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3D Printing and Service Learning: Accessible Open Educational Resources for Students with Visual Impairment

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Students with blindness or visual impairment face learning barriers in the typical higher education classroom where a great deal of information is conveyed visually. Instructors can use a variety of strategies to accommodate such students and make visually presented information accessible. One common and inexpensive strategy is the use of tactile graphics, which are graphics created with raised lines or bumps printed on special paper. However, due to the ways tactile information is processed, pedagogically these two-dimensional tactile graphics are not always ideal for understanding course concepts and developing mental models. We describe the benefits and logistics of a promising recent technology, 3D printing, that can benefit visually impaired students. The use of 3D printable designs shared as open educational resources can increase accessibility in the higher education classroom, even for instructors who have no interest in designing tactile learning aids themselves. The technology allows for incremental, iterative improvement and customization. For examples, we describe our experience using a 3D printed learning object in an introductory statistics course with a blind student, and we also describe our experience teaching an interdisciplinary service-learning course in which student teams worked with visually impaired individuals to design new 3D printable educational models.

The average higher education course relies heavily on visually presented information which is often inaccessible to students who are blind or visually impaired (BVI). In the classroom itself, for example, a BVI student will commonly hear an instructor refer to slides, handouts, or board work involving graphs, photos, diagrams, animations, artwork, and other visuals. Outside of the classroom these students encounter textbooks full of visuals (including subtle uses of visual information like text formatting and color usage), websites or software teaching important concepts through visualization, and so on. Without proper accommodation from instructors to make materials accessible to BVI students, these learners face significant barriers and inequality in the classroom (Bell & Silverman, 2019; Jones, Minogue, Oppewal, Cook, & Broadwell, 2006). Due in large part to these barriers, students who are BVI are less likely than their peers to attain a degree and are underrepresented in many fields like science and math (Blackorby, Chorost, Garza, & Guzman, 2003; Erickson, Lee, & von Schrader, 2016; Hasper et al., 2015).

Below we summarize many existing accommodations instructors with BVI students should consider, including converting visuals to hands-on tactile graphics when appropriate. However, considering the limitations of solutions like tactile graphics for learning some concepts, we describe the benefits of incorporating a newer technology -- three-dimensional (3D) printing -- for hands-on learning. While 3D printing may sound intimidating to many instructors, we describe how easy and affordable the technology has become (existing 3D designs can be printed from a file analogous to an inkjet printer printing from a digital file onto paper). The fact that 3D printing designs can be shared freely online as open educational resources (OER) means it can also remove cost barriers that currently limit some assistive technology for learners.

We also briefly describe our experience teaching a blind student in an introductory statistics course in which a 3D printed object (iterated with feedback from the student) was found to be very helpful for building a mental model of a central course concept and assisting during solution of some problems. We also describe our efforts to scale that process up in an innovative interdisciplinary service-learning course where student groups learned to design accessible 3D printable educational models in collaboration with BVI community members. These models can be provided for free online as OER that are ready-to-print for instructors who find themselves with BVI students in their classes. We end with a call for instructors to consider implementing similar courses or projects where students create or improve 3D printable educational models to help build a more accessible world.

Existing General Accommodations

Existing general accommodations to make learning accessible to BVI students come in many forms. For example, instructors may need to alter some of their in-class behaviors such as reducing reliance on gesture and deictics ("as you can see HERE"), verbalizing equations in unambiguous ways, describing important graphics aloud, and possibly setting up one-on-one time with BVI students outside of class (Chang, White, & Abrahamson, 1983; Quek & McNeill, 2006; Spindler, 2006). Just as important, though, is ensuring course materials and resources are accessible. We briefly survey best practices for many common accommodations here, but we would direct readers to the cited work for more detailed discussions.

First, visual impairment does not always imply blindness, and blindness does not imply a complete lack of vision. BVI students with some residual vision may use magnification devices or software, or they may require versions of materials with large font size or high contrast (this is good practice for making readable and accessible slides anyway: Richardson, Drexler, & Delparte, 2014).

