Developing printable content: A repository for printable teaching models

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Abstract

Alongside the development of RP technology, there is an increasing need to develop and share printable content. Like digital photography and digital music, content drives technology as much as technology drives content. This paper describes the development and population of an open wiki-style website (3Dprintables.org) that houses an archive of printable models for education. Teaching models were chosen as the initial focus for this effort for two key reasons. First, quality educational models are difficult for teachers to obtain due to high prices, limited availability, and limited customization options; and second, many studies have demonstrated that learning is enhanced when students interact with physical models. Such models are also indispensible tools for teaching the visually impaired and those with spatial reasoning difficulties. At present, the website contains models relevant to mechanical engineering, aerospace, biochemistry, mathematics, anatomy, and archaeology (e.g. proteins, airfoils, kinematics models, cuneiform tablets). These models are intended to serve as "seeds" to encourage educators to further develop and share printable models and the associated curricular materials.

Introduction

While rapid prototyping/3D printing technology has advanced significantly in recent years, public interest has not kept pace. This is due in large part to a lack of printable content. Consumers who purchase or have access to a 3D printing system must design their own parts to print, which can be a time-intensive prospect and often requires experience with CAD software. Other emerging technologies in the past have faced similar challenges. MP3 players did not become widely popular until large websites with many organized, downloadable music files were launched. Ease of content generation also contributes to the popularization of a technology. Digital photography content has been largely accelerated due to development of user-friendly image editing applications.

This project is intended to address content generation for RP systems, with an initial focus on educational models. An open repository, 3Dprintables.org, has been constructed to contain an archive of free, testable, downloadable .STL files along with the source models and additional materials. Since the site is wiki-based, users can upload their own content to share freely as well as expand and comment on files already on the site. The site also includes tools that allow the novice user to immediately begin creating printable models from various sources such as data files, equations, and Protein Data Bank (PDB) files. The two main objectives of this website are increasing the amount of printable content freely available online and empowering educators to bring physical models back to the classroom by downloading existing models and designing their own.

The widespread introduction of 3D printing to educational institutions has already begun. Prices for 3D printing systems are well within the reach of four-year colleges, community colleges, high schools and vocational schools and will continue to fall while the capabilities and speeds of these machines grow. Indeed, many such institutions have already purchased 3D printing equipment and are integrating it into their existing curricula. The NSF recently funded the development of a rapid prototyping curriculum. RP technology is not only being used to supplement engineering and CAD courses but also as a means to introduce young students to engineering and increase enthusiasm for the field (Wohlers, 2005). This website will give educational institutions an additional use for the 3D printing systems they already own and perhaps encourage more schools to purchase this equipment.

Motivations

Physical models have always been an important teaching aid, especially in math and the sciences. Maria Terrell, a mathematics professor at Cornell, adamantly supports the development of models. “When handed a 2-dimensional representation of a 3-dimensional object many students have difficulty imagining what that object actually looks like, in many cases their interpretation is incorrect. The image in the book is a level of abstraction of what the mathematical equation represents, models serve to bridge the gap and facilitate the learning of the student.” Traditionally, models were made by hand, often requiring a great deal of time and skill. Since these models were one-of-a-kind, only a small population of students could benefit from them at one time. Recently, increasing demands on teachers’ time have discouraged this type of model making. Older hand-crafted models are passed down within a school or department until they break or deteriorate. Also, these models are not able to evolve as scientific knowledge grows, making them increasingly inaccurate over time.

Commercial models have emerged as an alternative to these hand-made models. Commercial models are generally more up-to-date than hand-made models and often more accurate. However, they are expensive, which can be prohibitive for schools with small budgets. For example, an anatomical model of the heart can cost up to $600. More complex anatomical models (a full torso, for example) can cost upwards of $3,000. The high cost of these physical models combined with the decreasing cost of simulation and visualization software and computer modeling have steered educators away from physical models. Teachers increasingly use computer models in place of physical models for classroom demonstrations. Additionally, commercial models do not yet exist for some classes, such as multivariable calculus. Teachers are forced to create their own demonstrations i.e. a surface (the belly of a teddy bear) with tangent and normal vectors (pencils).

