to make every design revision before leaving the class. These students had to rely upon and catalog the notes given for modifications at their homes—where access only to cardboard became a highly flexible medium for iteration.

Analysis of the speaker reports revealed noticeable patterns in students' iterative processes and common combinations of filters and manifestations. Every student began their report with some form of 2-D rendering of their prototype, and the majority started with sketches outlining the physical measurement of the expected speaker enclosure. While there were two examples of CAD renderings as a starting prototype, both were accompanied by supporting sketches and/or mechanical drawings outlining the aforementioned enclosure measurements. These starting prototypes mostly addressed the appearance, data, and spatial structure filtering dimensions.

2-D renderings were commonly followed by working prototypes, which consisted of a cardboard enclosure held together with a combination of tape and/or hot glue, with wires and functioning drivers. These prototypes were then tested using a variety of audio spectrum analyzer apps on their phones or personal computers to determine audio quality. Based on their first round of testing, most students made adjustments to their speaker enclosure (e.g., changing driver positioning, adding or removing drivers, adding or removing padding). Before creating a second iteration of their working prototype, students would repeat their initial process of sketching, returning to the same filtering dimensions (appearance, data, and spatial structure). The students then created a final working prototype using these newly identified and executed adjustments, testing again using the same audio spectrum analyzer. No students created a third iteration of their working prototype. In their final reflections, the majority of students expressed their satisfaction with their final prototype and often included a video recording demonstrating the speaker's sound quality. The number of iterations for student projects ranged from as many as six (P1) to as few as two (P3) prototypes.

We further describe three contrasting examples from the course, shown below in Table 3. These projects were selected to include a diversity in the overall number of prototypes, number of filtering dimensions addressed, and level of detail and intentionality included in their accompanying speaker reports.

Table 3: Prototype Filtering Dimensions Across Three Contrasting Cases.

PID	Prototype Focus	Appearance	Data	Functionality	Interactivity	Spatial Structure
P1	Sketch	●	●	○	○	●
	Mechanical Drawing	●	●	○	○	●
	Physical manifestation with drivers	●	○	●	●	●
	Sketch	●	●	○	○	●
	Mechanical Drawing	●	●	○	○	●
	Physical manifestation with drivers	●	●	●	●	●
P3	Physical manifestation with drivers	●	●	●	●	●
	Mechanical drawing	●	●	○	○	●
P14	Loudspeaker specs	●	●	●	○	○
	Sketch	●	●	○	○	●
	Physical manifestation	●	●	●	●	●
	CAD rendering	●	○	○	○	○
	Physical manifestation	●	●	●	●	●
	Physical manifestation	●	●	●	●	○

● - *engagement with filtering dimension* | ○ - *no engagement with filtering dimension*

P1 demonstrated the limitations of using cardboard as the enclosure structures as their first working prototype was deemed too large (Figure 1), causing sound issues that resulted from a large amount of empty space. Scaling down from this first version, a second round of sketching followed as the student adjusted the overall size of the prototype and "included a midrange driver in the bottom enclosure per [the instructor's] suggestion." The student adjusted the spacing between the two drivers as well, referencing a textbook *Introduction to Loudspeaker Design* [17], indicating the student made these changes through a combination of testing and research.

Figure 1: P1's first working prototype (left) versus final working prototype (right), showing adjustments to enclosure sizing and driver placements

P3 only went through one round of sketching and created only one working prototype with a physical manifestation (Figure 2). P3's round of sketching—a mechanical drawing—addressed the same filtering dimensions as all other sketches (appearance, data, spatial structure), but the enclosure itself was more compact, lessening the amount of troublesome empty space as noted in P1. The student noted how "thicker cardboard...would help with the lower end" but was "happy with the flatness of the speaker response" and considered the prototype "an absolute success." The student noted how adjustments were made to the original sketch seen above ("widening the box which allowed the [enclosure] peak to slope down") but the student did not include any iterative sketches or working prototypes images other than the two seen here.

