Integrating 3D Design and Printing with Core Subjects:
A Collection of Resources and Tutorials

by

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B.A., University of Victoria, 2008
B.Ed., University of Victoria, 2013

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Abstract

This project examined the best advantages and considerations in integrating 3D design and printing content into generalist educator practices. Previous literature demonstrated that 3D design and print in education could result in beneficial learning for students, but obstacles existed in how to train educators in using the technology, as well as how to seamlessly integrate the technology with cotemporary curriculum delivery. This project offered a resource of various units which educators could teach to engage in 3D design and printing with their students without sacrificing the learning of traditional core subjects and proposed a shift from teaching 3D design and print to students as a stand-alone topic to using 3D design and printing as a supplementary tool to be used to weave curriculum. The resource is published as a webpage, found at https://integrating3dprint.opened.ca/.

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Chapter One: 'Making' Memories

As someone who enjoys engaging in reflective practice, I like to put myself in my students' frame of mind. Specifically, as a grade eight teacher (students are 13 years old), it is basically a required habit to effectively teach without burning out. In beginning my scholarship into the field of educational technology, I reflected on the available technology during my stint as a K-12 student. While there was quite a variety of marvels in my time as a student such as the overhead projector, the television mounted on a four-foot-high cart, and the ground-breaking compact disc burner, there was no more popular machine than the hot glue gun.

Especially as a younger student, being provided the opportunity to construct three-dimensional (3D) objects with craft supplies was always a fun exercise, but the hot glue gun allowed objects to be free-standing, durable, and functional. Instead of relying on superior paper folding skills and access to tools sometimes found in home garages, hot glue was available to all students in a school at little cost. Apart from the occasional burn when dared to hold the output of the machine, they were relatively safe to use, and easy to understand: cold plastic adhesive goes in one end, gets melted by the nozzle, is extruded in a malleable bead with the help of soft kinetic force, which is then applied in a way per the user's design. The glue would rapidly cool, allowing for structures to be built upon one another. As a rhetorical exercise, I would ask the readers who attended school in the 1990's in 2000's if they have any memory of using hot glue in an assignment or project. I believe most, if not all, would have a story.

Topic

In its application, abilities, and impact, 3D printing is the new hot glue gun. As a relatively new and complex technology, one may find it easy to declare that 3D printing is better left to the technologically inclined, requiring an aptitude for computer science and engineering. But when describing my use of the technology to the un-initiated, I find they simply do not know what 3D printers "do". In essence, 3D printers are analogous to the hot glue gun itself: cold plastic goes in one end, hot malleable plastic comes out the other, and is applied as per the user's specifications.

Obviously, there are many differences between the two: precision of hot glue is limited by the user's steady hand, while 3D printers are consistently accurate to tenths of a millimetre. Hot glue guns are a manual tool requiring constant input from the user, while 3D printers are automated machines which can be left to complete their task. With a hot glue gun, the user places the glue in real time while in 3D printing the placement of the plastic is pre-determined through software, which the printer hardware applies automatically. A simpler analogy may be to consider writing a hard copy essay by hand versus typing the hard copy on a computer. When writing by hand, the user applies the ink as they go. When typing an essay all word processing happens with software, which is then sent to an inkjet printer which automatically places the ink as per the user's specifications.

However, the analogy of writing versus typing an essay lacks the 3D aspect of the hot glue gun: hot glue can be applied to a surface on any axis in the real world, it is not constrained in the two-dimensional realm of pen on paper or typing on a computer monitor. By creating a structure with framing and motors to access all three axes, a 3D printer can also apply plastic material in the 3D realm.

Once again reflecting on my experiences as a student, I asked myself what I remembered about my education when using hot glue gun versus not. More specifically, what I learned or expressed when I had a fabrication machine integrated into my education, versus what I learned without one. Upon this reflection, I realised that in my entire run as a K-12 student, the memories and learning experiences that stuck involved artifact creation.

I created this project to deliver a path for students to cement memories of learning experiences through artifact creation akin to my own experience, but with the powers of the technology we have at hand today, specifically 3D printing. It is a rather simple connection to the colloquial understanding among educators that students will typically remember things that exist as a concrete object before creating transferring their understanding to abstract thought. This understanding is grounded in Constructivist thought put forward by Jean Piaget, discussed in my theoretical framework. From a learner's perspective, we tend to look forward to when we get to apply an idea, thereby learning by 'doing' and delving into more exploration and manipulation, an idea also grounded in my framework with

Seymour Papert's Constructionism theory. However, the perspective of the learner is only one half of my rationale for the project: there is also the perspective of the educator, and thereby the educational obligations, to consider.

Professional Journey

When I began my teaching career in 2013, computer technology in public schools was scarce. Of course, each school I would arrive to as a teacher-on-call had a computer lab, featuring 20 to 30 desktop computers running Microsoft's Windows 7. Students and teachers would share access to these labs, often through a booking schedule in the form of a non-live word document that was almost never current. Inevitably, there were conflicts both in scheduling and equitable use. Most teachers decided it was not worth the trouble. "Children shouldn't be learning on computers" they would say, "They need their basics with reading and writing, computers don't do any of that."

As a new teacher and substitute, I would often be imparted this knowledge from senior teachers, usually in the staffroom during lunch hour. As an early adopter I practiced active listening in these conversations, but would disagree with the point of view of these teachers. "What did they know about technology if they aren't using in practice?" I remember asking myself. In fairness to these teachers, my bias as an early adopter coupled with the naivety of a new teacher would later put me in situations where I would experience their point of views the hard way.

As each school years went by, the trials of different technologies progressed as I started to work in temporary contracts at various schools. Once, I found myself working at a school which had 20 laptops that could be used for word processing. I would plan lessons around the use of these laptops, but they fell apart for several reasons. The computers were not connected to a internet, so students would constantly lose their saved (or unsaved) work. The demand for the technology showed the supply to be vastly insufficient, and the computers were almost never available. Most importantly, I did not *need* to use the technology in my lessons; I was not teaching any sort of relevant curriculum connected to their capabilities. I experienced this arc several times with different technologies, such as iPads and Chromebooks, until the school district made two specific leaps in technology assets.

The first was my school district buying into the cloud computing of the Google Suite for Education. Students could now save their digital work and connect to it at any future time from any given machine. The time of USB sticks and emailing themselves their documents was over. Second, the school district diverted much more funding into hardware acquisition, bringing the ratio of computers available to students from 1:25 down to 1:3. This allowed computers to be integrated into practice in a much more comprehensive way, rather than using them for a block per week as a novelty.

With these major changes in the availability of technology in schools, I was able to plan and practice teaching that integrated word processing, cloud computing, and access to the internet as givens rather than scarce privileges. As my career progressed over several years, I would become more comfortable and knowledgeable about the curriculum in British Columbia (B. C.), specifically the curricular and core competencies (what the students would be able to know and do). To my dismay, I eventually arrived at a crossroads: for all the work I had done in integrating technology into my practice, were my students acquiring the competencies prescribed by the curriculum? Had I taken to the other extreme of those veteran staffroom teachers, rejecting their dismissal of technology in such a personal fashion that I had sacrificed my students' acquisition of curricular competencies in favor of technology use?

It was at this point that I began questioning my practice and attempted to explore more holistic ways of technology integration. During my exploration, my school, where I was now a full-time continuing teacher, acquired a 3D printer of which I had access to. In excitement, I had explored various things to print with my students, such as trinkets and key chains, but nothing substantial. This highlighted my integration problem: the 3D printer was not being used for anything substantially curricular. Of course, I could somewhat connect to Applied Design Skills, and Technologies (ADST) curriculum when using the printer, but not to any traditionally core subjects. The following section is an explanation of how

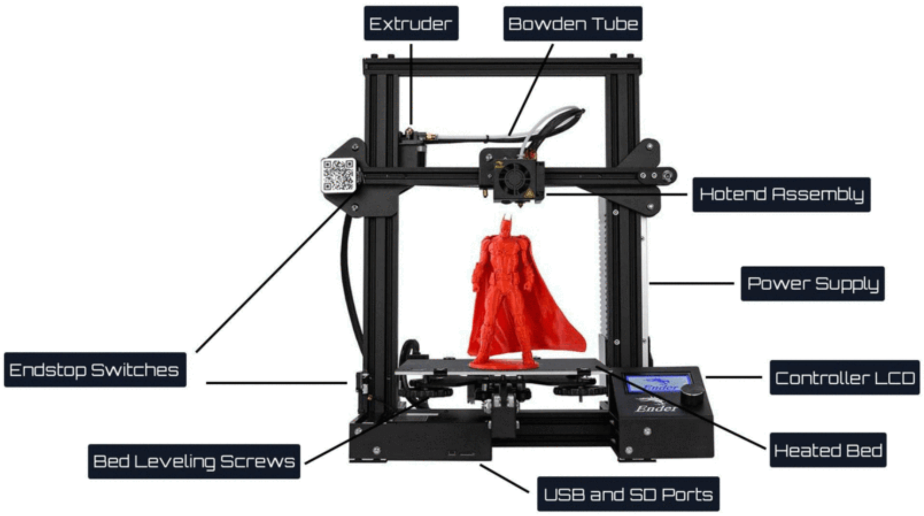
3D printing technology works and includes stories of professional 3D printer use which will highlight the problem of a narrow specialty curriculum and skill set.

