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The 3D Printing Revolution in Education

A new approach to learning in the 21st century

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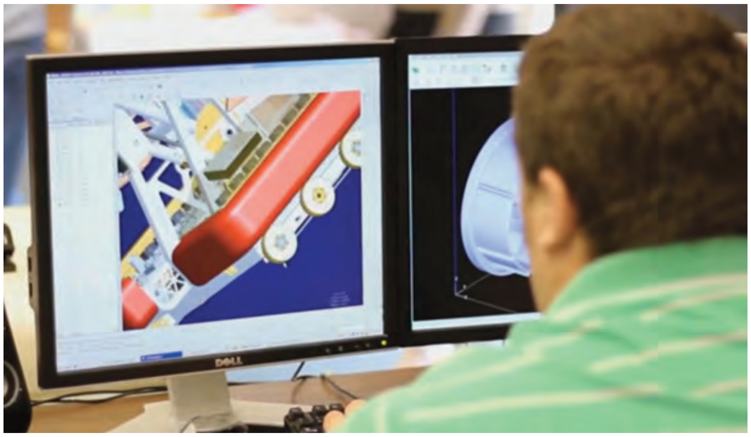
The 3D Printing Revolution in Education

by David Thornburg, PhD

This white paper is intended for district administrators, school leaders, and classroom teachers, to help them better understand the role that 3D printing can play in improving student engagement and learning outcomes within the context of some of the most important academic movements in education today.

INTRODUCTION



Even though 3D printers have been around for almost 30 years, the recent rise of low-cost printers has led **some to proclaim the onset of a new industrial revolution**. Schools and libraries all over the world are bringing these powerful tools to students in classrooms and dedicated "**maker-spaces**" where they are accompanied by other fabrication tools. For example, **China is putting 3D printers** in each of its 400,000 elementary schools. In the U.S., we are adding 3D printers into schools at a good rate, particularly into CAD programs, but also into traditional art and social studies classrooms and even business programs. Even President Obama, in his 2013 State of the Union Address, highlighted 3D printing as something that could fuel new high-tech jobs in the United States.

If 3D printing is starting a new industrial revolution, it is well on its way to revolutionizing teaching and learning as well. The result of bringing these tools into classrooms is a rekindling of the powerful pedagogy of hands-on learning, which was prevalent in American schools mid-twentieth century. As we will demonstrate, 3D printing leverages hands-on learning to deepen our educational approach to traditional academic subjects.

There are two aspects of teaching and learning that are addressed by 3D printing—the content of a subject area, and the pedagogy, the teaching and learning method to convey that content. In this white paper, we will look how content and pedagogy are converging in today's most promising education movements and the role that 3D printing plays in supporting these critical shifts.

CONTENT: STARTING WITH STANDARDS

Historically, critics of the U.S. curriculum have claimed that it is a mile wide and an inch deep, and that learning in school consists mainly of memorization of facts. While this criticism overstates the problem, the adoption of new standards, especially in STEM (science, technology, engineering and math), is addressing serious weaknesses in our current approach to content learning, in part by embedding powerful pedagogical approaches into the content standards themselves.

The first of the new standards that have strong connections to 3D printing are the Next Generation Science Standards (NGSS), which include engineering as one of the disciplinary core ideas, starting in kindergarten all the way through high school. Unlike older standards, the NGSS are less about a specific curriculum and more about how learning takes place. In this case, the focus is on inquiry-driven project-based learning where the student develops deep understandings through the creation of projects and products. In the domain of mathematics, the new Common Core State Standards have a similar emphasis on inquiry and learning through doing.

To see the connection between these 21st century standards and 3D printing, let's start with the Common Core Math Standards. There are only eight of them:

1. Make sense of problems and persevere in solving them.
2. Reason abstractly and quantitatively.
3. Construct viable arguments and critique the reasoning of others.
4. Model with mathematics.
5. Use appropriate tools strategically.
6. Attend to precision.
7. Look for and make use of structure.
8. Look for and express regularity in repeated reasoning.

Looking at these standards in the context of 3D printing, several of them leap out. Virtually all 3D projects call for accuracy in measurements (Standard 2). Modeling with mathematics (Standard 4) is also commonplace, as is the strategic use of appropriate tools (Standard 5). Precision (Standard 6) is important when structures are made of parts that have to fit together. The use of structure in 3D designs relates quite well to Standard 7. By challenging themselves in designing objects for the 3D printer, students will certainly participate in problem-solving and persevering until the object is made to their satisfaction (Standard 1).