While many students profit from computer models and simulations, blind students and students with spatial reasoning disabilities cannot benefit from these strategies. These populations are not insignificant. There are 10 million blind or visually impaired persons in the United States, and 93,600 of those are students. Out of these blind and visually impaired students, 55, 200 are legally blind (AFB, 2008). Students who are legally blind cannot benefit from illustrations in text books or on blackboards and can only interact minimally with computer simulations. Students who are visually impaired may not be able to experience the full value of these purely visual teaching strategies. Additionally, students who are blind and deaf (10,800 in the US) are in even greater need of physical teaching models, since their dominant sensory experience is touch. Clearly there is a need for educational materials targeting these populations to ensure an equal opportunity for learning. Due to lack of availability, minimal customizability, and cost, many educators who work with visually impaired, blind, or deaf-blind students must construct their own models (Wentworth, 2008).

Yet another group could benefit from the increased use of physical models – students with spatial reasoning deficiencies. These students do not perform as well as their peers in subjects such as anatomy which rely heavily on 2D illustrations of 3D objects (Rochford, K. 1985). It has also been shown that male students outperform their female counterparts in spatial reasoning exercises (Stericker, 1982), perhaps because boys have more opportunity to practice those skills. Increasing the use of models in the classroom could help eliminate this disparity. Finally, teacher education benefits from the use of models. (Callison and Wright, 1993)

Physical models have been shown to enhance learning in general student populations as well. Students learn in a variety of ways, and models allow students to include their sense of touch in the learning experience. "The role of experience is emphasized in Piaget's description of cognitive development, that is, to know an object a subject must act on it and thus transform it - displace, connect, combine, take apart, and reassemble it." (Cohen, 1983). Science education especially benefits from the use of models.

> "If one goal of science education is to enhance and maximize an individual's special conceptual ability, then access to manipulatives is advisable for those individuals. This access to manipulatives might also enhance development of their logical abilities… Internality is positively correlated with student achievement, and experience with manipulatives tends to move external subjects toward the internal end of the internal external continuum." (Cohen, 1982)

Graphic abilities have also been shown to have an effect on math and science performance.

> "A high degree of correlation was found between developed graphic abilities and high performance in mathematics, and a lower but still significant degree of correlation was found between developed graphic abilities and high performance in science. The findings support the second hypothesis as well, suggesting that children with developed graphic abilities reported that their favorite subject was mathematics and their second favorite subject was science." (Stavridou, 2008)

Educational approaches that use models and manipulatives heavily (such as the Montessori Method) have demonstrated benefits for students. Montessori kindergarten students studied in Milwaukee, Wisconsin significantly outperformed their peers at traditional schools in standardized tests of reading and math (Lillard, 2006).

The decreasing use of 3D models coupled with their broad usefulness in education was the motivation for creating 3Dprintables.org (Lipson, 2007). This archive site is intended to serve as a catalyst, encouraging educators to use models more widely in their classrooms and create their own models to share with other educators. Printed models are also cost-effective, especially for schools that already own a printer. Material costs for most 3D printers range from less than $1 to $10/cubic inch for model material (less for support material). The printers themselves cover a large range in cost, from $3,000 to well above $40,000. Even the largest model on the website would likely cost under $50 (material only).

Existing Work

RP technology is already being used to make educational models. A group at the University of Wisconsin–Madison is working with 3D protein models (Herman *et. al.*, 2006). The group also runs a for-profit company that designs and sells the models. The Nanoscale Science and Engineering Center, also at the University of Wisconsin–Madison, has created 3D models to teach blind and visually impaired students about nanoscience (Greenberg, 2007). Some artists are also using RP technology to make their work more accessible. Sculptor George Hart hosts a collection of .STL files for geometric sculpture on his website (Hart, 2008). Professor Gershon Elber of Technion hosts a collection of "impossible" Escher objects and scenes in 3D (Elber, 2008). For-profit sites also host large collections of models. The aim of this website is to collect and create educational models in one location to give educators easy access to a broad selection of free models.