Technical Aspects of 3D Printing

As a topic, (3D) printing is often thought of as a complex technological process which the layman tends to think is beyond them. I believe this attitude is fair considering the computer science and engineering required to produce the apparatus, but with a few simple comparisons, such as the glue gun analogy, the one can see that the attitude above is just a stereotype of being non-technological. The first four of the following figures and show the hardware of 3D printers, depicting an overall point of view as well as close views of key components. Figures five and six depict design and programming interfaces, and figure seven shows a 3D printed project.

Figure 1

3D Printer Overview

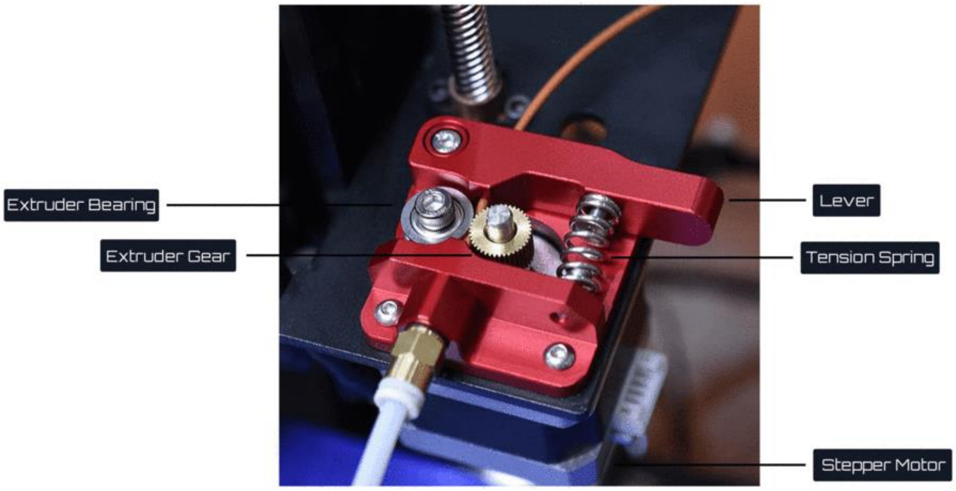


Note. Reprinted from *Ultimate 3D Printing Beginners Guide – Creality3D Store® Official Store for Creality 3D Printers and Accessories*, 2020. Copyright 2020 by Creality3D Store.

Figure 1 is a labeled photograph of the "Ender 3" 3D printer model produced by the commercial company Creality. The company produces a variety of models most of which use a process call Fused Deposition Modelling (FDM). A competing 3D printer manufacturer, Makerbot, explains FDM: "It uses an extruder, which acts similar to a hot glue gun. Plastic filament is fed in through the top, is melted at 215℃, and finally is 'extruded' out of a small nozzle into the layers that build a 3D print" (MakerBot, n.d., para. 1). When a FDM printer such as an Ender 3 prints an object, layers of plastic are deposited on to the heat bed from a nozzle at the end of the hotend assembly. Rails and motors are fixed on the frame of the printer allowing the hotend assembly to moved in all axes.

Figure 2

3D Printer Extruder



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In Figure 2, the printer's extruder (the motor that feeds the filament fowards) is connected by a tube to the hotend assembly, in Figure 3. In thinking of the glue gun example put forth by Makerbot, Figure 2 would be analogous to the rear of the gun where the glue stick is mechanically fed towards the nozzle, and Figure 3 would be analogous to the front of the gun where the glue is heated and then deposited through the nozzle.

Figure 3

3D Printer Hotend Assembly

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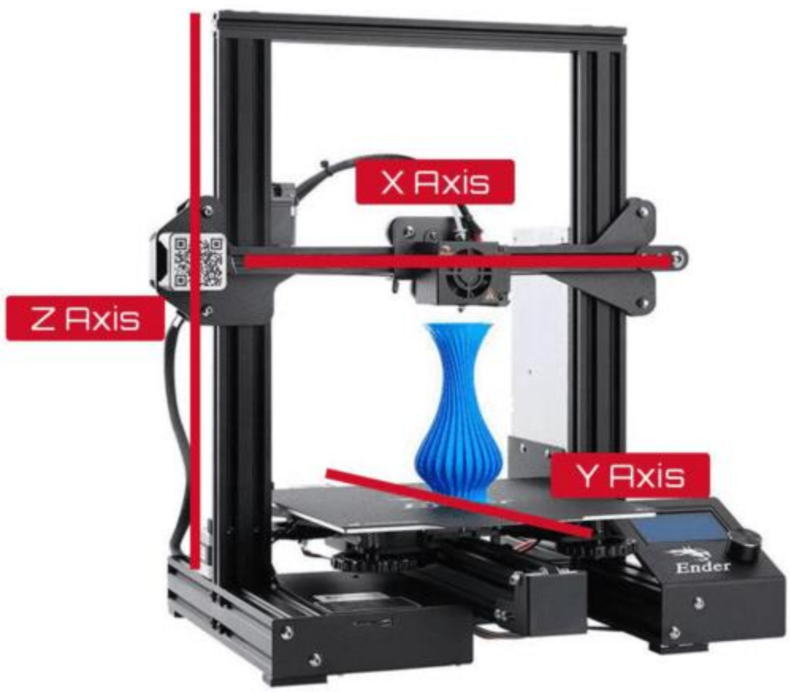
The above explains the hardware components of a 3D printer, but I will expand on the idea of "layers." Consider the construction of a residential apartment tower. The layers of a 3D print are akin to constructing the tower: Upon breaking ground, crews must lay a foundation, then build from the ground up. Once the first floor is complete, the second floor can be constructed on top of the first, and so forth. In this case, the floors of the tower are the "layers" of the tower's construction. Further, consider that each floor of the tower could be spatially considered in 3D measurements; each floor would have a length (x), width (y), and height (z). All 3D printers operate on the use of these measurements: they "know where to move using a 3D cartesian coordinate system which defines every point of a 3D model with a unique position along the X, Y, and Z axes" (MakerBot, n.d., para. 2). The hotend of a printer (the nozzle) is mechanically moved from one 3D coordinate to the next (sometimes laying a strand of plastic as it travels) with actuators and motors attached to rails on the frame of the entire apparatus, as shown in Figure 4.

Figure 4

3D printer Axes



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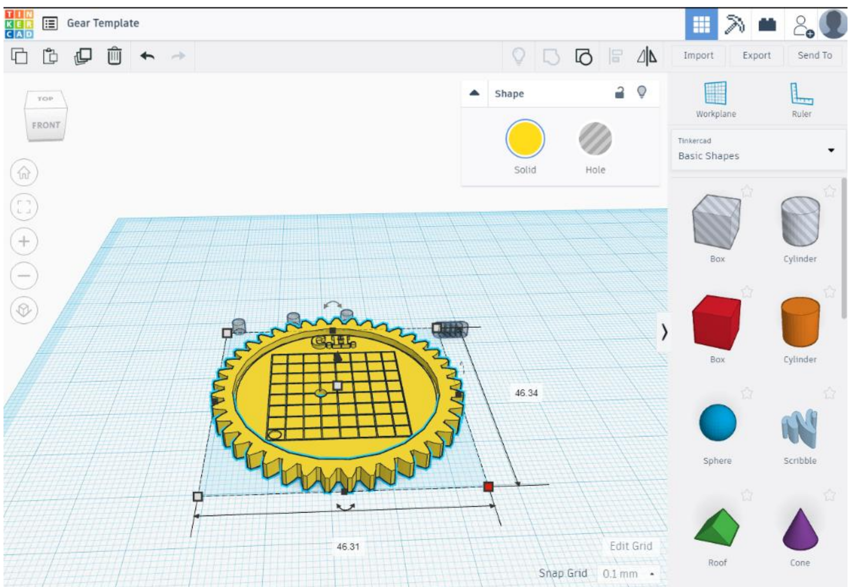
In some models, the extruder and hotend are built as a single unit and mounted on the rails. The filament is simply stored on a spool mounted to the frame, akin to thread on a sewing machine. As filament is extruded, motorized gears feed more filament into the extruder from the spool.