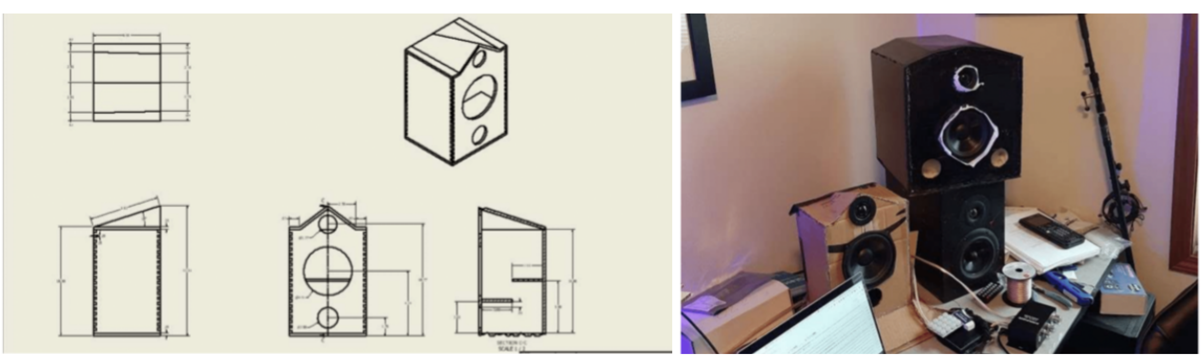

Figure 2: P3's mechanical drawing (left) and final working prototype (right), showing few iterative changes.

P14 began by analyzing driver specifications pulled from Dayton Audio. The student included notes detailing why they chose these specific drivers as well ("flat response in low end and mids" and "relatively [inexpensive]" for example). Similar to the previous two examples, the student sketched out the speaker enclosure, adding dimensions in consideration to the Dayton Audio drivers. The student noted how their projected working prototype enclosure would be "larger rather than smaller, since it's a lot easier to rim off cardboard." Moving into P14's first working prototype iteration (Figure 3), the student did not fully tape off the entirety of the enclosure, specifically the top, so "[they] could make changes as needed," recalling their previous insight about how adjustments would be necessary. The student used two separate spectrum analyzers to test this first iteration. The student noted the audio quality was acceptable, but made adjustments, including flipping tweeter polarity, adding polyfill, and iterated on their first CAD rendering. While the first CAD rendering was not included in the report, the second one included adjustments such as changing material thickness to 0.5 inches ("perfect for constructing the box from wood, and exactly equal to two layers of cardboard"), demonstrating that even though the student would not be working with wood as a material during the course, this allowed for the future possibility of doing so.

Figure 3: P14's first working prototype, with portions of the cardboard left untaped to allow for iterative changes.

Spring 2021: Back in the Studio

Artifacts from the Spring 2021 revealed many of the same iterations of prototypes as Spring 2020, with a stronger prevalence of students' use of CAD software in the early stages of the project. There was a noticeable uniformity in the appearance of the working prototypes, as students created these within the university's dedicated studio space and used the materials available there, unlike the Spring 2020 students who were forced to use household materials in response to transitioning to online learning during the pandemic. It is also likely that more students used CAD software than in the previous semester due to its availability in the lab.

Figure 4. Two examples of working cardboard prototypes from the Spring 2021 course.

As seen in the examples above, due to the availability of materials, working prototypes had a uniformity in terms of overall appearance compared to the previous Spring 2020 semester working prototypes when students "made do" with materials available in their homes, purchased at a local store, or ordered online. However, the flexibility afforded by cardboard—and realized in the Spring 2020 semester—had positive impacts on student experiences even when woodshop capabilities were available. For instance, in the Spring 2021 semester, a student had to buy a new component which delayed their progress, compounded by an inability to meet in the lab that week. Rather than the project coming to a complete halt, instead, the student was able to completely modify the front component and test it with cardboard even in the week that they weren't meeting physically in the lab.