Instructors can have text material translated to Braille (and specialized versions like mathematical Braille codes), usually by coordinating with the campus's educational access center or disability resources staff (if not, instructors should reach out to nearby government organizations or non-profit/advocacy organizations related to blindness, as those often have translation services). Braille translation can make textual material for things like handouts accessible, though instructors may need to plan for ample time to get materials translated. Braille versions of textbooks in many fields already exist, though they may not exist for a given book or may be for an old edition (AMAC Braille Library, 2020).

However, many – likely most – blind students are not actually fluent in Braille, so an instructor with a BVI student should communicate with the student about their needs (American Federation of the Blind, 1996). Auditory accommodations may be more essential for many students. Text-to-speech programs – commonly referred to as screen readers – allow BVI students to access electronic textbooks, text-based handouts, and properly designed websites by automatically converting to spoken language (WebAIM, 2015). Thus, for equitable access to class materials, instructors should allow BVI students to use a digital device such as a laptop or tablet even if other students in the course are barred from using such devices.

Instructors who use slides in class may want to share their slides with BVI students ahead of time where possible so that the student can follow along with a screen reader during class (e.g., with one earbud headphone in). Slides shared with students should be constructed with a layout accessible to screen readers and graphics should include alternative text ('alt text') descriptions; PowerPoint includes an Accessibility Checker tool to help with this (WebAIM, 2020). In addition, instructors should beware of using file formats that are inaccessible or poorly accessible to screen readers (PDFs, especially of scanned text, are notoriously bad, while the file formats of typical word processing programs are better).

In laboratory courses, one typical approach is to pair a BVI student with a sighted student (peer or teaching assistant); the BVI student then directs the sighted student to carry out lab tasks and describe what is happening (Pence, Workman, & Riecke, 2003; Sahin & Yorek, 2009). Of course, this may not lead to the same learning as carrying out the procedure directly, and hearing a description of, say, what is seen in a microscope may be less useful than a hands-on tactile model (Bell & Silverman, 2019; Supalo, Isaacson, & Lombardi, 2014).

Many courses utilize specialized software, and this software may range from highly accessible to completely inaccessible for BVI students; instructors may want to consider this when selecting software for their courses even if they don't currently have BVI students. For example, in the field of statistics, R is a very accessible statistical program with extensions available specifically for BVI users (Godfrey, 2013; Godfrey 2016, Godfrey 2020). Making other statistical and mathematical material (e.g., equations, formula sheets, online homework systems) accessible to BVI students may require more targeted solutions (for a general review, see Stone, Kay, & Reynolds, 2019).

Of course, most higher education courses utilize a variety of visual material which cannot be adequately translated into words and numbers; hence, screen readers and Braille may not suffice. Thankfully, tactile graphics (i.e., raised lines and bumps printed on special paper) can make many visuals accessible to the haptic modality, as described in the next section, though limitations inherent in the process mean that this won't be an ideal solution for all visuals.

Tactile Graphics and Their Limitations

Static visuals from textbooks, slides, handouts, and websites can often be converted into tactile graphics through methods such as a Braille embosser or thermal paper that creates raised lines and bumps when passed through a special printer. Many postsecondary campuses will have, or be able to easily acquire, such a printer (e.g., Pictures In A Flash is an affordable printer supplied by Humanware). Tactile graphics can certainly make some visuals accessible to haptic exploration if designed with best practices in mind, though studies have found significant errors and discrepancies when comparing textbook visuals to their tactile graphic equivalent (Braille Authority of North America and Canadian Braille Authority, 2010; Smith & Smothers, 2012).

More fundamentally, due to the limitations of tactile acuity and haptic processing, tactile graphics work best for simple visuals while complex and detailed graphics may not be easily translated to tactile form without significant adaptation (e.g., simplifying or converting to many simpler sub-components) (Edman, 1992; Quek & McNeill, 2006). One major limitation of embossed or raised-line printing is that the output is generally binary: each part of the paper is either raised or not raised. This can work well for simple line diagrams, but not for more complicated figures. Hasper and colleagues (2015) showed that adding more depth (i.e. extending the Z-plane) for a tactile graphic or raising the surface to various levels using a more 2.5-dimensional (2.5D) plastic model, allowed the tactile display of differences in shading or brightness from original images. For example, they used this to create more detailed tactile versions of spectra for an astronomy lab and skull morphology for a taxonomy lesson in biology. By comparison, raised-line versions of those same diagrams printed on thermal paper were not as durable and did not have the same level of detail. Other work has shown that adding 3D elements to tactile graphics can make them more effective. For example, blind users demonstrate better memory (fewer errors) for a tactile map when the legend symbols are 3D as compared to when they are 2D (Gual, Puyuelo, & Lloveras, 2014); Giraud, Brock, Mace, and Jouffrais (2017) likewise show the benefits of 3D printed maps over raised-line tactile graphics for BVI students.