The next figures depict the design and software tools need to use a 3D printer, as the printer must somehow know the set of coordinates which it will move to. Before a 3D model is physically printed, it is first virtually modelled in any given 3D modeling software suite. The process of using software to create a virtual model is called Computer Assisted Design (CAD).

CAD software is similar to drawing applications (such as MS Paint) which feature a canvas where users can insert or draw geometric shapes and then edit them to their specifications. However, the canvas in CAD software is three-dimensional rather than two-dimensional and is ubiquitously precise in what degree a user can alter an object's dimensions, often down to the tenth of a millimeter. Tinkercad is a free web-based CAD suite, good for beginner-intermediate level digital design. A Screenshot of the software is shown in Figure 5.

Figure 5

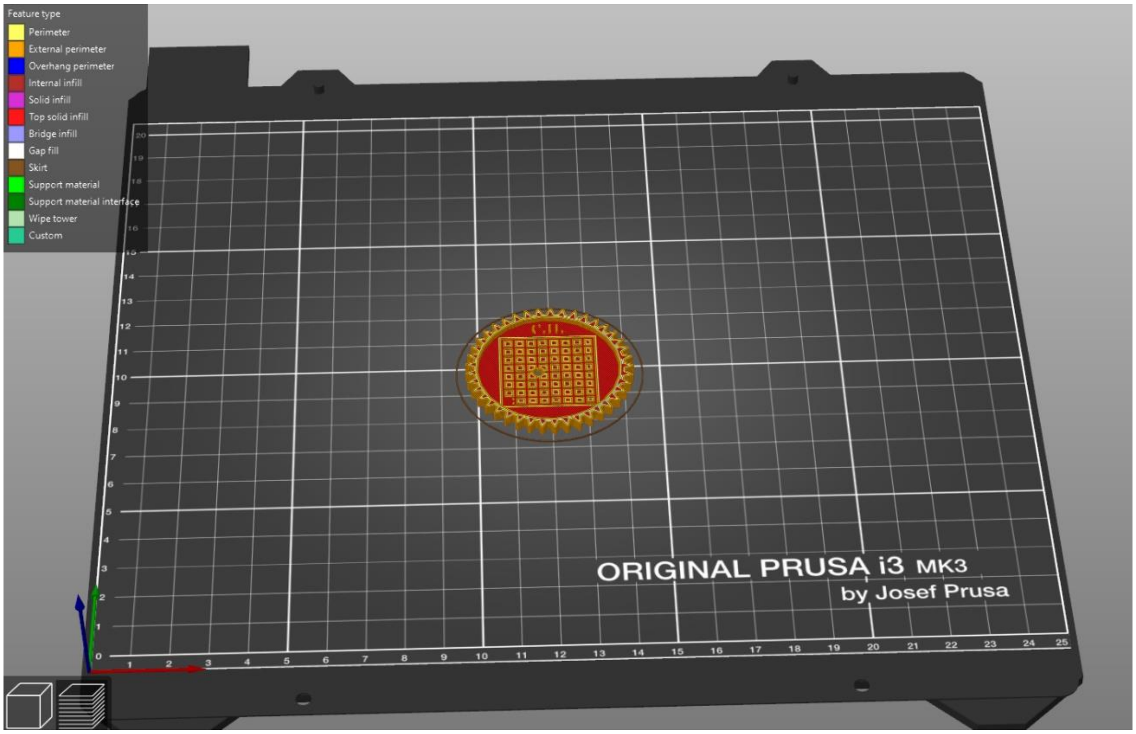
Tinkercad Interface



Once a user has drawn their virtual object in a CAD suite, the file must be transferred to additional software which translates the object "into a language the 3D printer can understand. This is referred to as slicing" (MakerBot, n.d.). Figure 6 shows the same shape from Figure 5, but sliced and ready to be uploaded to the printer. Usually, slicing software is specific to the printer model, but can also support other models.

Figure 6

Slicer Software



Note. This screenshot was taken in the Prusa Slicer 2.2.0 software suite.

In short, the workflow of 3D printing is thus:

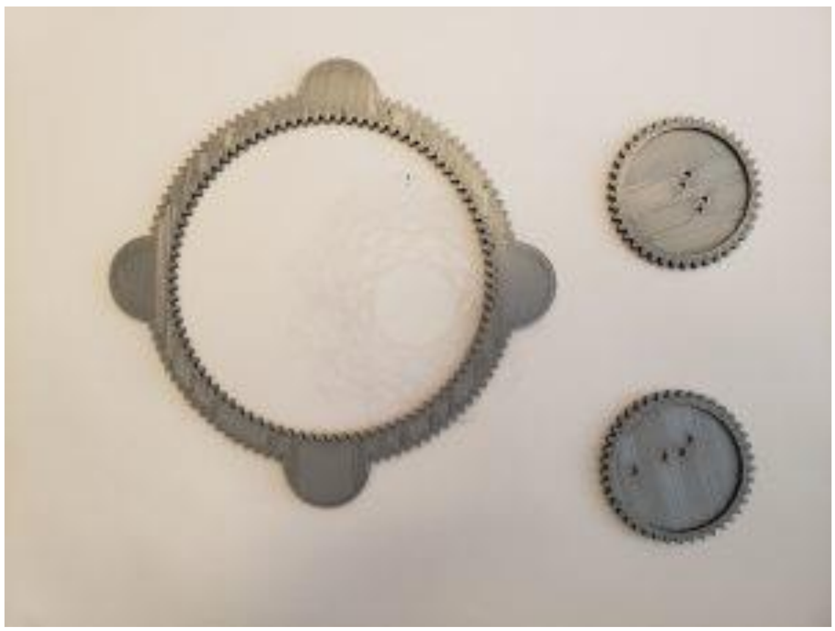
1. Create a virtual model with CAD software.
2. Slice the object using Slicer software.
3. Upload the sliced information to the 3D printer.
4. Print the model. Depending on the print settings, assembly may be required and/or waste filament may need to be removed.

Additionally, it is important to consider the various types of plastic filaments available, as “one of the most important parts of 3D printing is to use the right kind of material for the job in hand” (3D Insider, 2017, para. 4). For example, Acrylonitrile Butadiene Styrene (ABS) plastic, is tough and has impact-resistant properties, which makes it a good choice for printing plastic automotive parts, moving parts, musical instruments, kitchen appliances, electronic housings, and various toys. However extruding

ABS produces unpleasant fumes that can irritate some people (3D Insider, 2017). Whereas the Thermoplastic Elastomers type (TPE) has such high elasticity properties that it feels like real rubber, easily springing back into shape like an elastic band which makes it a good choice for seals for windows and doors, electrical insulation, and the soles of footwear (3D Insider, 2017). However, TPE can extrude inconsistently, and inexperienced users will find it difficult to use (3D Insider, 2017).

Figure 7

Printed Gear Shapes



In Figure 7, two copies of the fully printed shape from Figure 5 and 6 are displayed along with their 3D printed counterpart. These objects were printed with Poly-Lactic Acid (PLA) plastic, a durable, non-toxic, and beginner-friendly material. Looking closely, one can see striations on the objects, a result of the of how the strands of plastic are thinly layered and deposited by the printer nozzle.

Innovations: Narrow, Complicated, and Individual

Applications of 3D printing are often trumpeted by printer producers as they aim to innovate (and profit from) their product. Prusa 3D, best known for the “Prusa i3” line of printers, has digitally published stories of printing applications in fields categorized as medicine, art and design, education, and toys or hobbies. Said categories were convenient in sorting the stories, but I found each story in every category comes back to the same roots: designers would innovate existing technologies requiring artifact creation. Consider the following Prusa stories, beginning with the field/category of medicine, specifically in dentistry. Lukas Pekarek, the founder of Asana-dental, responded to a COVID-19 related problem:

> When dentists use their drills and other rotary tools, they need to cool those down with a constant flow of water. This water mixes with air and the patient's saliva and/or traces of blood into a potentially infectious aerosol. Like a hardly visible light mist, the aerosol could travel as far as 8 meters from the patient's mouth. (Prusa 3D, 2020, para. 2)

Pekarek developed the Asana suction system, which consists of a handful of parts created with 3D printing technology which come together to create an "apparatus which is put near the [dentistry] patient's mouth and traps the aerosol right at the source. Heavy water droplets still sprinkle around, but that's not such a big problem, as they fall down quickly and cannot be inhaled" (Prusa 3D, 2020, para. 4). The implied function of his apparatus is to replace the need of a nurse/hygienist to hold a suction tool, thereby removing one vector for disease transmission. As Pekarek was in the design phase of his creation, they closely cooperated with a medical professional to refine the design and tested prototypes (Prusa 3D, 2020). Pekarek noted that a real 3D object is always better than an image on a screen and helps him better prepare for the more difficult procedures (Prusa 3D, 2020).