In other words, virtually every design students make and print incorporates six of the eight math standards. It is fairly easy to connect to the remaining standards, particularly through collaborative approaches (Standard 3) and presentations of projects (Standard 8).

As for the NGSS, there are seven core principles that define the scope of these standards.

1. K-12 science education should reflect the interconnected nature of science as it is practiced and experienced in the real world.
2. The Next Generation Science Standards are student performance expectations, not curriculum.
3. The science concepts in the NGSS build coherently across K–12.
4. The NGSS focus on deeper understanding of content as well as application of content.
5. Science and engineering are integrated in the NGSS, from kindergarten onward.
6. The NGSS are designed to prepare students for college, career, and citizenship.
7. The NGSS and Common Core State Standards (English language arts and mathematics) are aligned.

All seven of these core principles of the NGSS can be applied to the use of 3D printing in the classroom because 3D printing is, at heart, about how hands-on, experiential artifact-making can engender deep understanding of the science behind how the world works, even for the youngest students.

As for the standards themselves, the NGSS are divided into four core disciplinary areas: physical science, life science, earth and space science, and engineering. While all 3D printer projects clearly connect in some way to engineering, it is also easy to connect 3D projects to other core subject areas, especially physics and life sciences, where modeling is a key component of learning.

While teachers are comfortable with some of the main disciplines, engineering is a concern for many, mostly because of a lack of familiarity with how engineers do their work but also because it's a subject that few have taken in their academic careers. Science explores the world of the found, engineering explores the world of the made. Rather than make discoveries of naturally occurring phenomena, engineers design new things from the ground up. One of the common practices of most engineers is "tinkering:" experimenting with a design through trial and error until it is successful. Since tinkering is a common concept to just about everyone, the general topic of engineering becomes less intimidating, even for those educators with no formal background in the discipline. 3D printing makes engineering come alive for even the most uninitiated educators, as it provides a powerful tool for scientific tinkering.

It is important to note that even though some states have not adopted the new standards, these states still care about STEM (science, technology, engineering and mathematics) education. The fit between STEM subjects and 3D printing is quite natural, whether or not the new standards are adopted.

PEDAGOGY: LEARNING THROUGH DOING

Every teacher knows there are multiple pathways to learning. Some students learn best from listening or reading, others from dialogue, some from reflection, and still others from the creation of artifacts. This latter form of learning is critical for deep understanding because it is through the doing of a task that one truly comes to know what is understood and what is not.

One of the pioneers in the exploration of the role of artifact creation in learning is Professor Seymour Papert from MIT who coined the word constructionism to describe the process of learning through doing. Constructionism differs from constructivism in that, while the latter is cognitive, constructionism is concrete. As Papert has said, whether the artifact is a poem or a sand castle, it is through the zbuilding of something that true learning is demonstrated.

The world of 3D printing in the classroom is abundant in opportunities for constructionism. The creation of physical objects with a 3D printer often requires a few tries to get right, especially for complex objects. Sometimes the flaw is in the design itself, other times it is a flaw in the choice of materials or print density resulting in parts that lack the strength needed to work properly. In any case, the process of refinement (what we have thus far called tinkering) is a critical step in the building of true understanding.

In one of our workshops, a middle-grade student wanted to design and build a key-operated lock. This required him to first explore how such locks worked, and then to design and build the parts needed for his own lock. In his case, the lock required gears and levers, a classic simple machines physics unit. This child put the theory of gears and levers into action, and, after several attempts, created a lock that worked to his satisfaction—a process that took well over a day to complete.

Had a physics teacher been observing the process, she would have seen the student learning about simple machines without the benefit of lectures or textbooks. He was learning through construction, and is it likely that what he learned will stay with him far longer than anything gleaned through more traditional routes. Moreover, when the project was completed, he was able to take his lock home and add it to his collection of things he had designed and built — a source of pride for himself and his parents.

Student engagement is a key element of deep learning, and anyone watching a child build something with a 3D printer gets to see fully engaged students. This engagement doesn't come from the novelty of the process, but from the joy of seeing something designed by actually take shape. When students are engaged, the things they learn have lasting value. Their learning transcends content because it is contextual.