STL Generation Tools

Most commercial CAD programs will output a .STL file from a model ("How to Create Stereolithography (.STL) Files," 2008). These .STL files can be sent directly to the printer to build parts or an assembly. Other commercial .STL generation tools exist for a number of applications, including making .STL files from medical imagery ("Medical Applications," 2008), and freeform designs ("Freeform Modeling," 2008). We also created an in-house application capable of generating .STL files from data.

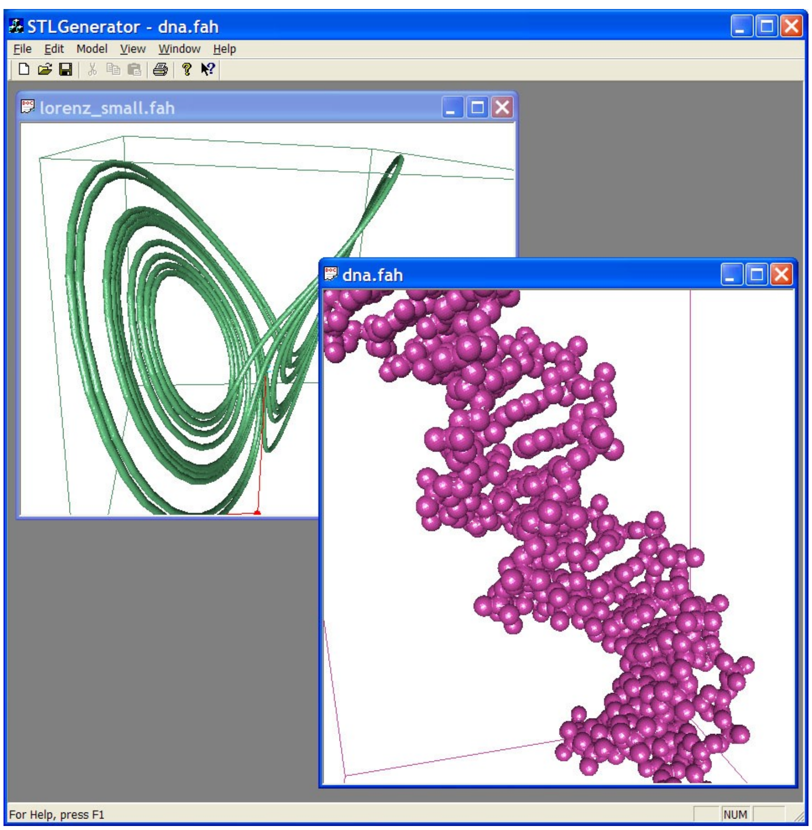

Figure 1. STL-Generator screenshot. Screenshot of open-source utility for generating STL files from point, curve, and surface data, as well as molecular biology (PDB) files. This image shows renderings of a Lorenz attractor and a DNA segment. See (Lipson, 2008)

STLGenerator is an open source utility for viewing and generating STL files from data. It can create an STL file directly from a list of points, line segments, surfaces, and PDB molecule files. The software uses the Marching Cube algorithm (Lorenson, 1987) to tessellate an iso-surface defined around a set of points or curves. A range of resolution can be selected resulting in finer or coarser meshes. The software is parallelized and makes efficient use of multiple cores. As an example, the external surface of protein molecule with 54,000 atoms can be rendered in approximately 5 minutes on a 2.8GHz quad core, resulting in a 1GB STL file. A variety of options are available for generating partial models (selected chains in a large molecule), as well as adjusting atom size and curve widths, etc.

