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The use of 3D printed media to improve the accessibility of engineering educational materials

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The use of 3D printed media to improve the accessibility of engineering educational materials

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Abstract

There is a need for improvement in teaching engineering, math, and science to students with blindness or visual impairment (BVI). Most media available for instruction are visual, and many concepts are taught visually, making them inaccessible to students with BVI. In addition to the wider use of alternative text (alt text) [1], swell paper printing, braille touch pads, sonification, and other technologies, individual instructors have made strides in using 3D printing to make graphical engineering content more accessible [2]. Other studies have been done to show the effectiveness of 3D printing in delivering instruction to students with visual impairments [3]-[4]. Ready access to 3D printable media for engineering education remains elusive despite 3D printing technology becoming widespread, partially due to cost and partially due to complications in transforming flat images into 3D printable objects.

Access to 3D printable files for graphs and illustrations in textbooks would improve instructors' ability to deliver accessible content to students with visual impairments, beyond alt text or tabular data alone. Several studies have shown that visually impaired students benefit from tactile media that 3D printing can provide. Examples of such work exist in chemistry [3], mathematics [5]-[6], and engineering [2]. Studies have also shown that 3D printed media can be designed to be useful across the whole spectrum of visual impairment as well as for fully sighted learners [7]-[9]. A survey of prior work is presented in this paper to collate possible solutions to making such a 3D printable file collection a reality, and to find ways to integrate such a collection into interactive online textbooks. Existing technologies are investigated for their advantages and disadvantages compared to 3D printing. The potential difficulties in creating a 3D file collection (including file conversion, file storage, dissemination, and compatibility) are discussed.

The effectiveness of 3D printed media to convey information is crucial. This paper is intended to serve as the basis of establishing a method and process for building a functional, textbook-integratable collection of 3D printable media for ready use to improve accessibility of

engineering educational content, and incorporating it into our interactive web native textbook, zyBooks.

Introduction

3D printing approaches to making STEM information more accessible to students with BVI have been reported. The authors in [10] propose a tactile-based solution. Unlike TangibleCircuits [11], which 3D prints all of the circuit schematics, [10] uses 3D printed tactile buttons with strings to represent analog and digital elements within circuit diagrams. Plus, dots and numbers were added on the sides of the 3D printed buttons to mark the element number in the schematic [10].

3D printing offers students with BVI the ability to interact with a physical object that can overcome the limitations of using braille, which inefficiently produces a literal translation of all elements of an equation. For example, 3D printed models are created for graphic visualizations in STEM [12]-[13]. The CamIO [12] uses a Kinect camera combined with real-time text to speech audio feedback based on where a user touches the 3D model. Alternatively, the TPad System [13] creates a 3D printed frame as the tactile graphic, which is placed on a tablet screen. In the field of electrical engineering, TangibleCircuits [11] produces a 3D printed model of an electrical circuit, similar to [10], from a Fritzing diagram. An audio interface is also extracted from the diagram to deliver audio feedback while a user with BVI interacts with the model, as in [12]. Other examples of audio-tactile devices that use 3D printing exist in the literature; see [14]-[17].

Alternative methods exist to make instructional media accessible to students. Printing on swell paper with a fuser is a ready alternative to 3D printed images. Swell technology [18] relies on special paper which expands when heated, allowing an image to be printed on the paper. Then, a fuser instrument is used to expand black lines that become tactile features on the paper. These instruments have the advantage of being able to transform images to tactile media in a matter of minutes, whereas 3D printed images take about an hour. The images have to be extracted from the medium they are presented in for printing and must be black and white, which adds to the spot processing time. The main drawback is cost. Fuser prices start at around $1600 and go up from there. Sheets of swell paper are $1.50 per page, which also adds to the cost of regular use. In comparison, FDM 3D printers are available for as little as $200, and material cost for a printed image is $0.30. Additionally, most institutions of higher learning have readily available 3D printing facilities, but access to fusers is less prevalent. Swell paper and fuser technology is superior for speed, but costs substantially more which reduces student access.

Sonification is a process of converting information into an audible medium. Work [19] has been done in using a combination of sound pitch and stereo headphones for modeling line graphs in an auditory space. Challenges to this approach include complex set up for imparting the audio information to a student, complicated processing to convert graphic files to audio information, and limitations to student engagement when wearing headphones in a classroom. Efforts [20] continue to be made towards developing accessible sonification technologies. However, communicating complex data or graphical information sonically remains a challenge and no universally adopted sonification system exists [21].

