Creating Online Maker Education Courses Incorporating Invention Kits and Desktop Manufacturing

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The COVID-19 pandemic required the transition of a maker education course for teacher education students to an online format. A series of *Make to Learn Invention Kits* anchored the course. These kits, developed in collaboration with the Smithsonian Institution, enable students to reconstruct transformational inventions in history. Students use the foundational concepts attained in this way to create their own innovations.
Because students no longer had access to maker tools such as 3D printers, CAD files developed by students were used by instructors to fabricate components for projects. The fabricated parts were then shipped to students by mail. Students were able to complete their maker projects successfully using this adapted design cycle. Student responses to a course evaluation at the end of the semester were positive. The resources developed for the online maker education course are available to other schools of education on the *Make to Learn* website (www.maketolearn.org).

Keywords: Maker Education; Makerspace; Making; 3D Printing; Online Education; Design Thinking; Computational Thinking

INTRODUCTION

In 2005 Neil Gershenfeld published a prophetic book titled *Fab: The Coming Revolution on Your Desktop from Personal Computers to Personal Fabrication* (Gershenfeld, 2005). He predicted that in the near future the equivalent of a desktop factory would enable consumers to design and make anything in their homes. The term *desktop manufacturing* was adopted to describe use of desktop fabrication machines such as 3D printers. Affordable desktop fabrication machines fueled development of the maker movement and associated maker spaces in schools, libraries, and community centers. Makerspaces provide the technological tools used to design and build physical objects; use of the tools creates experiences that contribute to understanding of how objects work (National Academy of Sciences, Engineering, and Medicine, 2018).

Gershenfeld's book also inspired a collaboration among the School of Education and Human Development at the University of Virginia, the School of Engineering and Applied Science at Princeton University, and the Society for Information Technology and Teacher Education (SITE). The *Make to Learn* coalition was formed by these collaborators with the goal of identifying effective ways to employ school maker spaces for teaching and learning.

The pedagogical basis for this work is grounded in a framework developed by the late David Billington and Michael Littman at Princeton University (Littman, 2020). Their premise is that foundational inventions such as the telephone, the telegraph, and 19^{th}-century relays use minimal parts and, therefore, can be easily understood. Their operation is more accessible to learners than the black box of modern-day engineering systems such as cellular phones and solid-state relays (Billington & Billington, 2013).

The coalition developed a series of *Make to Learn Invention Kits* in collaboration with the Smithsonian Institution. Pivotal inventions now archived in the Smithsonian Institution – such as the telephone, the telegraph, and early electric motors – changed the course of history. *Make to Learn Invention Kits* enabled students to use school makerspaces to reconstruct these transformational inventions.

Make to Learn Invention Kits provide online resources that include the following: (1) a scanned 3D image of the invention digitized by the Smithsonian, (2) a CAD model of the invention, (3) animations that depict its operation, (4) related historical resources in the Smithsonian's collections, such as patents and descriptions from inventors' notebooks, and (5) accompanying professional development materials (Bull, Standish, Johnson, & Haj-Hariri, 2016). Students in K-12 schools not only use these online resources to reconstruct historic inventions, they also extend them to create their own original inventions.

This work formed the basis for an introductory maker education course at the University of Virginia, An Introduction to Design through Making. This course anchors a maker education strand (Bull, Garofalo, & Rutter 2018) in the education school. The course is taken by both education students and students from the college of arts and sciences. A variety of tools such as 3D printers, laser cutters, vacuform systems, and a hydraulic press in the *Make to Learn Laboratory* provide fabrication capabilities that support the course. Some of the materials and activities developed in this course have also been used in subject-specific pedagogy courses offered for teacher education students, including mathematics education, language arts, and social studies pedagogy courses for preservice teachers.

Similar tools are used to support studio courses for students at Princeton. The Princeton courses include a popular maker course for non-technical students with an average enrollment of about 100 students each year. An advanced course for Princeton engineering students enables them to use fabrication tools and microelectronics to automate a model railroad.

Table 1
Types of Maker Courses

Audience and Instructional Objectives	*Tools*
Preparation for School Maker Spaces	Foundational
Scientific Literacy and Personal Enrichment	Intermediate
Engineering Education	Advanced

The three courses share a common philosophy and goals, but differ in the levels of the tools and sophistication of the design software employed. The maker course developed in the education school, of necessity, focuses on tools and software typically found in school makerspaces. In contrast, the course tailored for engineering students makes use of computer aided engineering analysis (CAE) software with finite element modeling and animation capabilities.