Another reason that it may not be sufficient to simply convert pedagogical visuals to tactile graphics is that visual representations often embed cues like depth and perspective to represent three-dimensionality. While it is standard for the visual modality to convert 2D representations to 3D mental models in the brain (vision, after all, starts with a 2D projection of light on the retina, which the brain reconstructs into representing a 3D world), processing through touch does not work the same way. Objects rendered as raised lines may allow simple extraction of contour information, for example, but the conversion of 2D contours to 3D shape representation doesn't work as straightforwardly for haptic processing in the brain (Klatsky & Lederman, 2011). Experiments show that the more 3D information is restrained, the less effective haptic object recognition and understanding is (Klatsky & Lederman, 2011). Indeed, tactile graphics of familiar objects like a comb or carrot are very hard to recognize through touch (even for those with extensive visual experience and a long time to explore); the lines and spatial relations can be encoded, but not turned into object perception (Lederman, Klatsky, Chataway, & Summers, 1990; Wijntjes, Lienen, van Verstijnen, & Kappers, 2008).

Tactile Learning in the Third Dimension

In other words, tactile graphics alone won't always be sufficient for making pedagogical visuals accessible; BVI students won't necessarily be gaining the same understanding or building the same mental models as sighted students if information is presented in a format that isn't conducive to haptic understanding and learning (Jones & Broadwell, 2008). Instructors may need to find ways to represent important concepts in 3D form.

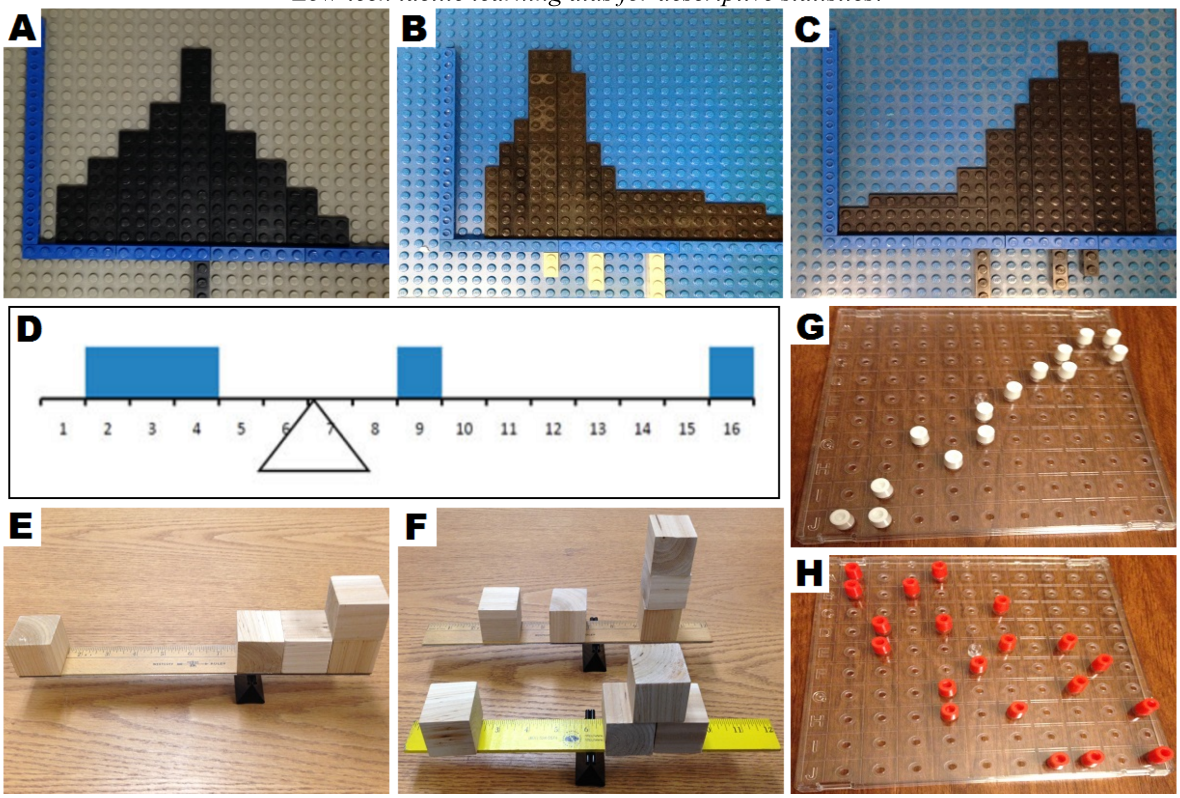
In some cases, low-tech 3D tactile models can be created from cheap, everyday materials or by repurposing existing objects like cheap children's toys (see Fig. 1 for some examples we created when teaching introductory statistical concepts to a student who was blind). For some concepts, this will be sufficient, but for many topics in higher education, a proper hands-on model for effective learning will require a custom-designed object created from scratch specifically to teach that concept. Reynaga-Pena (2015), for example, documents many custom-made, low-tech, 2.5D and 3D tactile biology models made for BVI students using fabric, paper, resin, and so on; however, many of these educational models are patented (which can imply learning objects that are accessible in a sensory but not a financial sense), and none are available outside of the institution at which they were created. On the other hand, a major benefit of 3D printed objects is that the design can be distributed freely over the internet as OER and printed any place on Earth that has a consumer-level 3D printer. In a field like chemistry, for example, commercially produced and proprietary models do exist for teaching many concepts, but (1) the existing models may be inaccessible due to relying on color and other visual elements, and (2) they cannot be easily adapted or improved by instructors. For this reason, 3D printed artifacts are starting to see wider use in chemistry to teach about molecules, proteins, crystals, and so on where a simple low-tech stick-and-ball model isn't sufficient and commercial products can't easily be iterated and improved by instructors (Rossi, Benaglia, Brenna, Porta, & Orlandi, 2015).