Printing on swell paper with a fuser presents a fast but expensive solution for converting images to tactile media. Printing an image can also require image manipulation depending on the image. A few specialized solutions exist in the field of sonification, but none of them can address complex images. No universal standard for sonification exists.

The current approach, across the industry and zyBooks is to create alt text that, at a minimum, is in accordance with the Web Content Access Guidelines (WCAG) 2.1 Level AA standard. Recent work [1] developed accessibility standards for textually describing images, figures, graphs, animations, and other visual elements for a series of interactive web native mechanical engineering textbooks [22]-[23]. These new standards include: (i) alt text that balances precision with conciseness; (ii) structuring alt text to initially capture key information, then incrementally adding in finer details; (iii) well-defined procedures for describing specific, yet common visual elements (e.g., phase diagrams, phase transformation plots, T-s and p-v diagrams, and time-response plots); and (iv) alt text for animated visual elements that fully describe all dynamic processes and intermediate movements. Conveying complex graphical information requires detailed and lengthy alt text. The improved alt text, however, makes information available in complex visual elements that is otherwise inaccessible to students with BVI. In adapting extant texts into interactive web native zyBooks, a concerted effort is made to update all alt text to meet WCAG standards and also meet the needs of an engineering audience.

3D printed models have been proven effective in a number of studies, and 3D printers have become low cost and are commonly available on college and university campuses. Our goal is to provide students with BVI the ability to access tactile media with minimum effort and at low cost. Making 3D printable files available for images presented in zyBooks will accomplish this goal.

Methods

The method of converting graphs and images to 3D printable files is described below.

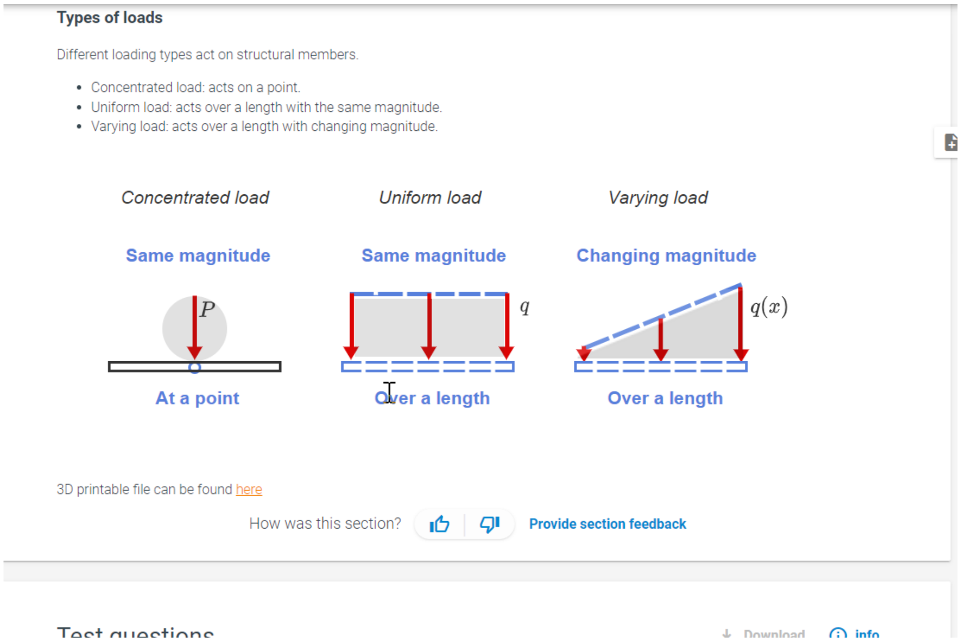
Multiple tools were used in the conversion of images to a 3D printable medium. Text in the images were translated to braille using [24]. The images translated to braille were converted to .STL format using the Image to Lithophane tool [25]. Files in .STL format are 3D printable. Braille characters were scaled with the Image to Lithophane tool to meet the 2010 ADA

Standard for Accessible Design Section 703. The 3D printed images were printed on a Prusa MkIII 3D printer.