The Website

3Dprintables.org is a wiki-style site, hosted by WikiMedia. Any user with internet access can create an account, edit pages, and upload content. Wiki sites have been proven to work with non-technical users, which is consistent with the success and size of Wikipedia, the 7th most trafficked site on the World Wide Web (Desilets, A. 2005). Currently the models are divided into categories based on academic area, with some subgroups within these categories. Populated categories (so far) include kinematics, mathematics, molecular biology, archaeology, aeronautics, and chemistry. Also included on the site is a section on STL visualization and generation tools, including a free download of STLGenerator and instructions for its use. The page for each model contains images of the models and supporting images, information and suggestions on the educational use of the model, downloads for the .STL file and CAD, if applicable, links to resource material, and source and credit information.

Creating the Models

Models for this project were chosen in three ways. First, the authors chose models that are broadly applicable to high school or undergraduate students. These models relate to topics that are a staple of every high school science and math curriculum, such as revolutions about axes (calculus), catalytic enzymes and DNA (biology), and crystal structure of minerals (Earth science/chemistry). Second, the authors searched the internet for models that had already been created in order to add these models to the collection for centralization purposes. Models obtained in this way include a Mayan pyramid (Figure 2-t) and the kinematic models from KMODDL (KMODDL, 2008, Figure 2 a-h)). Finally, the authors solicited input from educators (including Maria Terrell). Educators were asked to describe models that would be useful to them on a daily basis in their classrooms. This was an essential part of the project, since the key is for educators to take ownership in the site and begin creating their own models. It is simple to show an educator a few examples of the types of models that can be printed so he or she can see the limitations of the medium. From there it is as simple as drawing a picture or giving the modeler an image from a textbook and modeling can begin.

Mathematical models, such as the Lorenz Attractor (Figure 2-m), were generated from a list of XYZ points in a text file. In order to obtain the coordinate list, the appropriate equations were entered in MATLAB and a coordinate list was generated. This list was imported to

STLGenerator. The user can select whether STLGenerator should interpret the list as points, a curve, a surface or a solid volume. Then the user can choose the thickness of the curve to be generated. Revolved and intersecting solids were generated using a different method (Figure 2 j,k). A CAD program was used to create simple shapes and revolve them around axes.

Models such as the revolutions about the axes and the intersecting volumes of cylinders can be used to teach the student how to visualize in addition to being the visual subject. By having a tangible model a teacher can move it around the axes, trace intersecting edges in three dimensions and otherwise show how the resulting volume was formed. This will help the student read the 2-dimensional representation (e.g. textbook illustration) more accurately in looking for key aspects. The more models a student sees the easier it is for them to visualize an unknown 3-dimensional object from a new equation or 2-dimensional representation.

Selection of each protein to be modeled was based on several factors. The first was the protein's relevance to high school or introductory college level biology. Second, macromolecules with a reasonably small number of atoms (>60K) were selected for processing time considerations. This limit is not absolute, and should increase with faster processors and better printer software. Third, an effort was made to select models that had two parts – DNA and a binding factor for example – that could be printed separately and fit together, making the model interactive. The selected proteins were downloaded from the Protein Data Bank (PDB) ("RCSB Protein Data Bank", 2008) and the PDB files were imported to STLGenerator. Separate "chains" within the molecule, such as a binding factor and the DNA it binds to, were rendered separately and exported as separate STL files. In PDB files, "chains" do not always refer to individual peptide chains. Proteins made up of several chains may appear in the PDB file as a single chain. Each chain was printed in a different color to highlight the interaction between them (Figure 2-q). A model T4 bacteriophage was generated in a CAD program. This model is not intended to be accurate to molecular detail, but rather demonstrate the general shape and mechanics of a virus. Ideally, the full virus could be rendered from a PDB file, but at present, virus capsid files contain <100K atoms and are very difficult to work with. Other possible large structures to be modeled include bacteria and eukaryotic cells or cell organelles.