Table 2
Levels of Design Software

Level	*Application*	*Time Required to Introduce*
Foundational	Tinkercad	Single Class Period
Intermediate	Fusion 360	Several Class Periods
Advanced	Solidworks	One Semester

For example, Tinkercad is the 3D design program currently used in the maker course for preservice teachers. Its capabilities are basic, but students can begin creating 3D-printed designs within a single class period. This program is freely available for use without charge. In contrast, Solidworks is a design program used by professional engineers. A single license for its use can cost hundreds of dollars.

Despite the differences in technical sophistication and cost, the underlying principles are the same. Similarly, the design principles underlying use of a $100 digital die cutter are the same as the design principles governing effective use of a $25,000 laser cutter. One fabrication tool can cut thin materials such as cardstock while the other can cut wood and plastic, but the design methods underlying their use are similar.

Activities developed in one of these courses can inspire related projects in one of the other courses. A weekly videoconference between the instructors at the University of Virginia and Princeton is used to compare, coordinate, and plan activities and projects that span courses. Therefore, when the COVID-19 pandemic required the transition of all three studio courses to an online format, the joint planning for this transition was continued. The sections that follow describe similarities and differences in the methods used, results and lessons learned, and plans for the future.

INNOVATION

Three basic methods or strategies were employed to address the transition to an online format at the midpoint of the semester.

1. *Desktop Manufacturing Systems*
   The premise of Gershenfeld's (2005) book was that affordable fabrication systems that would fit on a desktop would be available to consumers. Therefore, one approach to supporting a transition to an online format might be to transfer fabrication tools in a university makerspace to students for use in their homes. Placing fabrication tools in a common makerspace has obvious advantages. Students working together can inspire one another and assist in troubleshooting when problems arise. However, when working together in a common makerspace is no longer feasible for students, transferring tools to students for home use offers an alternative pathway.
2. *Remote Design and Fabrication*
   Some tools are too costly, complicated, or large for students to use in their homes. In some instances, safety is also an issue. For example, a hydraulic press in the *Make to Learn Laboratory* cost $2,000 and weighs several hundred pounds. In these instances, remote design and fabrication provides an alternative strategy. In this case, the student designs the component using software at home and then transmits the CAD file electronically for fabrication in the central makerspace. Once parts have been fabricated at the central location, they can be shipped to the student for assembly and testing at home.
3. *Simulation Software*
   A third option is use of a simulation. The student designs a component or circuit and then uses a simulator to troubleshoot problems. Facility with simulation software is a useful design skill because it enables students to identify and troubleshoot problems before fabricating physical components, saving time and expense. In some cases, simulation software may be the only feasible option in an online format.

All three of these strategies were implemented to various degrees in the spring 2020 semester. They are being more fully developed and expanded for the fall 2020 semester.

A typical design cycle in a maker project consists of (1) conceptualization of a design, (2) realization of the design using Computer Assisted Design (CAD) software, (3) use of the CAD files to fabricate the components using tools such as 3D printers and laser cutters, and (4) final assembly of the components and testing. In instances in which electronic components and a microcontroller such as an Arduino are used, an additional phase involving coding and circuit testing may be required.

Since in spring 2020 the students taking the course no longer had access to the fabrication tools in the school makerspace, the course instructors and staff used the CAD files created by the students to fabricate the parts for them. The fabricated parts were then shipped to the students via surface mail for assembly and testing.

RESULTS

All of the participants in the respective courses were able to complete their projects successfully using the adapted online format. Several challenges were inherent in this format, however. One challenge is the lag time introduced by the process of shipping components to students via surface mail. In the local version of the course before the pandemic, students at the University of Virginia could work through a half-dozen iterations of a laser-cut part in the course of an afternoon, as they refined the components for a project. After classes were moved online, we had students participating from as far away as Panama and South Korea. Once fabrication files were received from students, we used videoconferences to share the results of fabricated components with students and collaboratively develop revised versions if needed.

The University of Virginia developed an online survey to secure feedback from students regarding their experience taking classes in an online format. All of the students in the Maker Education course responding to the survey reported that they either *Agreed* or *Strongly Agreed* that the course had been effective in its adapted format. One student commented, "You have made this course a great experience. I have definitely enjoyed my time designing this course's projects!" Another student said, "Thank you all so much for this semester. This has been one of the most relaxing and fun classes I've taken." Based on these responses to the initial offering, it appears that a maker education course for teacher education students can successfully be offered in an online format.