Braille characters have required specifications, resulting in braille text taking up substantially more space than writing in the Latin alphabet. Thus, the text on images had to be edited so that the braille translations would fit and that the images would have a reasonable print time of approximately one hour or less. A detailed example of the conversion process to braille is shown in Figures 1a and 1b. The edits included omitted or alternative words and image modifications due to spacing. For example, "same magnitude" was replaced with "same F", as magnitude referred to a force. These conversions required 15 to 20 minutes.

The images were converted to black and white images, as color or grayscale is translated as varying heights by Image to Lithophane . In one case textured gray regions were added to texture certain areas of the image as a stand in for shaded regions in visual images. The images were then converted to .STL format to produce 3D printable objects on the order of 15 cm in length and width. This size was achieved by setting the "Maximum Size" setting on Image to Lithophane to be one tenth of the largest dimension in pixels of the image. This conversion allowed each pixel to translate to 0.1 mm in the .STL produced. "Thickness" was set at 1.5 mm and "Thinnest Layer" was set to 0.8 mm, producing braille characters that meet specification heights. The other settings were not changed from default ("Border" = 0 mm, "Vectors Per Pixel" = 4, "Base/Stand Depth" = 0). Conversion of an image to .STL took on the order of a minute. The .STL files were prepared for printing in PrusaSlicer software, with 0.15 mm layer heights with other settings at default. The layer height was chosen based on a target 1 hour print time. The files were then printed using PLA filament. Examples of printed images are shown in Figure 2 (c), (d) and (e).

A page modeling the customer facing portion of zyBooks with a test for the file distribution was built on our platform. Sections in accordance with zyBooks' pedagogy were written supporting chosen test images, shown in Figures 1(a), (b) and (c). The .STL files of the test images were hosted on an internal file hosting system, and links embedded into the test page.