In the art field, Joshua Lee is an animatronic model senior designer, with more than 25 years of experience in the film industry (Prusa 3D, 2019). They began using 3D printing when working on animatronics for the 2012 *Prometheus* and progressed to building the "droids" for the recent *Star Wars* films. As they're tasked with creating models, sculpts, and animatronic robots in rather short timeframes, they have found that a 3D print is just an incredibly good starting point for very complicated processes (Prusa 3D, 2019). Interestingly, Lee makes a distinction between object *concepts* versus object *construction* in their trade, a point I will address later:

> The best thing about my job is, that every film, you get a very clever director and writer coming up with new challenges. What I really enjoy is someone saying, wouldn't it be great if we could get a robot that did that? It's like being given a puzzle, and you have to work it out. I really enjoy

just getting those puzzles from directors and writers. And figuring them out. I am not very good actually at inventing those puzzles myself. (Prusa 3D, 2019, para. 26)

Along the same vein of creating solutions, Prusa's educational examples feature the story of Petr Dušek who created a "Haptic Model of the Night Sky," which is a printed night sky dome which allows visually impaired people to "touch the stars". Like Lee, Dušek was presented a puzzle to solve, one specific to education:

> Teaching [astronomy] is usually based on learning about astronomical phenomena observable with the naked eye. The problem, of course, arises when sight does not serve as it should. A visually impaired person is deceived by many astronomical beauties that non-visually impaired people take for granted - there is a significant information deficit in the field of astronomy for the visually impaired, which I am trying to reduce. (Dušek, n.d., para. 2)

Thanks to media coverage and community vigor, a rather ubiquitous example of creating solutions using 3D printing is the encouragement by both owners and producers of 3D printers to create face-shields. As COVID-19 overwhelmed healthcare systems, suppliers struggled to meet demand for Personal Protective Equipment. In reaction to the shortage, Prusa quickly developed and started to mass-produce protective face shields. In their blog, Prusa stated:

> We have already printed and donated almost 200,000 shields to medics and other professionals in the Czech Republic. But the shortage is global and everyone with a 3D printer can help! 3D printing communities across the world became a massive driving force in the effort to produce protective wear for those, who need it the most. This is why the design of the shields is fully open-source, anyone can produce it and/or modify it. Also, the shields are made from easily accessible and inexpensive materials. We would like to ask you to help us by spreading the word or even joining the collective endeavor - as a community, we can help thousands of people in need. (Prusa 3D, n.d., para. 3)

The preceding example demonstrates that the use of 3D printers can also be for simpler designs and shows how the 3D printing community can be put to action with no cost or licensing. Big problems can be solved through prototype designs and said designs can be shared and modified on individual bases allowing designers to hone their skills, innovate existing technology, and apply their skills to aid communities at large.

In all of these examples, users and creators identified how 3D printing could improve their own ability to practice their trade, be it educational or vocational. In their stories, they were able to start with an existing medium of a given concept then shift, or re-hash the concept into the 3D design realm, and then manufacture objects seemingly superior to the original medium, implying that use of 3D printing would become mainstay in their practice.

However, each example demonstrated a narrow and complicated application of the printer which required high levels of expertise from each user and a background in specific education/curriculum. In learning of these stories and others, I was without a plan of how to weave 3D printing with K-12 students. The turning point came during a conversation with one of my colleagues during a recess break. As I proclaimed my hatred for teaching poetry in conversation with my colleague, she patiently allowed me to vent while chuckling at my complaints. She then asked me “Could you find a way to teach poetry with 3D printing? That would fix your problem.” I began to smile at her lighthearted sarcasm, but then I had a moment of insight: I thought of a unit which *could* teach poetry by having students create artifacts with the 3D printer. These artifacts would connect back to the core and curricular competencies in literacy and numeracy, specifically English Language Arts and Mathematics. This epiphany shaped the second half of my rationale for my project.

Purpose

I believe there is a gap between the application of Science, Technology, Engineering and Mathematics (STEM) and traditional literacy, numeracy, and artistic expectations. Educational content should be developed to bridge this gap, and it should do so in way that allows students to create lasting memories of their learning using physical artifacts.

Therefore, the first goal of this project is to provide educators with several 3D printing units which can be integrated into their practice without detracting from typical or established content. Second, this project aims to demystify 3D printing as something only meant for the technologically inclined. To these ends, I have designed several of units which integrate areas of curriculum which are often found apart from one another or are too easily taught only in abstract ways without artifact integration. The technological limitations of the units in this project are that the units do require access to a 3D printer, internet capable computers, and a camera.

Project Overview

My project will feature three 3D printing units which integrate with traditional curriculum. Each unit will include the overall unit plan, lesson plans for each module of the unit, and the resources (templates, handouts) required of the unit. Further, the project will feature five videos which will:

- Introduce 3D printing and each unit (Video 1).
- Demonstrate each unit (Videos 2-4).
- Reflect on the challenges or difficulties of teaching the units (Video 5).

The most tested unit in this project is introducing 3D design software, also known as Computer Assisted Design (CAD), to students with several metrics found in poetry. The unit begins with teaching students about syllabic and word count importance in poems, moves onto ordered pairs and basic algebraic equations, then into CAD, culminating in a recorded and narrated artistic expression of their poem with a printed artifact in the form of a spiral-drawing (akin to the Spirograph toy) gear.

The second unit integrates CAD with Fine Arts and First Nation studies, where students are tasked with creating stencils for basic First Nation drawing shapes, then refining the stencils so that other students may learn and practice the techniques to draw them. The stencils are first produced on paper, then students practice uploading and modifying their scanned work into printable plastic stencils. In this case, the artifacts are the stencils, which can be various sizes or shapes or even an entire image. In an effort to encourage student driven creation of the materials, students will only be provided with a small amount of pre-made stencils before they are asked to create stencils of other shapes, or perhaps common and/or difficult drawing components.

The third unit, meant for beginners, focuses on measurement as it will teach students the basics of using CAD software (which is measurement heavy). Students are tasked with creating a ruler which will double as a writing aid, where they will embed custom shapes as voids to serve as a personalized stencil. After teaching students Standard International units (specifically meters, centimeters, and millimeters), the students will design their ruler on paper to scale, then transfer the scale and values of their design to the medium of the CAD software. This unit is more obvious in its connections to CAD, as geometric qualities are ubiquitous with the CAD process.

Ethical Considerations

In the presentation of the units on the website resource, anonymized student examples are included in digital galleries respective of each unit. Participants were recruited by a third party and were required to consent to having photographs of their works published. Approval to conduct the research (the collection and publication of their works) was provided by the Human Research Ethics Board (protocol #21-0044) and the Greater Victoria School District.

Search Methods

To inform my literature search, I began with research conducted by Nemorin and Selwyn in 2017 which examined the experiences of 3D printing by a high school tech ed teacher, as well as research by Trust and Maloy in 2017 which examined the impact of tangible objects on students learning. These two articles formed the base of searching and exploring the benefits and caveats of 3D printing in the classroom.

I conducted most of my research through the University of Victoria database, which suggested articles as I searched for the terms “3D printing,” “artifacts,” and “design thinking,” with filters to only include journal articles tagged with educational content from the last three years. Three trends emerged during my searches in the database.

First, articles would widely vary in their content: 3D printing has been applied in my different fields and fashions, therefore the database returned articles that ranged from comparing brands of printers to printing artificial organs in the medical field. Due to this fact, it was difficult to narrow down the content in the search engine, and I found more success in researching the cited articles in applicable results.

Second, the filter of including only articles in the last three years substantially reduced the number of results when partnered with the education filter. When I changed the filter requiring within three years to five, substantially more results were found. I assume this was due to 3D printing being more of a boom in the mid-2010s, coupled with its trend to be more common in higher education and industrial manufacturing at present day.