The students in the online studio courses at Princeton also were successful in creating original designs and projects using the adapted online format. For example, one student developed an original project to sort coins. The final mechanism was able to sort pennies, nickels, dimes, quarters, half dollars, silver dollars, and Eisenhower dollars. Some items available on site – such as a tachometer – were not included in the components of the kit provided. The student was able to compensate by dissecting a gear-motor and extracting the direct drive portion – a DC motor when spun acts as a tachometer, producing a voltage proportional to speed – to create a sensor. All of the students created working projects of original design.

The *Make to Learn Invention Kits* used in the adapted online maker education course are hosted on a website maintained by the Society for Information Technology and Teacher Education, which can be accessed at www.maketolearn.org (Figure 1).

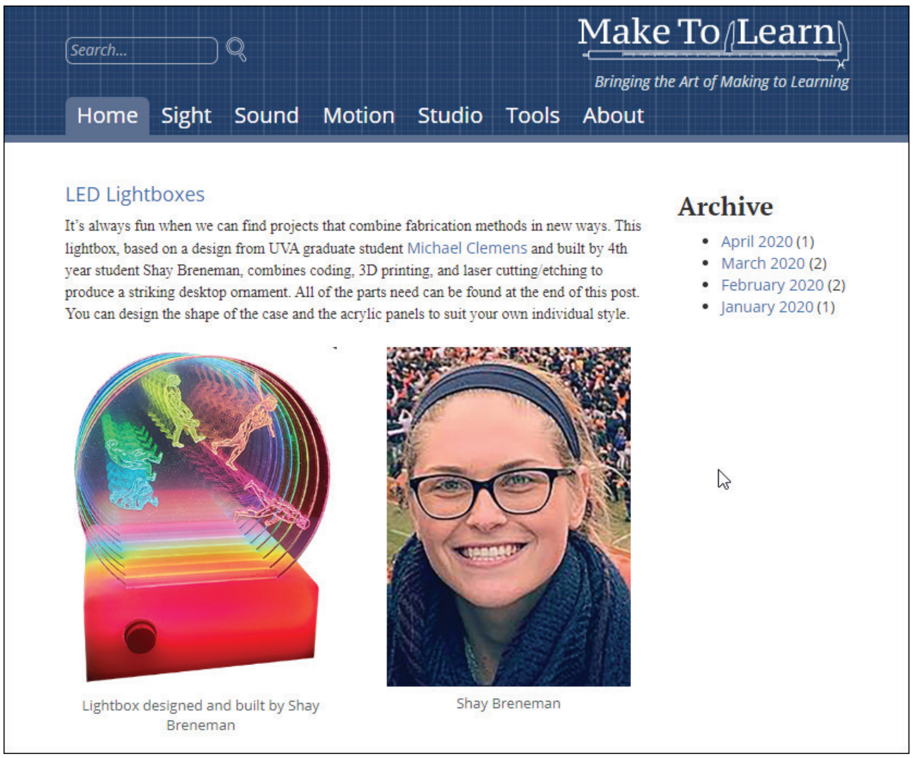

Figure 1. The Make to Learn Website (www.maketolearn.org) provides online resources.

The *Invention Kits* available on the website (Figure 2) are organized by themes that include *Sight*, *Sound*, and *Motion*. For example, the *Sound* tab includes *Invention Kits* that enable students to design and fabricate a working loud speaker or an electric guitar.

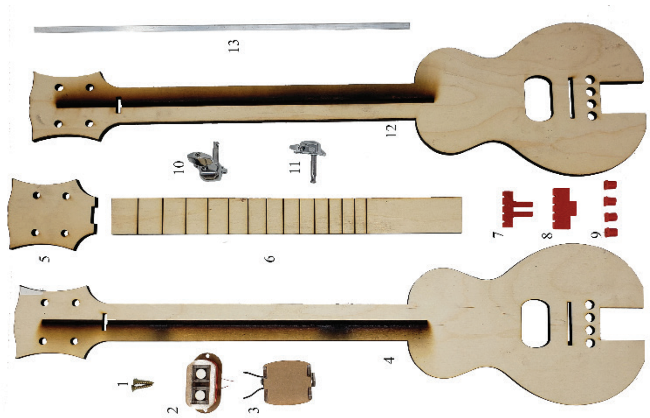

Figure 2. Each Invention Kit includes fabrication files and resources for replication of inventions.

IMPLICATIONS

The original intent underlying SITE's participation in development of Make to Learn Invention Kits was to enable students and instructors using makerspaces to access resources that were previously available only through a visit to the Smithsonian. While in an ideal environment, students would have direct access to fabrication tools such as 3D printers, much of the creative work lies in use of design software to create an original design. The adapted use of these kits demonstrates that they can also be effectively employed in an environment in which students do not have direct access to fabrication tools themselves.