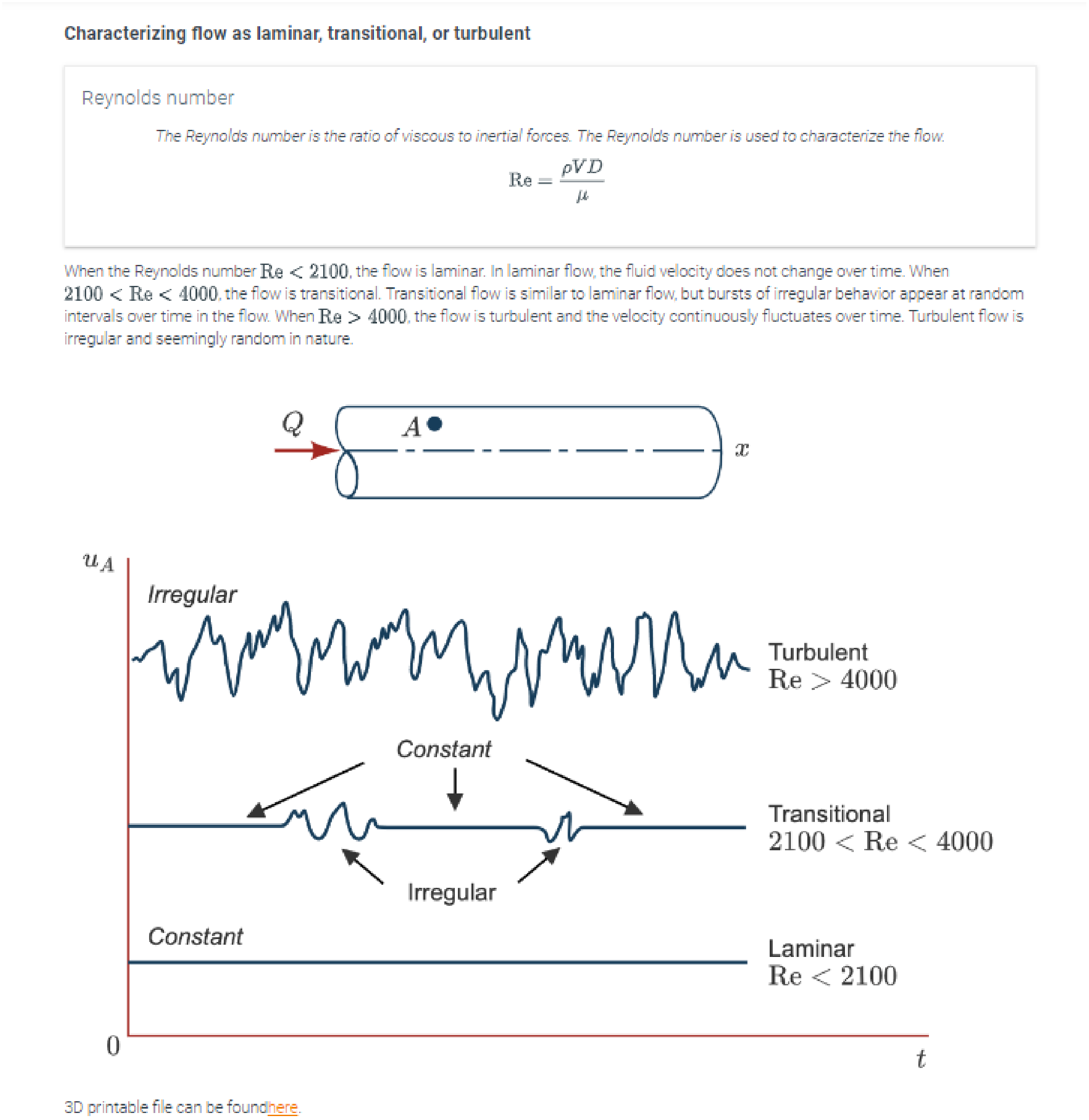
Types of loads

Different loading types act on structural members.

- Concentrated load: acts on a point.
- Uniform load: acts over a length with the same magnitude.
- Varying load: acts over a length with changing magnitude.

3D printable file can be found here

(a)



Characterizing flow as laminar, transitional, or turbulent

Reynolds number

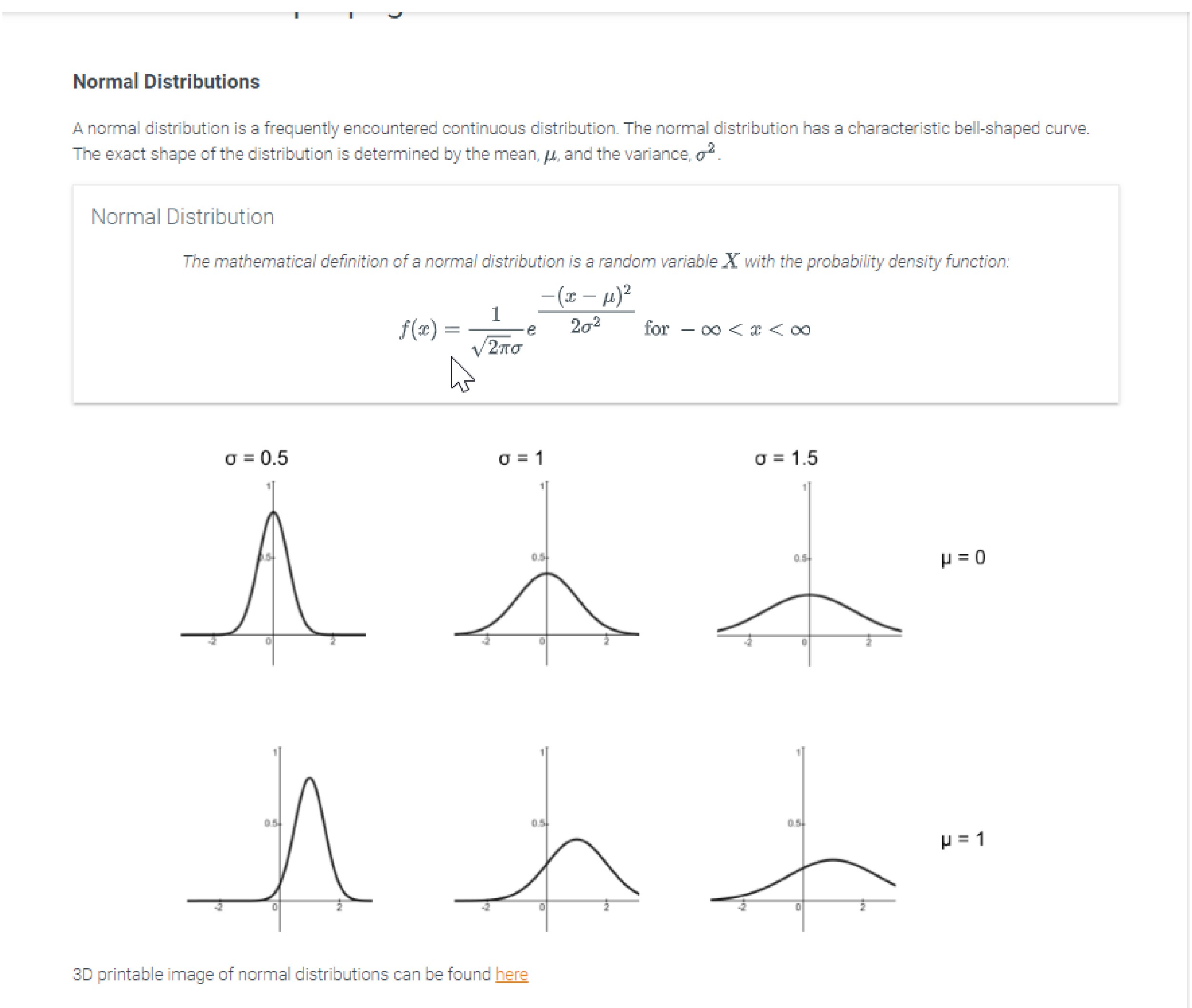
The Reynolds number is the ratio of viscous to inertial forces. The Reynolds number is used to characterize the flow.