Older teaching methods focus on content, not context, which often prompts students to ask if something is going to be on a test, since they fail to see the lasting value in what they are being asked to learn. The fact is that all subjects can be taught in a contextual manner, and this kind of learning comes automatically for projects using 3D printers.

THE ROLE OF DESIGN AND THE RIGHT DESIGN TOOLS

Chris Anderson, author of the book ***Makers: The New Industrial Revolution*** has said: “We are all designers now. We may as well get good at it.”

He makes an important point. Before anything is built on a 3D printer, it first must be designed. One might even go so far as to say that the design process is, in fact, the goal, and the creation of the physical object is the reward. Given that some complex objects take a long time to print, this makes the design process even more important. I've had items take overnight to print that turned out not to work properly because of avoidable design flaws. While the design process may require a few tries before success is achieved, a constructive learning environment helps students identify and correct design errors in advance.

Of course, the design process requires tools—software that is used to draw 3D models that can be exported as STL files for printing. While some amazing commercial 3D design tools exist, there are plenty of free programs that make sense for classroom use, especially for students in the primary and secondary grades. In general, these tools can be put into three categories: drawing, sculpting, and programming.

The first category, drawing tools, consists of programs that let students draw designs that can be assembled with a blend of simple geometric shapes along with other shapes assembled from simple lines by the designer. This category includes popular software like **Sketchup Make** and **Tinkercad**, which are perfect tools for almost any design task.

A new tool I would add to this category is **Tinkerplay** from Autodesk, which lets the user design articulated models from a large library of predefined parts. Once printed, these parts can be snapped together to make various creatures with moving pieces, making this a nice tool for younger users of 3D printers.

The second class of tools employs the sculpting metaphor. Instead of working with a library of traditional geometric shapes, the user starts with a ball of “clay” that can be shaped into finished designs using analogs of the modeling tools used by traditional sculptors.

This class of software is perfect for creating organic shapes with a preponderance of smooth elements. I've used this kind of tool to design shapes that resemble fanciful insects. Software like **Meshmixer** and **Sculptris** fit into this category. While a mouse is an adequate drawing device for traditional 3D software, sculpting benefits from the use of a graphics tablet, although one can use a mouse if that is available.

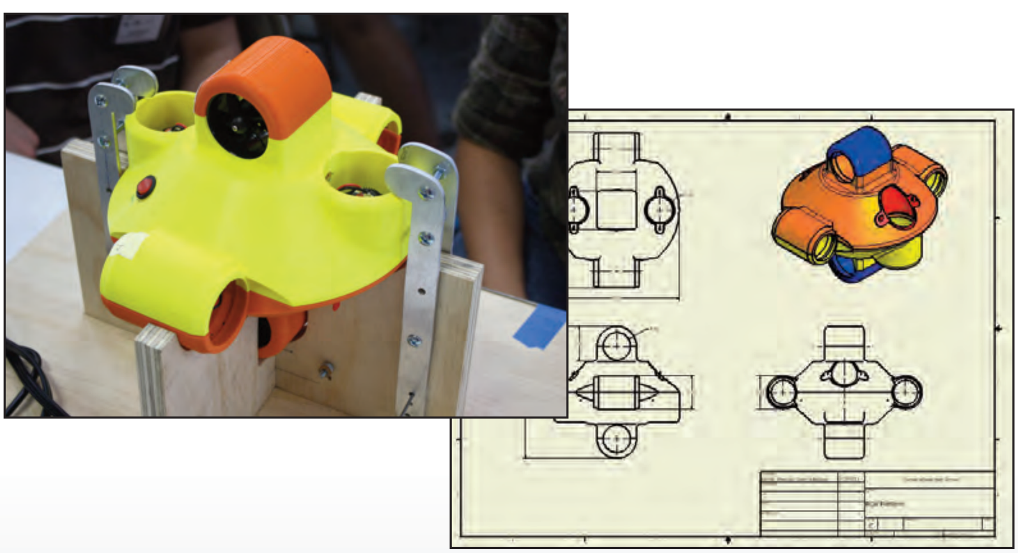
Finally, there is the domain of programming shapes using a language designed for computer-aided design (CAD). The idea here is that shapes are created by writing text-based programs that are compiled and exported to draw and assemble various shapes, useful when creating shapes that are either very simple, or very complex. This kind of tool is also perfect when designing things that require critical control over dimensions. By far the most popular language in this domain is **OpenSCAD**.