Third, articles which promoted 3D printing never included examples of how to adequately connect activities to curriculum. Of course, any article on 3D printing quite easily pointed out how a basic knowledge of the field connected to STEM, championing the possibility for innovation in education with new and exciting technology. Nemorin and Selwyn (2017) found that it was a tendency of school administrators to use buzzwords like “innovation” when describing their school’s acquisition of a 3D printer, never actually providing examples in its educational value. I found most articles I reviewed to examine the same flaw, which motivated me to create a project which could provide educators with examples of real educational application.

As I have chosen to focus my project on the use of 3D printing and design, I could only blush at one of the first pieces of literature I examined: in her report of her year-long experience of 3D printing in an instructional setting, Brown “could not go more than ten minutes in any meeting on campus without mentioning digital printing” (Brown, 2015, p. 20), which basically describes my (and unfortunately for them, my cohort’s) experience in grad school. I did question whether I had fallen prey to early-adopter hype; with a cursory internet search, one can find a plethora of videos and articles demonstrating the wonders and imagination that come with 3D printing, spurring the mind into imagining all the problems and issues that can suddenly be answered with 3D printing. I admit that if one does not do their research, they may simply be sold a product by companies that have a bottom line. However, this admission energized my research and allowed me to determine a recurring theme in the literature, including how that theme leads to other prevalent topics of discussion in the literature.

Chapter Two: Theoretical Framework and Literature Review

Theoretical Framework

Ackermann's (2001) contrast of Piaget's Constructivism theory and Papert's Constructionism theory provided framework needed to address the benefits of learning through making, specifically starting with the pedagogical ideas which Constructivism suggests and then transitioning to Constructionism praxis.

Regarding Constructivism in education, Ackermann (2001) described teaching as always being an indirect activity, in that students would both absorb literal sensory input but also transform the input to suit their prior knowledge. Therefore, a teacher cannot assume that a given student's wholesome learning experience is sufficient in a stand-and-deliver style, or as Ackermann (2001) states:

> The transmission model, or conduit metaphor, of human communication won't do. To Piaget, knowledge is not information to be delivered at one end, and encoded, memorized, retrieved, and applied at the other end. Instead, knowledge is experience that is acquired through interaction with the world, people and things. (p. 3)

To move away from the "transmission model", a student's acquisition of learning in traditional core subjects through exposure and practice with CAD and 3D printing could be a path forward, in that it would shift the typical pedagogy associated with those traditional subjects. Ackermann (2001) argues that conceptual change has almost a life of its own and any theory of learning (or pedagogy, I would put forward) that ignores resistances to learning misses the point, as students have good reasons to not simply take a teacher for their word. However, this does not hold as a justification as to why CAD and 3D printing are contextually important for students: one could argue the gradual shift from situational to universal logic which Constructivism puts forward could be accomplished by other means.

At this junction, Ackermann argues that the role of context, uses, and media in human learning is important, and overlooked by Piaget (2001). Papert's concept of Constructionism is a highly contextual approach, which "helps us understand how ideas get formed and transformed when expressed through different media, when actualized in particular contexts, when worked out by individual minds" (Ackermann, 2001, p. 4). To Papert, knowledge is essentially grounded in contexts and shaped by uses, thereby making knowledge "situated" and should not be detached from the situations where it is actualized (Ackermann, 2001). The idea of situated learning has been interpreted in multiple ways which vary, but they all challenge the Constructivist notion that knowledge *needs* to transition to universal thinking (Ackermann, 2001) which strengthens the cause for learning in multiple ways, which is a "principle of learning" in British Columbia (British Columbia Teacher's Federation, n.d.).

However, Ackermann shows Papert acknowledging that "different individuals may develop their own ways of thinking" (2001, p.6) implying that both theories are valid, as both Piaget and Paper are Constructivists in that they view children building their own cognitive tools and their external realities, and that both define intelligence as the ability to maintain balance between continuity and diversity.

Since my research project will involve designing and printing 3D artifacts, Ackermann's (2001) conclusion of the feedback loop between Constructivism (stepping back) and Constructionism (dwelling in) provides the best grounding for my work:

> There comes a time when one needs to translate the experience into a description or a model. Once built, the model gains a life of its own, and can be addressed as if it were "not me." From then on, a new cycle can begin, because as soon as the dialog gets started (between me and my artifact), the stage is set for new and deeper connectedness and understanding. (p. 10)

Why Use 3D Printing in Education?

The first theme apparent in the literature was promoting use of 3D printing and design in education. Brown's (2015) feelings of excitement for possibilities and applicability of 3D design and printing in a school setting are ubiquitous to educators introduced to new resources and technologies. Trust and Maloy (2017) findings encompass a collection of optimism from teachers:

> Educators, policymakers, and community members are asking, "Why 3D Print?" as they weigh the costs and benefits of investing in 3D technology for schools. In this study, we found that a majority of teachers, from multiple grade levels and subject fields, who are using 3D printing in

> their classes, believe these tools promote student learning of 21st-century skills. Not only does using this technology introduce students to the procedures and practices of 3D modeling, but it also promotes creativity, technology literacy, problem solving, perseverance, and critical thinking. To a lesser degree, those same teachers see 3D printing supporting teamwork, communication, decision making, mathematical reasoning, and adaptability among students. While these findings are tentative and invite further in-depth research, 3D printing does provide engaging ways to motivate the learning of 21st-century skills in school classrooms. (Trust & Maloy, 2017, p. 265)

The particularly important concept is the notion of inspiring or empowering learners as “using physical materials is a great start to help foster creativity and develop basic analytical and critical thinking skills” (Trust & Maloy, 2017, p. 265). In the context of 3D printing, not all students may achieve a functional print, but in simply using CAD software (which often features premade, modifiable templates) allows them to experience creative/free-form manipulation of a virtual 3D object.

The connection between creativity and critical thinking suggests that we are “enabling students to create and construct knowledge as they transform ideas from their imaginations into physical objects and models that represent those ideas” (Trust & Maloy, 2017, p. 265). I will refer to “physical objects” and their digital models henceforth as artifacts, as it is the creation of objects and their inherent connection to the creator which my research is examining. Specifically, how artifacts:

> Can provide clear descriptions of designs, principles and processes. They can communicate across boundaries of discipline and experience. They can support the progress of research and they can be instrumental in eliciting knowledge, including tacit knowledge, in and from individuals. (McAra, 2019, p. 586)

In terms of promoting technological literacy, problem solving, and mathematical reasoning, consider 3D printing in the field of STEM. In their study of “Making Classrooms” Chu, Schlegal, Quele, Christy, and Chen (2017) argued that early self-efficacy in STEM domains seems to be critical to promoting long-term interest and persistence in STEM fields (p. 111), Brown (2015) similarly found that engineering as a practically applied activity offers students opportunities to gain an understanding of scientific and mathematical concepts in context. Imagining that students followed through with their interest and opportunities, Nemorin and Selwyn (2017) argued that students could be ready for the STEM field based on Eisenberg's (2013) claim that "3D printing has obvious correspondences with the growth of 'additive manufacturing' industries and what has been heralded in some quarters as 'industrial revolution 2.0" (as cited in Nemorin & Selwyn, 2017, p. 579).

When searching for the keywords 3D printing and STEM in the University of Victoria database, almost all articles stated or implied that any application of 3D printing and design would inherently overlap all four of the subjects in STEM in a multi-disciplinary approach. Some literature reflected the focused, specific application of 3D printing and design in a single subject of STEM, shown in Table 1.

Table 1

3D Printing Tasks Specific to One Domain of STEM

Author	Domain/Subject	Project/Assignment	Findings
Porter et al., 2016	Science (Secondary, Post-Secondary)	Alterable designs, including ready to 3D print files, of a Colorimeter (a device which measure the absorption of wavelengths by a solution) were given to students in order for them to produce inexpensive equipment or alter the equipment to suit their needs.	Students found they could easily customize the models to explore concepts inaccessible with conventional models, and the printed models performed quite well compared to commercial models.
Schelly et al., 2015	Technology (Elementary, Secondary)	Teachers attended a workshop where they built a 3D printer. Parts for the printer were made available to the teachers from the outset. Assembly instructions were available on the web as open source blueprints.	Teachers felt empowered to create a functional piece of technology through open source guidance coupled with their own trial & error and suggested the students would see themselves as active creators if they engaged in the same process at school.
Nemorin and Selwyn, 2017	Engineering (Elementary, Secondary)	Observed the application of 3D printing in a Technology Education class, specifically creating 3D printed model race cars.	A lack of 3D printing fluency and experience on part of the teacher, a lack of student involvement in the printing process, and the length of time to print large models led to ineffective implementation of 3D printing in practice.
Ng, 2017	Mathematics (Elementary)	Students learned of and explored the concept of geometric volume while designing keychains	All students who participated demonstrated a fluency in computer assisted design, and they also developed the mathematical vocabulary related to the subject/task.