5. Discussion

Our early analysis of artifacts and project reports—with a focus on prototypes from the Spring 2020 semester—shows students' capacity to "make do" in the face of the pandemic and a lack of traditional fabrication resources that revealed new forms of prototyping flexibility that have the potential to impact future curricula. The forced use of cardboard proved to be a fortuitous opportunity during the transition to virtual learning, which resulted in design outcomes that were substantially more complex than typical fabrication techniques, since students felt that cardboard was more approachable. In addition, students were able to make design changes inside their own residences as cardboard manipulation involves very little complex tool needs, with some of these prototypes even being generated overnight to address instructor feedback. Additionally, some of these cardboard models were later used to construct prototypes out of more typical wood materials, representing a logical transfer of design concepts across different materials.

Maker Movement + Design Theory

The promise of the maker movement has often linked rapid digital prototyping to design and engineering success, with inconsistent rationale regarding appropriate levels of fidelity to address particular design process questions. We found the forced introduction of cardboard to help us identify what cardboard is "good enough" for and what questions require more detailed forms of modeling (e.g., in wood). The shift from "we can fabricate it" as part of the maker identity to a more detailed investigation of how prototypes act as "filters that traverse a design space" [5] with intentionality and purpose may show an opportunity to enhance maker attitudes with greater precision from a design theory perspective. There are several potential connections between these spaces which illustrate future research opportunities. First, we discovered that cardboard is not appropriate for speakers of all dimensions as a *final* physical output, that there are material limits to all prototyping approaches, and that certain dimensions and iterative challenges that are better suited to other prototyping material manifestations. As the course instructor reflected on the experiences from Spring 2020, he noted: "Cardboard is a crappy acoustic mirror. [...] If [P1] had made it out of wood, it would have been amazing." The pandemic forced the students to simplify and distill their concept into what they could produce in cardboard, while future prototyping engagement could further consider what physical manifestation and combination of variables is most important to include in a given prototype, rather than modeling a prototype in wood because "they can." Second, the constraints of the pandemic revealed new ways in which the promise of making could be considered in relation to lower fidelity materials that allowed for much easier accommodation of shifts in student location. The ability to "iterate overnight" without access to lab materials presents a new way of looking at the democratization of design that relies only upon cheap, flexible materials. Third, the use of cardboard paradoxically was more difficult for some students to adapt to—with a higher capacity and comfort with higher fidelity modeling tools, even if that comfort did not always point towards competence. Thus, while prototyping in cardboard and hot glue was not a type of design engagement that was immediately comfortable to students, once students were initiated, it gave them a broader sense of how materiality and questions that one brings to prototyping might be connected: some questions can be answered simply and quickly through a mundane use of cardboard, rather than through a CAD model or wood prototype that may take much longer to produce.

Pedagogical Engagement in Prototyping

The logistical demands of shifting instructional labs and the additional challenges of the pandemic allowed us to reflect upon the role of prototyping in the curriculum and the opportunities to encourage a range of prototyping practices across different levels of fidelity. The rapid adaptation of speakers to accommodate design changes shows a potential for students to engage more deeply in the limitations of certain modeling approaches, and their relative impact on speaker performance; for instance, speakers that sound different, but look relatively similar using analytic outputs alone. This rapid iteration work could also be connected to intentional exposure of students to a wider range of speaker experiences, building their acoustic memory or *repertoire*—not only providing a vocabulary through which to label certain acoustic experiences, but also to build a body of these experiences on which they can build future knowledge. The teaching experiences from the pandemic also brought forward limitations to only virtual engagement; for instance, it is impossible to tell a "good" speaker from just a video or spectrum analysis output. This speaks to the limits of prototyping methods as they intersect instructional and critique approaches, with some speakers that the instructor found that they "couldn't tweak virtually," even though they could have done so easily in a physical setting.

6. Conclusion

In this paper, we have described how students used cardboard as a prototyping medium during the pandemic—not only "making do" given logistical constraints, but also using cardboard to rapidly iterate on design concepts using inexpensive materials. Using a content analysis approach, we identify common manifestations and filters of prototypes and evaluate places where cardboard is a useful substitute for more resource-intensive modeling methods and also identify key limitations that relate to material quality and questions that lead to the creation of a prototype. We conclude with opportunities to increase pedagogical engagement in prototyping and identify ways to connect maker identities with a more expansive approach to prototyping.

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