Benefits for BVI students

While 3D printed models can certainly help all students learn and develop mental models by presenting materials that engage more than one sensory modality (Horowitz & Shultz, 2014; Reiner, 2008), the technology is especially promising for BVI students. Powell and colleagues (2013), for example, successfully utilized 3D printed objects in conjunction with auditory resources to accommodate a blind student learning programming. Jo and colleagues (2016) used 3D printed objects and side-by-side hands-on instruction by a teacher to guide BVI students exploring 3D maps and relics in a fifth-grade history class. In that case, scaled down models allowed tactile exploration of relics otherwise too large to explore haptically (and normally presented visually in a picture); map details were expressed with different heights of plastic contours. The 3D objects had to be simplified during creation to find the optimal size and level of detail (e.g., to highlight core features), and by the end both students and teachers were highly satisfied with the convenience and learning effect of the 3D printed models.

While 3D printing can be a great tactile solution for making many higher education concepts accessible to

Figure 1
Low-tech tactile learning aids for descriptive statistics.



(A-C) LEGO histograms of symmetrical and skewed distributions marking the mean, median, and mode. (D) Common textbook visual to model the mean as a balance point (Lane, 2020). (E-F) Wooden blocks on a ruler balanced on a binder clip to demonstrate the mean as a balance point. (G-H) Battleship game pieces used to create a scatterplot with strong positive and weak negative correlation.

BVI students, it is important to understand that designing objects for tactile learning requires more than just haphazardly converting a 2D representation to a 3D object. Designing for genuine learning can require creativity and thoughtfulness, but perhaps more importantly, input and feedback from actual users (for examples of such participatory design and user-sensitive inclusive design with BVI users, see Gooda Sahib, Stockman, Tombros, & Metatla, 2013; Newell, Gregor, Morgan, Pullin, & Macaulay, 2011).

Thankfully, a benefit of 3D printing technology is that designs can easily be adjusted and iterated based on feedback or new needs, not just by the original creator, but by a community of others online. Creating and customizing 3D printed models for educational use has become surprisingly easy and affordable and thus should be considered as one useful accommodation strategy – where appropriate – for instructors of BVI students in higher education. Below we describe the technology and how to use it (whether as a designer or just printing existing designs), present a call for more designs as OER, and finally, as a model for others, we present our experience teaching an interdisciplinary service-learning course where student teams created 3D printed models in collaboration with BVI users.