With general knowledge of STEM curriculum, an educator could argue that the assignments of 3D printing featured in Table 1 do not differ in their domain, in that the overlap of skills in STEM is quite large. However, it is important to demonstrate that different assignments in 3D printing can specialize in different subjects such that the applicability of 3D printing can be instituted by educators comfortable in various fields. Thanks to movements and initiatives geared to open source, that is to make instructions, blueprints, and software free and accessible, teachers are being provided free instructions on how to both build printers and designs. As mentioned in Table 1, Schelly et al. (2015) studied how teachers (in a learner role) responded to a workshop where they built open source 3D printers. The motorized components as well as the electrical components of the printer were bought separately, but all plastic pieces were previously 3D printed. The workshop also linked to open wikis and online tutorials of how to construct the printers. The participant's responses indicated that teachers learned ways to use 3D printing in their practice, where "only two out of 14 said they were still unsure how to tie it in to required teaching curriculum" (Schelly et al., 2015, p. 232). It is uncommon for a teacher to assemble a 3D printer as they would lack the expertise or time to do so, and most printers can be acquired pre-assembled. However, the construction of the printer did allow some teachers to acquire expertise or generate ideas of 3D printing integration.

Most of the literature used teacher observations to "indicate that learning activities, which require the creation of digital artefacts, produce a greater engagement with learning literature," (Walton, Childs, & Jugo, 2019, p. 1070) and that "the prospect of creating a 3D physical model motivated students to take ownership of their learning" (Trust & Maloy, 2017, p. 263). As my project will be focused on my own observations, and perhaps those of other teachers, this leads to another common theme in the literature, the methods and realities of implementation.

The Realities of Implementing 3D Printing

The previous theme in the literature has an optimistic and exciting tone, but in each piece of literature, the reality check of implementing 3D printing and design soon followed. In the previous example, not all learners (the teachers) benefited from constructing printers. Furthermore, considering that 3D printing requires some CAD software, a common problem which researchers found was that "while this evolving technology offers great potential for educators, the barrier to entry is often intimidating for those unfamiliar with CAD software and fabrication equipment" (Porter, Washer, Hakim, & Dallinger, 2016, p. 1305). In encountering said barrier, a teacher will at could develop their expertise from a beginner level such as in a workshop where printers are built. However, continual professional development or training would likely be needed in order to develop their expertise to a point where they would be comfortable, and not intimated, with the prospect of teaching their students in how to use both the hardware and software.

Beginning with Porter et al.'s reference to software, Schelly's et al. (2015) study of a 3D printing workshop revealed a concern regarding open source, when one participant stated that the workshop really showed how much copyrights and patents will be an issue with this technology. I believe this concern to be valid, but not a current problem in an educational setting. While there are indeed many professional level software suites meant for commercial use, there are also freely available suites repositories featuring designs and instructions. Not all the suites are opensource, and some are only free with limitations or conditions. For example, Tinkercad.com is a free product maintained by Autodesk, a software company specializing in computer assistant design. Tinkercard requires users to make an account with an e-mail address and cannot be used as a guest. While Autodesk ultimately owns any designs created on Tinkercad, users can set their own licensing permissions to retain privacy or share publicly (with or without a requiring attribution).

However, it should be noted that Autodesk and similar groups are (likely) not solely interested in just the objective designs that users create on their services. Consider that when using Tinkercad, it is an interactive canvas which predicts and responds to a user's input, demonstrating a two-way transfer of data. Obviously, the concern of personal data being sold to vendors for profit is a ubiquitous concern in perpetually connected word, but in the case of Autodesk, their privacy agreement forbids such action on their part (Tinkercad, 2020). I would speculate that Autodesk is far more interested in applying user data to maintain and refine their product. Consider Wu, Yu, and Wang's claim in regard to their research of learner interests in open learning environments:

> Learner interests are reflected in learner generated content and dynamic interactions between the learner and the web-based resources. Essentially, learners express their knowledge interests and knowledge requirements through their online behavior. In open learning environments, the massive amount of data, on both learner generated content and their interactions with online resources, provides opportunities to detect learner interests automatically. At the same time, use of this data enables open learning environments to improve their educational services by adaptively discovering learner needs and automatically recommending relevant resource. (Wu et al., 2018, p. 192)

Autodesk implies that Tinkercad is meant to garner interest of users so that they might purchase more complex software suites (Tinkercad, 2020). I would argue that Wu, Yu, and Wang's claim matches with Autodesk's data collection practice, but this only reflects a single case of a cloud-based service's practice.

On the topic of Porter et al.'s (2016) reference to hardware, 3D printers are sometimes simply thrust into the educational environment championed as cutting-edge and innovative, while ignoring the fact that "training and well-equipped classes are important factors for teachers to use this type of technology" (Menano et al., 2019, p. 225). If an educator does indeed take up the mantle of 3D printing and design in their school, "there is a steep learning curve for setting up, using, and designing for 3D printers, which takes time away from teachers' already busy schedules" (Trust & Maloy, 2017, p. 255). Further to that point, the routine of the average school may not allow for proper integration/education of the technology:

> The difficulty that formal school contexts add is at least two-fold: first, the characteristics of Making and of the Maker tend to be counter to schooling cultures and frameworks, and second, in the classroom the goal of the teacher is to teach about the specific topic or subject matter of the class (science, language arts, history, etc.). What then is the role of Making in such contexts, and by which pathways may a Maker identity be fostered? (Chu et al., 2017, p. 111)

Despite these potential problems, there are external and internal supports educators can be provided with to become proficient and confident experts. For example, administrators and district level facilitators would find it “necessary to work closely with teachers to understand the complexity of their working contexts and the difficulties they can experience in embedding new technologies into their everyday pedagogic practices” (Avramides, Hunter, Oliver, & Luckin, 2015, p. 251). Professional development is often the driver for most implementation of new practice, so it seems obvious, but interestingly required, to state that “teachers are likely to use 3D printing if they feel they have the necessary knowledge and support as well as classes equipped with the required resources” (Menano et al., 2019, p. 224).

Additionally, teachers could internally practice “immersion in the culture and practice of desktop fabrication using software and 3D printing devices” (Brown, 2015, p. 17), which seems to be “the most immediate, effective and thorough method of developing the type of understanding necessary to articulate the processes involved in 3D printing as well as the advantages, challenges, and limitations of 3D printing as an educational activity” (p. 17). This implies that an approach of constructionism would be appropriate, where teachers could develop educational activities (curriculum) with 3D printing if given the time to dwell in activities of design and fabrication.

I believe these points lead to the crux of successful implementation of 3D design and printing, being that it all comes down to the teacher and their training: “Teachers are the key players in the success or lack of success of any technology initiative in the classroom” (Christensen & Knezek, 2018, p. 15), and as with any technology, “teachers agreed that the success of technology depends, first and foremost, on teaching practices rather than technology per se” (Lackovic et al., 2015, p. 347). In their report of a video design project meant to train pre-service teachers in the differences between technology “use” and technology “integration,” Sun and Okojie argued for better training in the latter, and using Hamilton’s definition (2007) for the former:

> Integration is NOT the use of managed instructional software, where a computer delivers content and tracks students’ progress. Integration is NOT having students go to a computer lab to learn technical skills while the classroom teacher stays behind to plan or grade papers. Integration is NOT using the Internet to access games sponsored by toy manufacturers or popular television

> shows. Integration is NOT using specialty software for drill and practice day after day. (as cited in Sun & Okojie, 2020, p. 449)

Sun and Okojie would go on to explain that in practicing technology integration, teachers would ensure its usage would be purposeful, including the technology as an essential component of the learning process, indispensable for achieving the specific learning goals and objectives (2020). In this context, using a 3D printer part of the process of achieving a learning goal, rather than being reward or achievement in itself.