$$\mathrm{Re} = \frac{\rho V D}{\mu}$$

When the Reynolds number $\mathrm{Re} < 2100$, the flow is laminar. In laminar flow, the fluid velocity does not change over time. When $2100 < \mathrm{Re} < 4000$, the flow is transitional. Transitional flow is similar to laminar flow, but bursts of irregular behavior appear at random intervals over time in the flow. When $\mathrm{Re} > 4000$, the flow is turbulent and the velocity continuously fluctuates over time. Turbulent flow is irregular and seemingly random in nature.

3D printable file can be found here.

(b)



Normal Distributions

A normal distribution is a frequently encountered continuous distribution. The normal distribution has a characteristic bell-shaped curve. The exact shape of the distribution is determined by the mean, μ, and the variance, σ^2.

Normal Distribution

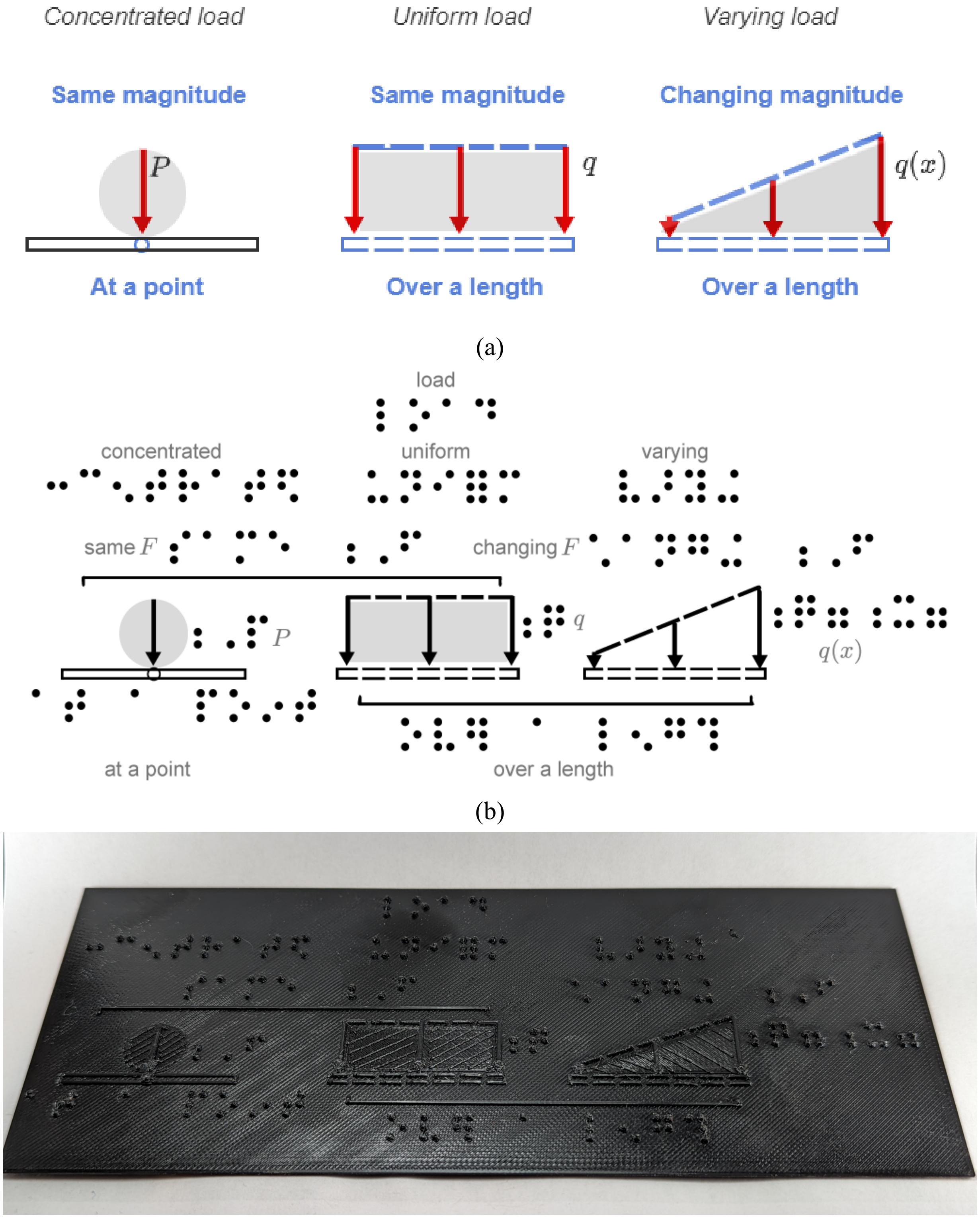
The mathematical definition of a normal distribution is a random variable X *with the probability density function:*

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \text{ for } -\infty < x < \infty$$

3D printable image of normal distributions can be found here

(c)

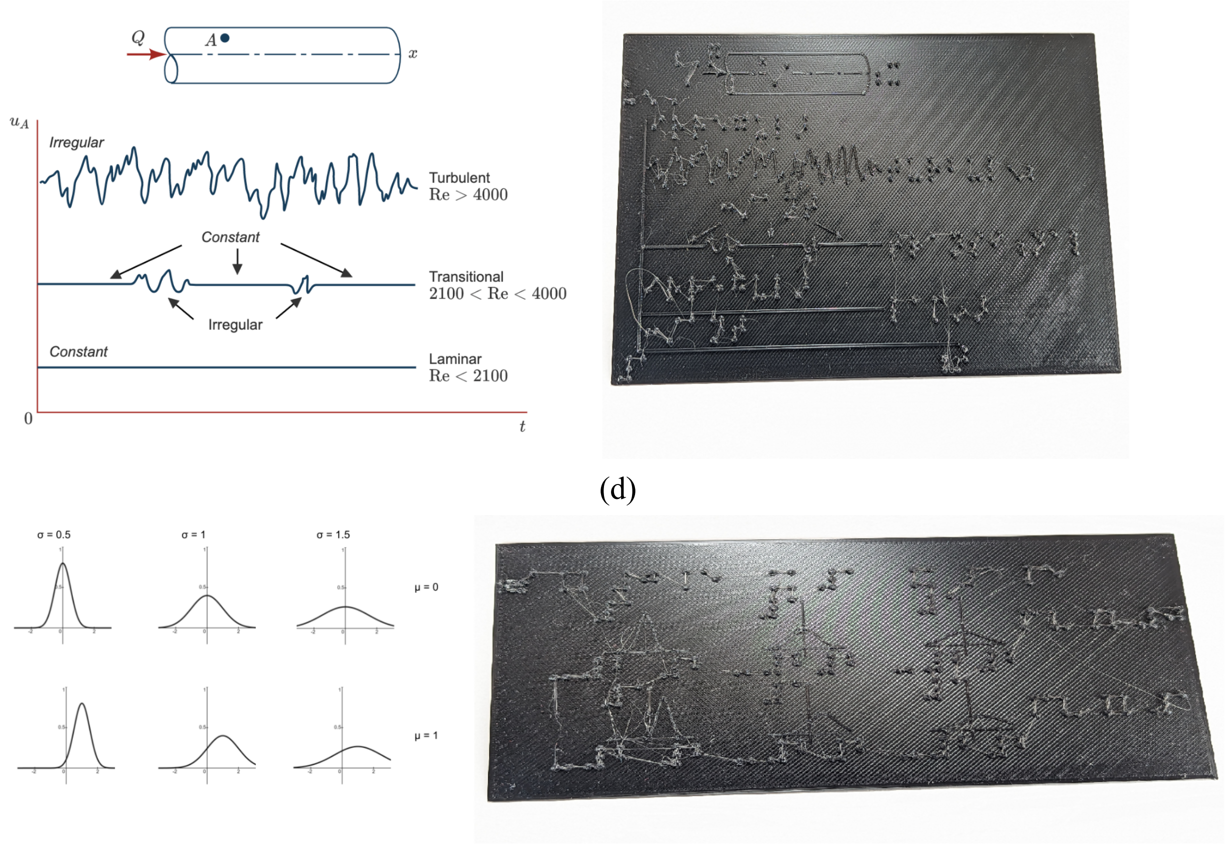
Figure 1:(a-c) Examples of zyBook pages with STL link embedded at the bottom