The OpenSCAD language can be used to draw simple shapes (like intersecting cones) and it also supports recursion, letting students design 3D fractals and other shapes that would be nearly impossible to make any other way.

But, to me, the biggest advantage of this tool is that it lets users create parametric designs. For example, if students want to design and build some propellers, they can write one program that uses variables to choose the number and size of the blades. By changing the values of the relevant variables, different propellers can be created with the same software. It is hard to overstate the value of parametric designs. File download sites like **Thingiverse.com** often include OpenSCAD files so that users are free to modify designs to their liking.

Other ways to make things to build include the use of 3D scanners and downloading finished designs from sites like Thingiverse. From an educational perspective, these options are not as interesting as using design software to create something from scratch. In the case of scanners, the user takes an existing 3D shape and scans it into the computer for printing. Aside from copyright issues, this task doesn't support the creative process.

Similar limitations arise with complete designs downloaded from web sites. With the exception of special parts (complex gears, for example,) students should avoid using downloaded parts and design their own shapes. There is a lot more learning going on when they design their own parts.



PRINTERS IN SCHOOLS

As this is being written, there are many 3D printers on the market at a wide range of price points. The printers most often found in schools use extruded plastic filament that is laid down on the print bed, layer by layer, to build a part. The two common plastics used are ABS (acrylonitrile butadiene styrene,) the same plastic as that used in popular snap-together blocks, and PLA (polyactic acid,) generally made from corn starch. This plastic is biodegradable, and either plastic works well for school projects.

Because parts are made from very thin layers, it is not uncommon to see print jobs take an hour or more to print—more time than a traditional classroom period. Student projects typically are printed overnight. And while steps are being taken to make faster printers, one present-day solution is to use a printer with a large print bed. This allows several projects to be printed at the same time. The total print time may be the same (typically determined by the largest part,) yet the ability to do several student projects together improves overall throughput.

CONCLUSION

Just as personal computers have become commonplace tools for learning, we see a similar future for 3D printing. As with the computer before it, schools may start with one printer, and then move to one printer per classroom. In addition (as with computers), it is likely that low-cost printers will start showing up in student homes. Since the format for 3D shape designs is universal, most printers can make the same parts (given size constraints).

3D printers have a powerful role to play in the classroom. In addition to strong curricular connections to modern standards, these machines support 21st century pedagogies that not only engage students in their present learning but teach them how to be "tinkerers" in learning the rest of their lives.

ABOUT THE AUTHOR

Dr. Thornburg has been writer, speaker, teacher, and visionary in the field of educational technology for decades and is the lead author of the book ***The Invent to Learn Guide to 3D Printing in the Classroom***, the first book to address the use of 3D printing technology in school settings.

CASE STUDY: CYPRESS WOODS HIGH SCHOOL

BUILDING REAL-WORLD VEHICLES FOR NASA

The High Schools United with NASA to Create Hardware (HUNCH) project provides students with the opportunity to design and build products for potential use in space missions. Its goal is to provide work experiences that inspire high school, career technology and engineering academy students to pursue careers in science and engineering.

As part of this project, NASA asked the students of Cypress Woods High School, near Houston, to design and build a remotely operated vehicle (ROV) that carries a camera and can maneuver around the International Space Station (ISS) under the direction of ground control. The ROV is needed because ground controllers need to be able to monitor experiments, check parameters on displays and gauges, verify switch settings, and perform other similar tasks without taking up the valuable time of the crew.

NASA engineers visited the school and presented the design requirements for the ROV such as size constraints, safety concerns, and avoiding interference with existing wireless equipment. Under the guidance of Mike Bennett, technology teacher for Cypress Woods High School, the students began by brainstorming different design concepts. Then they broke up into teams to research different aspects of the design such as propulsion systems, cameras, control systems, batteries, and so forth. Based on the results of their research, the students developed their initial concept design, first with hand sketches and later as detailed design in their CAD system.