Logistics of 3D Printing

3D printing is a process for manufacturing three dimensional objects by adding material layer by layer based on a digital model. A wide variety of 3D printing technologies exist today, ranging from laser sintering (using a high-power laser to fuse a powdered material into the desired shape) to stereolithography (using ultraviolet light to selectively solidify layers of a photopolymer resin) (Griffey, 2012; Melchels, Feijen, & Grijpma, 2010). The most accessible form of 3D printing available commercially at low cost is fused deposition modeling (FDM; also known as fused filament fabrication) which deposits melted thermoplastics through an extruder nozzle that moves horizontally and vertically within the build space to lay down thin cross-sectional layers of the object one at a time. The digital model of the object to be printed is typically stored as an .stl file (from stereolithography). The model itself can be created in a variety of software programs, many of them free to use while others may be free or discounted for faculty and students or offer an affordable institutional license (McGahern, Bosch, & Poli, 2015). Overall, the cost of FDM-style 3D printers has dropped dramatically in recent years, bringing the technology within reach of hobbyist communities while simultaneously becoming commonplace in public libraries and the libraries of educational institutions (Scalfani & Sahib, 2013). For the purposes of this article, we will focus on FDM-style 3D printing.

Learning to use 3D design software may seem like an imposing task to handle alone, even with the extensive support and tutorials of online hobbyist communities. Thankfully, as 3D printing widely comes to the libraries of educational institutions, the library itself can provide support for instructors or their students learning to design and print 3D objects. As cost has come down and libraries integrate the technology, 3D printing on college campuses has moved from gated access (often only available to students and faculty in selected departments like engineering) to general access for all. "A library can provide a central point of access and support for 3D printing for students and faculty across disciplines and programs beyond engineering and technology" (Van Epps, Huston, Sherrill, Alvar, & Bowen, 2015, p. 16). For example, Scalfani and Sahib (2013) report success implementing a 3D printing studio into a campus library; they describe a two-step training procedure where librarians assist students and faculty in learning the basics of 3D printing, after which users can experiment independently in an open access environment (see Groenendyk and Gallant, 2013 for another example of successfully integrating a 3D printing space in a university library).

Makerspaces: A Case Study in Collaborative Design

That said, librarians are not the only resources for instructors learning to 3D print; many campus libraries have formed active and exciting makerspaces (sometimes called maker labs). A makerspace is "a place where people come together to create and collaborate, to share resources, knowledge, and stuff. Maker spaces […] evolved from a desire to understand, tinker, remake, and share" (Britton, 2012a, p. 30). In other words, it is a collaborative community space where anyone can be a creator as well as a consumer, a space that encourages an informal or even play-like atmosphere for learning (Britton, 2012b). The culture around makerspaces (often considered a marriage of do-it-yourself culture and hacker culture) places a high value not only on collaboratively learning and using practical skills, but also on sharing, remixing, and in general on free, open access to tools and knowledge (Forest et al., 2014; Lakhani and Wolf, 2005). Public libraries have been integral in bringing 3D printing to communities as part of makerspaces. While many post-secondary libraries have started to follow suit in terms of bringing 3D printing to the campus community (Scalfani & Sahib, 2013), we think the most promising model will incorporate the technology into a makerspace (perhaps within a library) where members of the campus community can support each other in learning 3D printing.