At the time this is written, the University of Virginia and Princeton have not finalized the formats for fall courses. However, instructors have been asked to prepare for the possibility that courses will need to be offered in an online or hybrid format. Therefore, the instructors and staff are developing a Make to Learn Creativity Kit that will be shipped to course participants at the beginning of the course. The kit will include a Silhouette Portrait digital die cutter and a Hyperduino kit (https://hyperduino.com/starterr-kit.html) developed by Roger Wagner that includes an Arduino microcontroller and associated electronics. The combined cost of each kit is approximately $200. In this instance, the cost of the kits is being defrayed by internal seed funding. However, it may be feasible to offer the kit in place of a required text book in future iterations of the course.

Several implications can be suggested related to offering the course in this revised format in the future.

1. The course will be accessible to more diverse audiences. Until now, it has only been possible to offer the course to students who are at the university. Increasingly, students in the school of education are enrolling in online degree programs that do not require them to attend classes in person on the campus. Offering the courses in an online format will allow the full range of students enrolled in education degree programs to participate.
2. By providing an inexpensive fabrication tool in the form of a digital die cutter, students will be able to develop prototypes using materials such as cardstock and vinyl before transmitting CAD files for fabrication in materials such as plastic or metal. This approach will enable students to experience the full design cycle when developing prototypes.
3. Because students will keep the tools provided in the *Creativity Kit*, they will be able to continue using these design tools when they become employed by schools after completing their degrees.

RECOMMENDATIONS

Based on the results and outcomes of the initial online implementations, we have the following suggestions and recommendations for others who are planning online studio courses.

1. *Extend the Boost Phase*
   An engineering approach to project development consists of several phases that include (1) initiation and planning (brainstorming and preliminary design), (2) budgeting and scheduling, (3) construction and implementation, and (4) presentations and reviews of outcomes. In an online course, we have found that extending the boost phase (i.e., the initial planning and design, budget, and scheduling) can yield improved outcomes. Because of the overhead involved in remote implementation and coordination (latencies associated with shipping parts, etc., to remote sites), we found that it was productive to spend more time working with individual teams at the beginning to ensure a higher probability of success.
2. *Facilitate Teamwork through Differentiated Roles*
   The collaboration that is a serendipitous outcome of working in a shared makerspace must be explicitly scaffolded in a remote learning environment. In the next iteration of these studio courses, we are planning to provide different team members with different types of resources. For example, one member of the team will be provided with a 3D printer while another team member will be given a kit of electronics components. The team members will need to collaborate and work together to successfully complete a project. This approach is also a more parsimonious, since rather than purchasing one 3D printer for each member of the team, a single unit can be assigned to one member of the project who will assume responsibility for this aspect of the project.
3. *Collaboration with Corporate Partners*
   By its very nature, an applied maker course requires more physical resources and consumable supplies than does a theoretical course that entails use of few if any physical resources. Developing online extensions entails additional expenses and overhead associated with shipping costs and so forth. Collaboration with corporate partners cannot eliminate these additional expenses entirely, but it can reduce costs. The members of the *Make to Learn* consortium have always worked closely with corporate partners to ensure that maker resources are aligned with the needs of educators. This type of resources can become even more beneficial in the implementation of an online maker course. For example, Silhouette America has agreed to provide digital die cutters to students at wholesale cost in the next implementation of the *Design through Making* course. The cost ultimately will be about the same as the cost of a textbook, making continued implementation of this model more sustainable.
4. *Provide Bounded Spaces for Exploration*
   Students working in a physical makerspace are often encouraged to make their imaginations the only limit. Teaching an online maker course is much more intensive in terms of both staff time and physical resources. One way of making this course more feasible is to provide bounded spaces for exploration. For example, one of the Princeton courses focuses on design of model trains, while a future course planned for the University of Virginia will focus on design and fabrication of musical instruments. A bounded approach makes development of online resources such as instructional videos more feasible and increases the likelihood of student success. Students still have the flexibility to pursue a wide range of possibilities within a given theme, but constraining the range of projects in this manner allows limited resources to be more focused and in-depth in support of projects.

FUTURE RESEARCH

All of the materials and resources developed to support this work (instructional videos, interactive tutorials, CAD files, etc.) will continue to be made available to other schools and colleges of education on the *Make to Learn* website (www.maketolearn.org). This strategy offers the possibility of preservice teacher education students collaborating across universities at some point in the future.

To explore these collaborative possibilities, the *Make to Learn Creativity Kits* are being piloted with institutions in Maine and Colorado in summer 2020. Based on the results, the materials will be refined and updated before the Maker Education course is offered again in revised format at the University of Virginia in fall 2020.

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