“In the past, the tooling costs involved in conventional manufacturing methods such as injection molding would have made it impractical for the students to build a real version of their design,” Bennett said. “Fortunately, our school system had investedin Dimension 1200es 3D Printers for all of our drafting classes. So we were already familiar with the ability of FDM to build functional prototypes and end use parts with the mechanical properties needed to stand up to tough applications in space or on Earth.” Fused Deposition Modeling (FDM) technology is an additive manufacturing process that builds plastic parts layer by layer, using data from CAD files.

The student's ROV design features six FDM components including the bottom and top shell and four motor covers. The ROV is powered by six ducted fans providing two different directions of pitch, roll and yaw motion. The camera transmits audio and video on the 900 MHz spectrum. A radio control system designed for use with model helicopters was used.

The use of FDM technology made it possible to quickly improve the functionality of the design. For example, in the original design the motors would only fit one way in the housing. "After looking at the prototypes, we decided that it would be nice to be able to install the motor in either direction so we added a channel and a lip on the opposite side and printed out new shells," Bennett said. "The ability of Dimension to quickly and inexpensively produce parts that are strong enough for use in real applications opens up a world of opportunities for schools such as ours," Bennett concluded.

CASE STUDY: PARADISE VALLEY HIGH SCHOOL

KEEP STUDENTS EXPERIMENTING

Phil Howardell loves to watch his young engineers solve problems. As the lead instructor in charge of Paradise Valley (AZ) High School's Center for Research in Engineering, Science and Technology (CREST), Howardell takes pride in giving kids a solid foundation for careers in engineering.

For many CREST students, Howardell's Introduction to Engineering Design course is their first exposure to basic engineering principals and practices. It's easy for him to visualize the wheels turning inside his students' heads…and occasionally grinding to a halt.

"Our coursework is rigorous and challenging, even for students who have a good understanding of math and science," said Howardell. "Physical modeling is a huge part of bringing relevance to our curriculum and helping students analyze the work they're doing on the computer."

One of the students' first projects is to design and build a toy train, following precisely engineered plans. The lesson is designed to teach the importance of precision measurement; ideally, every train will be modeled identically according to the plan, but that is rarely the case. The students learn a valuable lesson about engineering: every detail matters.

The next project is more complicated—designing and building a model of an arbor press, one of engineering's most basic tools for machining parts. For both projects, Howardell uses a Dimension 3D Printer as a critical part of the lesson, helping students troubleshoot design problems based on actual, physical results.

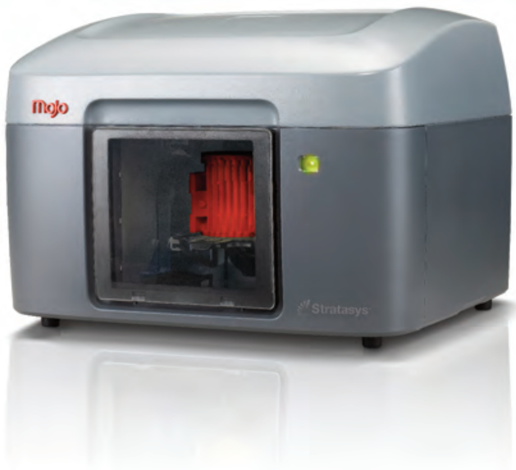
"Most students, when they first tackle the projects, will simply design and print non-working parts, so they can see how the process works," Howardell said. "As we get more advanced, we talk about things like clearance for moving parts, and they work through design revisions using the Dimension 3D Printer, in much the same way real engineers would use prototypes."

Howardell says one of the biggest benefits of the Dimension 3D Printer is that its use is scalable based on individual student abilities. If there are students who wants to explore design principals in greater detail, they can produce scale models without needing carpentry or machine tool experience. Likewise, for student who are struggling to master engineering concepts, a 3D prototype will help them see, touch, and feel his designs which enables them to better understand the design process.

For Howardell, "The ABS modeling materials is a key component for us, since we do a lot of post-forming with drills and lathes," he explained. "With other 3D printers, you can paint your models, but they crack and splinter when you try to mill them. With the Dimension 3D printer, I've made custom motorcycle parts that are durable enough to last for years."

Howardell believes that 3D printing is one reason his engineering courses are growing in popularity. "What I love about this printer is that my students can be as creative as they want," he said. "Our entire program is fueled by student interest and creativity and the Dimension 3D printer keeps them experimenting."

STRATASYS 3D PRINTERS



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