Concentrated load
Uniform load
Varying load
Same magnitude
Same magnitude
Changing magnitude
P
q
$q(x)$
At a point
Over a length
Over a length
load
concentrated
uniform
varying
same F
changing F
P
q
$q(x)$
at a point
over a length

(a)

(b)

(c)



(d)

(e)

Figure 2: Conversion of an image to printed object: (a) original image (b) braille annotation (latin characters for reference only, and not included in the image converted to .STL) (c) final printed artifact. (d-f) Additional examples of converted images.

Discussion

The process of converting images to printable files is straightforward but potentially labor intensive. In total, 300 hours of contact time would be required to convert a test case book's images to .STL files. The process could likely be streamlined, but is still a rate limiting step. Designing images with conversion in mind would have several benefits. Reducing image text would shorten conversion time significantly since translation to braille is time consuming. Additionally, images designed with less text make alt text more effective as well, and drive good design practices for non-blind students with visual impairments. Choosing images selectively would reduce the time required to build an initial image library since some images are more readily described with alt text. Therefore, focus should remain with complex images and graphs with multiple curved lines and regions of interest that are difficult to describe succinctly in alt text.

The efforts presented here are in their initial stages, and have yet to be tested by students with BVI. Effort has been made to meet the required standards of accessibility that are available. Other researchers have used a very similar process to generate tactile media and they demonstrated success in conveying information with 3D printed media [3]. Due to the nature of our images, we expanded on their efforts as we incorporated braille text on our images. Testing the utility of braille combined with printed images is planned.

Data storage costs are a potential issue given the need to store many .STL files for each text produced. Typical cloud storage costs are $0.02 per GB of data stored per month. The file size of the .STL files is on average 20 MB. There are approximately 600 images in a statistics book analyzed, which is approximately 12 GB of storage if all images are converted and stored. With a total cost of $0.24 per month, no significant cost is incurred for storage.

The proof of concept expansion of zyBooks to include 3D printable files has been successful. File storage is straightforward, and easily incorporated similar to how data sets in a homework problem are incorporated.

Conclusion and Future Work

A process and framework for a new solution to accessibility of images in STEM texts for students with BVI, 3D printing images, has been developed. The conversion of images to a 3D printable medium, and a method for their incorporation into existing zyBooks has been shown. The 3D printing approach promises to be a superior tool to a number of other existing tools. Improvements in processing images to printable .STL files would increase the viability of this approach.

Testing 3D printed media with students with BVI is also necessary. The work presented in [3] will serve as a model for testing our 3D printed images. The work presented here is intended to serve as a first iteration in an ongoing effort to improve access for students with BVI to images in learning materials. The input and partnership of students with BVI and instructors of students with BVI will be key in further iterations. Our intention is to seek equal partners who will be able to best speak to their own needs. This work is intended to serve as a basic prototype that we can present to future partners as a basis for collaboration.

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