As professionals, "teachers must weigh the costs of using this new technology given its many challenges" (Trust & Maloy, 2017, p. 255) when deciding to integrate 3D printing and design. As an educator, a thought that strikes me is using a work versus play test. Becker (2018) uses her system of *4 pillars of educational games* (4PEG) as a test for educational games. Each pillar questions whether the game is of educational value by measuring different properties. The second pillar asks "whether this game has been created specifically for learning or purely for entertainment" (p. 910), a question which could be applied to test a new technology like 3D printing. While not a game, printing activities might only be used as a novelty to print trinkets or novelties, thereby making it a tool for entertainment. Becker's second pillar, coupled with Sun and Okojie's integration versus use argument can help an educator determine if their 3D printing is a gimmick, or a hook to garner student interest in content.

When Lackovic et al. (2015), Becker (2018), and Sun and Okojie's (2020) ideas are amalgamated to connect success in meaningful use of 3D printing to teachers' experience with the technology, it follows that if teachers lack the proper training in 3D design and printing, they will not practice any meaningful application of the technology, and therefore their use of the technology may lean towards entertainment. As Brown (2015) points out, "what seems to be missing at the moment is a curriculum that organizes the 3D printing activities in a manner that helps teachers and instructors design and facilitate structured learning events" (p. 23). It is this "bottom-line" which has influenced the contents of my project. To make the point, Sun and Okojie (2020) state that "existing educational technology courses, focusing on technology knowledge and skills, exclude students from the landscape of preparing pre-service teachers for technology integration" (p. 449). Put simply, teachers need training and plans in 3D printing *integration*.

Results Trending in 3D Printing Implementation

Of course, I cannot simply claim that the integration of 3D printing will lead to success in the classroom, nor does the literature suggest it would be so. To that end, I searched for what did and did not work in 3D printing and design instruction, as well as the (implied) recommendations for refining its implementation. While Sun and Okojie (2020) recommended comprehensive training in Technological Peadgogical Content Knowledge (TPACK), the interplay of content, pedagogy, and technology training for teachers as a solution to meaningful 3D printing integration, this was only localised to pre-service teachers. Therefore, the last theme I identified as particularly prevalent in the literature is the collective experiences of 3D printing and design in active classrooms taught by employed teachers.

Teachers and instructors were commonly asked to engage in reflective, autoethnographic, or action research focusing on how they found 3D printing and design to be impacting their classroom, but "participant observation and fieldwork have disadvantages and limitations" (Brown, 2015, p. 17). For example, teachers all have their individual way of implementing content, therefore some "data collected is based on an individual researcher's interests and may not accurately reflect the phenomenon in general" (p. 17). Despite this, a clear pinch point between traditional teaching and "maker culture" was identified in studies set in classrooms. During their study in how students created artifacts outside of school time, Wong's (2013) philosophy was that "students should ultimately become life-long autonomous learners who are able to decide when, where and how to learn with self-identified resources within their learning spaces" (p. 210). However, this ideal is not always successfully employed in practice of everyday teaching.

The most apt example is the study by Nemorin and Selwyn (2017) of the grade eight woodshop featuring a 3D printer to build a 3D printed car. They found that the teacher in their study often had to do the work *for* the students rather than *with* them, and concluded:

> In many ways, the ‘new’ technology of 3D printing acted only to reinforce and/or rejuvenate ‘old fashioned’ and traditional educational practices – e.g. behaviourist forms of instruction and training, the privileging of the classroom as the sole place of learning, teacher as expert, and so on. (Nemorin & Selwyn, 2017, p. 593)

Furthermore, they concluded that the use of the 3D printer disrupted the overall purpose of a course like woodshop:

> For all [of 3D printing’s] engaging features, this could not be described honestly as a case of each young person ‘making for themselves’. In contrast, this was a set programme of work that was highly mediated by the teacher, and directed through a transmission model of instruction more than exploratory learning. (Nemorin & Selwyn, 2017, p. 592)

These findings are something to keep in mind when considering Pantazis and Priavolou’s (2017) argument that students can acknowledge and further develop their motives and cooperation when in an institution with a shared purpose of open-source design. For example, we could apply their argument to Nemorin and Selwyn’s (2017) study and draw the conclusion that a contributing factor to the woodshop teacher failing in his endeavors was that his class wasn’t properly involved in using the 3D printing technology.

One aspect of the classroom in Nemorin and Selwyn’s study was similar to Walton, Childs, and Jugo’s (2019) observation of student engagement with design software and 3D printing: “although no single technology was particularly complicated, it was challenging to keep large group numbers simultaneously using the technology and on task” (pg. 1068). They also observed how students can struggle to link the activities to the academic content during instruction of 3D printing and design activities, demonstrating the need of direction and instruction from a teacher.

Nemorin and Selwyn’s (2017) argument then pivots, suggesting that perhaps the pedagogy of 3D printing and design has been applied incorrectly; misappropriated into being something ‘innovative and immersive’ and all other buzzwords. In the case of the 3D printed car:

> The least significant stage of the project was the actual printing of objects through the ‘UP Plus’ printer. Far more significant was the sustenance of the project through the vast amount of personal enthusiasm, organization and support from one motivated and interested teacher, alongside sporadic episodes of student attention, effort and energy. (Nemorin & Selwyn, 2017, p. 592)

Indeed, the 3D printing itself did not really matter to the students’ education in the teacher’s classroom, as they were engaging in Sun and Okijie’s (2000) definition of “using” the 3D printer for one single task which could have been accomplished with 3D printing, let alone 3D design.

Retrospectively, the teacher in Nemorin and Selwyn’s (2017) study was a motivated teacher and did attempt to ensure connections to curriculum during the project, but they could have improved their practice by enabling students to participate in finding solutions to design and print issues. In their study of designing artifacts connected to literature, Walton, Childs, and Jugo (2019) suggest “interjecting moments of reflection in order to make these processes explicit to the students” (p. 1073) to enable participation. In doing so, the teacher could task students with problem solving throughout the design and printing process, which would serve a more holistic integration of 3D printing and design. Menano et al. came to a similar finding in their study of various 3D printing settings: “the engagement and excitement of students when they discussed problems and necessary adjustments for their objects was more important than the actual printing of the object” (Menano et al., 2019, p. 226).

Therefore, I want to highlight how additional literature suggests that 3D printing and design can be a meaningful enhancement to the current curriculum, rather than an entirely new realm of learning and instruction. In some cases, 3D printing hardware would not be available, but this does not preclude the teacher from using the design software to create digital artifacts. Consider junior secondary teacher and researcher Oi-Lam Ng who researched the way his students learned the concept of geometric volume by designing key chains in Tinkercad:

> Throughout the course of the project, the students became increasingly fluent in talking about and calculating volumes of composite solids. They developed a discourse about the volume of

> composite solids that was inextricably linked with the 3D CAD environment. This observation was consistent with my hypothesis that the learning of volume in 3D CAD environments would be markedly different from that taught in traditional classrooms. (2017)

In the end, Ng did 3D print the designs made by his students, but prior to doing so, all of their students "demonstrated their fluency of working with composite solids" (2017) in the realm of digital design prior to physical printing. Ng's activity linked abstract representations to concrete artifacts, and the process of design and print was *integrated* in their unit.

Teachers may not need to engage in 3D printing and design to specifically teach STEM, but rather simply use it to expose students to STEM processes while at the same time activating desired modes of thinking as per the current core competencies. Walton, Childs, and Jugo (2019) came to this conclusion rather explicitly in their research of designing electronic artifacts: "it is our view that including the creation of e-artefacts in the curriculum, in tandem with more traditional approaches, offers the most inclusive and rewarding provision of learning for both students and staff" (p. 1073). When lessons and units that both supplement others area of curriculum while teaching the methods in 3D print and design were used in practice, "Teachers saw benefits to the design process, less in terms of students remembering specific information and more in terms of how it activated individual creativity by allowing students to pursue areas of personal interest and self-expression" (Menano et al., 2019, p. 224).

Summary

Thus, the narrative of literature can be summarized: Continuing to lean on Sun and Okijie's concept of technology use versus technology integration (2020), teachers have a path to facilitate lessons and units which engage students in both traditional curriculum in tandem with 3D printing if they have adequate training and knowledge to do so. While 3D printing can be used to promote student creativity, as well as provide motivation (Menano et al., 2019) to students, there exists more in-depth benefits. Designing and producing artifacts can supplement students' learnings in a variety of subjects by creating an alternative visual approach, in turn giving students a new means of analytically gathering insights that otherwise could have potentially remained dormant (McAra, 2019).

As the technology for 3D design continues to develop, there is “a new area to explore regarding how computer-based learning environments that attempt to integrate construction and inquiry allow students to explicitly establish ownership and investment in products of both of these processes in a connected way” (Wilkerson-Jerde, 2014, p. 118). Artifact generation does not have to be localized to 3D printing: “Constructing computational artifacts also encourages students to combine multiple ideas into a cohesive process, organize their understandings in new ways, and 'debug' understandings if their instructions produce something unexpected” (p. 102), and explores students’ ability to view things from various angles (Pantazis & Priavolou, 2017).