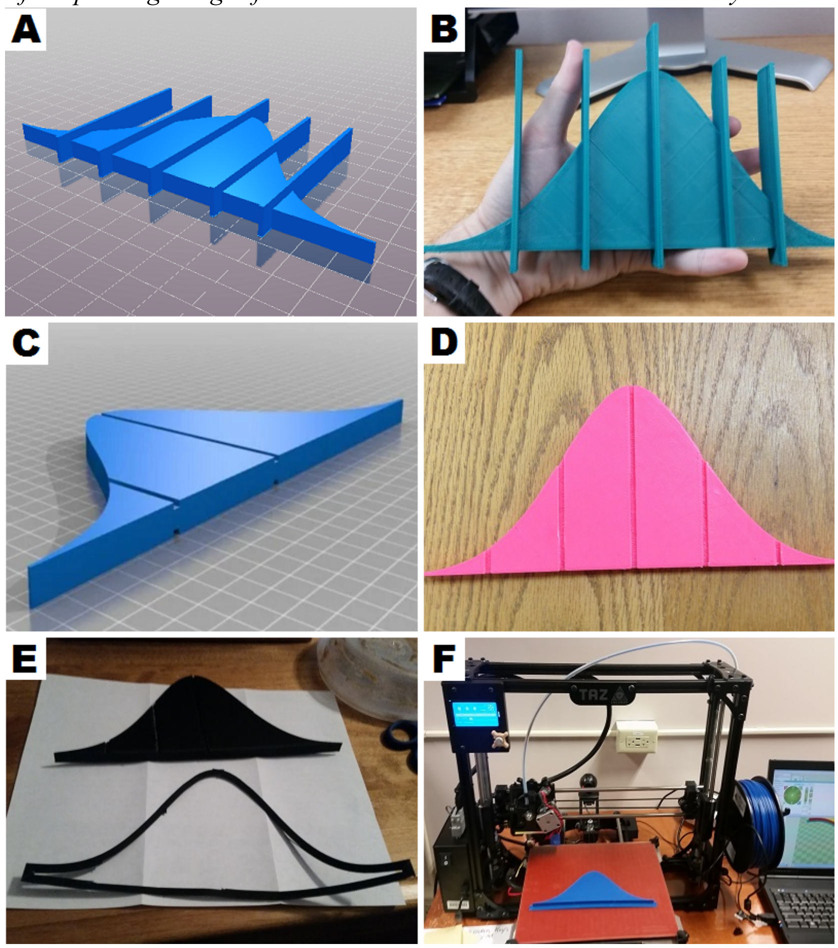
For example, our institution houses 3D printers within a makerspace in the campus library so that beyond the initial training and user authorization by librarians, there is also extensive informal peer support, mentoring, and resource sharing within a collaborative community of students and faculty. Librarians support, facilitate, educate, and advocate, but putting the people – the community members – of a makerspace at the heart of learning skills like 3D printing makes the process much less an imposing individual task and more a collaborative and fun experiment.

In our case, author DK, an undergraduate teaching assistant in our statistics course, became an integral member of the makerspace community based out of the library, and through that community he learned and honed the skills to create 3D printed objects for pedagogical use. A blind student in our course had reported finding our low-tech models of the normal curve helpful, but due to the materials used, those models had to remain in the professor's office, whereas a 3D printed object would be robust enough to travel in the student's backpack and be usable both in class and outside of class. The author in question started with an existing 3D printable normal curve design freely available on the internet (Ayoung, 2013) and improved upon it with feedback from a blind student in the course, for example by replacing raised lines representing standard deviations with channels cut into the curve (Fig. 2A-2D)(Kay, 2016). He also added a removable brim to the design for better printing on the local printers, in this case a Lulzbot TAZ 5 (Fig. 4E-F). As part of this iterative process, librarians and members of the campus makerspace were very helpful in learning to create successful designs.

Open Educational Resources

Of course, as Jo and colleagues (2016) point out, designing models for 3D printing has a significant learning curve and time investment, and for many instructors of BVI students this may be prohibitive. Thankfully, there is a solution for instructors who do not want to create their own designs: use existing designs created by others. This extends to the hobbyist

Figure 2
Iterations of 3D printing designs for the normal curve used in our Introductory Statistics Course.



(A) Early 3D model using raised lines to indicate the mean and one and two standard deviations from the mean. (B) Printing of that early model. (C) A variety of improved 3D models used channels cut into the curve, based on feedback from a blind student. (D) Printing of the improved model, used by student. (E) Printing of the model showing removable brim added for better printing. (F) Lulzbot TAZ 5 used to print a blank normal curve, brim included.

and online communities surrounding 3D printing. For example, one of the largest online communities, Thingiverse (https://www.thingiverse.com) is a huge database of 3D designs hosted by MakerBot, where all designs are encouraged to be shared under a Creative Commons license (i.e., a copyright license emphasizing free and open reuse and alteration of work)(Griffey, 2012). An instructor who desires free 3D printed resources for a BVI student could in theory just download the desired design from such a database and print it at their campus library, a public library, or any other local makerspace with a 3D printer.