Aeronautical models were created in a CAD program. Several wings were produced with different purposes. A scale model of a Boeing 737 wing was made from four different airfoil profiles – one each for the root and tip of the wing and two mid-span. The airfoil sections were obtained from the UIUC Airfoil Coordinates Database (Selig, 2008). This database contains thousands of airfoil sections, so the potential exists for many more wing models. The wing was tapered and scaled based on known Boeing 737 wing dimensions ("Wing Design", 2008). Two other wings were generated for demonstration purposes. One uses a Clark Y airfoil, which is ubiquitous in general purpose aviation, and the other uses a generic high-lift airfoil. The purpose of these two wings is to demonstrate how airfoil shape affects wing capabilities. Both were tapered slightly and scaled to approximately the same size as the Boeing wing. Other possible aeronautical models include helicopter rotor blades and full propellers.

Figure 2. Selection of Models from 3Dprintables.org. Kinematics models from KMODDL: (a) Clock Escapement, (b) Double slider crank, (c) Wedding chamber crank, (d) Worm drive, (e) Davies engine, (f) Annular slider crank, (g) Slider crank, (h) Arithmometer. Mathematics: (i) Interlaced tetrahedrons, (j) Volume from intersection of 2, 3, and 9 cylinders (right to left), (k) Revolved solids, (l) Cavalieri's Principle, (m) Lorenz attractor, (n) Trefoil knot, (o) Triangle swept over circle. Molecular biology: (p) DNA strand, (q) Binding factor. Chemistry: (r) Buckyball, (s) Quartz (SiO_2) crystal. Archeology: (t) Mayan pyramid, (u) Cuneiform tablet.

Chemistry models were made in two ways. Simple geometric molecules (e.g. Buckyball, Figure 2-r) were generated in MATLAB and exported as XYZ coordinates. The XYZ coordinates were imported to STLGenerator and the atoms were scaled so that the representative spheres intersected enough for structural stability. Crystal structures were taken from text files ("Crystal Lattice Structures", 2008). These text files were cleaned so that they only contained XYZ points. For crystals with two or more elements, radius scale factors were added in a fourth column to account for different atomic sizes (Figure 2-s). The modified text files were imported to STLGenerator and rendered. Some trial and error experimentation was needed to determine which atom scaling was best for structural stability and accuracy. A range between .6 and 2 was found to be optimal. At present, the software can only generate space fill models (intersecting spheres to represent atoms and bonds). This approach is useful because the resulting models are strong and stable and also best represent a real molecule, but some accuracy and clarity is lost, especially in larger crystals or molecules. Adjacent atoms that are not bonded may appear so because their spheres overlap. Ideally, space fill and ball and stick models should be used together for the most accurate picture of molecular or crystal structure. Very simple ball and stick models (H_2O, sugars) may be created in CAD software.

Another function of this site will be facilitating the exchange of archeological models between research institutions. Since many countries do not allow archeological artifacts to cross their borders, it can be difficult for archeologists to study artifacts from other countries, especially with shrinking travel budgets and increasing travel costs. There is also a great need to protect one-of-a-kind artifacts from damage, theft, or loss. Artifacts can be scanned with a 3D scanner and rendered in .STL format. These files can be posted on 3Dprintables.org for archeologists all over the world to download, print, and study (Figure 2-t). Increased printer resolution will also facilitate this effort.

A person with no training in CAD software or 3D printing can easily create most of these models. STLGenerator allows a novice user to create complex molecular models in minutes. The key to this project is to empower educators to use these simple tools to customize models for their individual classroom needs. The website contains links to all the source material used for the models as well as all .STL files and CAD models. A list of STLGenerator settings and model dimensions accompanies each download. Users can easily recreate and customize any model on the site.

Future

As the costs of 3D printing systems continue to fall, colleges, high schools, and secondary schools will begin to purchase and use these systems. As the technology becomes more ubiquitous, educators will become increasingly aware of its power and begin integrating it into the classroom. This paper presents a jumping-off point for this projected trend. As awareness of this site and others like it grows, the art of model-making will be streamlined and placed back in the capable hands of educators.

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