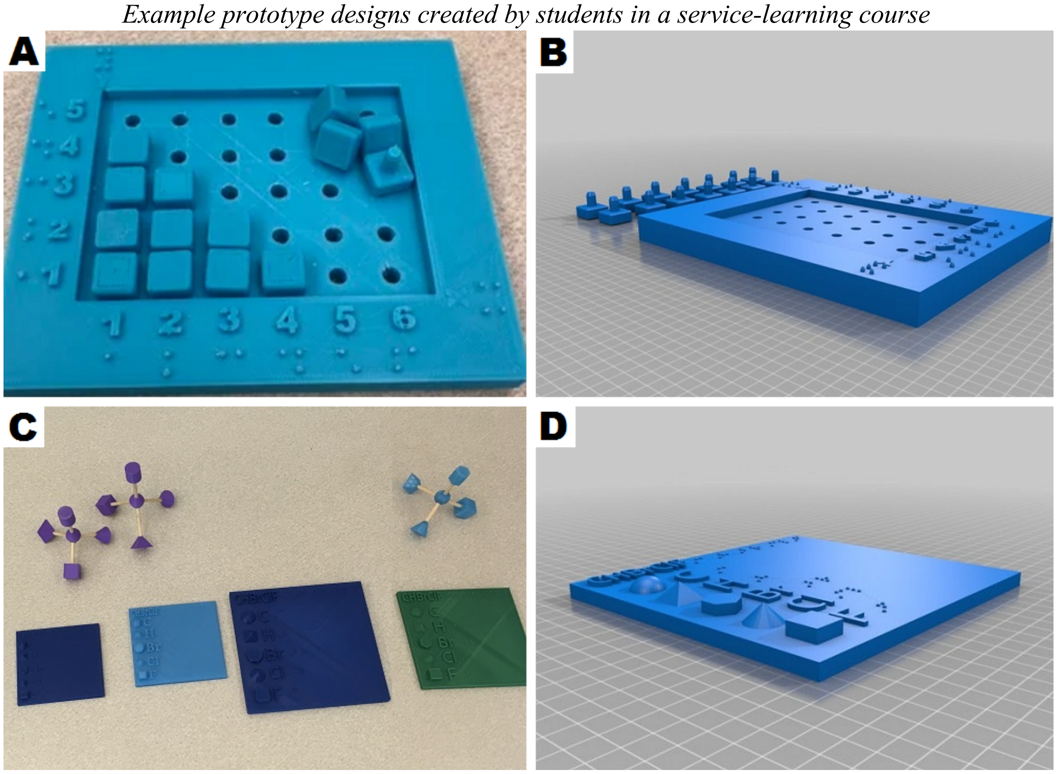
The current barrier to wide-spread use of 3D printed objects for teaching higher education concepts to BVI students is not the technology itself, nor the cost, nor the learning curve of creating 3D models, but rather the scarcity of designs publicly available. While many designs do exist for, say, simple science and math concepts, they represent only a tiny fraction of the topics covered in even introductory-level courses. Horowitz and Schultz (2014) present some examples of models they created for astronomy and the geosciences, and they end with a call for data centers and research departments in STEM fields to create libraries of 3D models for the use of students and researchers. They suggest that these could be shared online in an open-access database like Thingiverse and printed as needed. This aligns with the movement in education toward open educational resources which has been gaining momentum (Littlejohn & Hood, 2016). Rather than reinventing the wheel, instructors could find appropriate resources already designed and print them easily and cheaply without the learning curve necessary to create their own designs.

Service Learning as Sources of 3D Printable Models

Of course, these open-access designs must come from somewhere, so we urge instructors to participate in creating new education models or iterating, improving, and remixing existing ones. However, another idea which may scale up for even wider participation is to have other students on campus create 3D printable models which they subsequently share freely online. Faculty in engineering, design, art, computer science, and many other fields could assign project-based learning activities that ask their students to create 3D printable models for accommodating BVI students in a variety of other courses. Projects like this would not only provide OERs for wider use; rather, they would also build useful and marketable skills for the students themselves (McGahern et al., 2015). For example, a data analytics company recently reported that 35% of engineering job advertisements across a variety of fields asked for familiarity with additive manufacturing like 3D printing (Platt, 2015). Student projects designing 3D educational models may work best in a team setting (see our example below). Teamwork is not only pedagogically valuable but increasingly an important skill for future employment (in fact, employers have specifically called on universities to better prepare their graduates to work in team-based environments; Riebe, Girardi, & Whitsed, 2016).

Projects like this could also fall under the umbrella of service learning and help the students develop social awareness (Suchow, 2016). For example, Kostakis, Niaros, and Giotitsas (2015) describe a project in two Greek high schools where sighted students created 3D printed artifacts (using open-source 3D printers) with the goal of communication and collaboration among BVI and non-BVI students. Ideally, students creating or improving designs for 3D printable tactile learning aids could work directly with BVI students or other stakeholders (e.g., a nearby school for the blind, an advocacy organization, or a government commission for the blind).

Figure 3
Example prototype designs created by students in a service-learning course



(A-B) Prototype of interactive tactile graph, after feedback from visually impaired users (https://www.thingiverse.com/thing:3243094). (C-D) Iterations of tactile stick-and-ball chemistry models to demonstrate stereoisomers (bromochlorofluoromethane shown) with a legend utilizing shape, print, and Braille (https://www.thingiverse.com/thing:3270250).

An Example Course

To give one example of how accessible 3D printing design can be scaled up by students, we developed an interdisciplinary service-learning course where student teams created accessible 3D printed models in collaboration with BVI community members. In the course, titled "Perception, Design, Accessibility," students learned about visual impairment, including assistive technology, history/advocacy, and the science of tactile and haptic perception. Through guest speakers, readings, podcasts, and vidcasts the students heard directly from a wide variety of BVI voices, and they gained experience using assistive technology like screen readers to successfully accomplish everyday tasks.

A large focus of the course was the educational barriers faced by BVI individuals, so students also read about those challenges, surveyed BVI individuals on educational barriers, analyzed use of visuals in standard textbooks, and collected observational data of pedagogical reliance on the visual modality in a variety of actual college classrooms. Meanwhile, through a partnership with the university library's Maker Lab (which houses many consumer-level 3D printers), the students learned about and got experience with basic 3D design and 3D printing. Then, in partnership with the state's Commission for the Blind and Visually Impaired, student teams designed accessible 3D printed models and used input, feedback, and user data from BVI community members to iterate and improve their designs. For example, one group created interactive graph prototypes for quickly making (or interpreting) simple histograms while another group created accessible hands-on models for stereoisomers that could be used in a chemistry class (using shape and Braille labeling to convey information usually conveyed visually with color and print)(Fig. 3). By creating these as digital OERs shared in a free online database, the teams ensured that the models could be accessed -- and improved upon -- by anyone, anywhere.

We urge instructors to consider incorporating assignments like this into their courses with the goal of contributing or improving open educational resources for worldwide access in the form of digital models for 3D printing. Instructors of BVI students, especially those who find themselves with a BVI student for the first time and feel unequipped to provide tactile accommodations for concepts they usually present visually, could then print these models with minimal technical knowledge or perhaps just assistance from a librarian or the helpful community at a makerspace.

Conclusion

Students with blindness or visual impairment face barriers to learning within higher education, and instructors have an obligation to make their classes accessible and provide accommodations to lessen those barriers wherever possible. While technology like screen reader software and tactile graphics work well for many learning purposes, the increasing consumer-level accessibility of 3D printing offers a promising complement to other existing accommodations and in some cases can mitigate the limitations of tactile graphics. 3D printing allows for an endless variety of highly customized tactile learning aids tailored to specific pedagogical needs, and these objects are cheap to produce and often are robust and mobile enough to travel in a backpack. While there is a learning curve to create new 3D printable designs, libraries, makerspaces, and online hobbyist communities offer extensive support for those who want to create new designs or iterate existing ones. More importantly, though, open educational resources (making 3D designs widely available for free) mean that instructors can use 3D printed objects without having to create their own designs. We call specifically for more contributions to open online repositories of 3D designs, either by individual instructors or by students completing service-learning projects in other courses. Together, we can create a more accessible curriculum for all students.

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