The idea which Ackermann (2001) describes of the interplay between Constructivism and Constructionism (stepping back versus dwelling in) will ground my project, and succinctly describes its purpose: I will create resources to support how CAD and 3D artifact generation creates meaning when integrated with traditional curricular ideas, exposing students to the integration 3D artifact generation to propel their own inquiry.

Chapter Three: Integrating 3D Design and Print with Core Subjects

This document and all associated of *Integrating 3D Design and Printing with Core Subjects: A Collection of Resources and Tutorials* have been uploaded to Uvic Space in April 2021 and contain the original versions as it appeared on that date. Current editions the website will be updated and available on the website itself, https://integrating3dprint.opened.ca/. As well, updated editions of this document will be uploaded to the same website. List of associated files uploaded to Uvic Space:

- This document:
    - HowlettClayton_MEdProject_2021_001.pdf
- Unit plans and handouts:
    - HowlettClayton_MEdProject_2021_unit1_002.pdf
    - HowlettClayton_MEdProject_2021_unit2_003.pdf
    - HowlettClayton_MEdProject_2021_unit3_004.pdf
- Video files:
    - HowlettClayton_MEdProject_2021_introduction_005.mp4
    - HowlettClayton_MEdProject_2021_spiral_poetry_006.mp4
    - HowlettClayton_MEdProject_2021_supplementary_indigenous_arts_007.mp4
    - HowlettClayton_MEdProject_2021_custom_ruler_008.mp4
    - HowlettClayton_MEdProject_2021_considerations_009.mp4
    - HowlettClayton_MEdProject_2021_conclusions_010.mp4
- Website capture via PDF:
    - HowlettClayton_MEdProject_2021_websitePDF_011.pdf

Chapter Four: Conclusion

Summary of Learning

From the beginning of this program, my learning revolved around using 3D print and design in my practice. The topic was different, new, and seemingly open with possibilities, and most importantly would not constitute creating a re-hash of earlier research when it came time to complete my project. In very first course of the program, I had already established a basis for where my project would go, creating the Spiral Poetry unit as a way of teaching poetry with 3D design and printing. Throughout the rest of the program, I was dead set on that goal and tailored most of my assignments, blogs, and practice literature reviews to speak on the topic.

When I began to write what would be my final literature review and plan my project on Integrating 3D design and print into core subjects, I followed the same path as the literature in trying to answer the question: How can one teach curriculum with 3D printing? As I worked through my project, I found that this question was the not the one to answer. Instead, I should try to answer: How can one integrate 3D design and printing into what they are already teaching? My resources in this project attempt to provide various answers.

Reflections on Growth

I made a choice early in the design phase of my project which was whether I should feature 3D design and print as a stand-alone, innovative, specialty topic, or as something which could be used by the rank-and file teacher in their daily practice. Trust and Maloy (2017) conducted a study of teachers who were using 3D printing projects in their classrooms and found that teachers were reporting that students were able to learn skills which coincided both with ADST curriculum and the trade of 3D design and printing itself, providing one example of the legitimacy of using 3D design and print in education.

However, the majority of teachers of which Trust and Maloy sampled did report that they were technology teachers, denoting that they were specialists in their practice. Trust and Maloy also described how 3D printing and design was quite a time-sink for teachers based on the challenges presented by the technology and the steep learning curve which came with overcoming the said challenges (2017).

As a generalist teacher, I had to question whether 3D design and print had a place in my practice when I also had an individual responsibility to teach a much wider range of topics than a specialty teacher, and whether a generalist teacher would even have the time to do so. I attempted several units which would make use of 3D design and printing, and my first was a failure. The unit was an attempt to teach the geometrical relationships between three dimensional shapes (such as cubes, rectangular prisms) and the two dimensional drawings of "unfolded" three dimensional objects, called "nets". A common project to demonstrate this relationship is to cut out a collection of squares grouped in a "t" shape on paper then fold and glue the cut-out together to make a cube. I designed a series of lessons where students would first receive a crash-course in the use of Tinkercad, then be provided with an example of the end-product of the project which was a 3D printed net with built-in hinges which could fold into a prism.

Students were not taught what nets were before the unit. The experiment of this unit was to see whether students could understand the relationship as they constructed their design, or at the very least, after it was printed. My findings were negative, and the process was troublesome: some students did indeed learn the relationship between nets and prisms, but at great cost of my time both in and out of the bell-schedule. Furthermore, students required major interventions on my part to aid them in their work. Some students could not finish the work, and for other others, I was often doing the work *for* them.

Grounding the lesson around using the 3D printer as *the* means of teaching did not work. Rather, it seemed to be a gimmick. The students' learning in the mathematics content did not require 3D printing and design, and the ADST curriculum was not being taught in the drafting phase as the skills required were outside of the students' pre-existing knowledge. The entire experience seemed to be a waste.

My experience with the nets unit was confirmation of research conducted by Nemorin and Selwyn (2017) when they examined the use of 3D printing by a secondary level technology teacher as he engaged his students in a term project of building mechanized race cars through 3D printing. The results of their unit were like my own, in that students did not learn much in their unit when it came to curriculum. Furthermore, they found that:

> Perhaps the least significant stage of the project was the actual printing of objects...Far more significant was the sustenance of the project through the vast amount of personal enthusiasm, organisation and support from one motivated and interested teacher, alongside sporadic episodes of student attention, effort and energy. (p. 592)

It was part way through teaching the nets unit when the above quote by resonated with me. I felt that I had ignored a warning by Nemorin and Selwyn, and that I had replicated a mistake without realizing it. I went back to their research and searched for inspiration in how I might pivot the application of 3D design and printing. In their conclusion, Nemorin and Selwyn (2017) determined that:

> 3D printers appear no more capable of challenging institutional school interests in this way than previous technological innovations of the past 100 years. To expect 3D printing to somehow provoke a sudden democratic turn in the institutional arrangements of schools is fanciful at best. (p. 595)

Comparing their conclusion with my experience, this finding by Nemorin and Selwyn demonstrated that a shift in approach was required: 3D design and printing was ill-suited as the center of a lesson or unit in practical teaching. My failure in the nets unit was not a waste, but rather an opportunity to re-think the way a 3D design and printing should be applied in educational practice.

Recommendations for Future Research and Practice

Having the realization that my experience with nets had intersected with Nemorin and Selwyn's research, I shifted how I would use 3D design and print in my practice, pivoting the technology to a supplementary role rather than that of a primary vehicle in learning. I could not find any research or material which grounded a 3D design and printing activity in a non-ADST setting from the outset, or at the very least, could not find resources which were ready to teach in a non-ADST setting. Therefore, I would have to create my own and test the viability of the integration.

Developing and attempting the units featured in this resource was a successful endeavour. In teaching each unit, the 3D design and print portion was not an integral part of any learning of non-ADST topics, meaning students could still access traditionally core curriculum even if they encountered problems with the technology. In addition, the units were designed such that the use of the technology was simplified. Therefore, the first recommendation for educators practicing the integration of 3D printing is to create the opportunity in each lesson/unit for students to conduct simple and achievable troubleshooting independently and rapidly. This was accomplished by keeping the design requirements of each drafting phase rather minimal and ensuring scaffolding had taken place by ordering units in a particular sequence (which I have done in my video series).

As a second recommendation, generalist educators should identify what sort of balance between exploration (or inquiry) versus prescribed outcomes is important for what curriculum that they are currently teaching. Looking back at the theoretical framework for this project, promoting exploration in students' learning by leaving them to create and manipulate 3D designs for their work can lead to new learning (as per the beveled stencil example in Video 5) was an excellent example of constructionism in practice.

However, the question of available time arises: as per Video 5, if students can engage in a constructivist process by building the abstract knowledge of transformations by using them in real-time, is their model for this knowledge sufficient such that the teacher can move forward to other curriculum needing to be taught this school year? Perhaps an examination of the question of how long the cycle of constructivism and constructionism would take in these units could be future research. Future research could also determine what amount of supplementation of 3D printing and design in units such as my own affect curricular uptake.

As a third recommendation, school districts must pivot in how they introduce 3D design and print to educators. In my experience, professional development events introducing 3D print technology (and others) are fraught with the hype of "innovation" and "creativity". Relying on educators to create a paradigm shift in education with the use of 3D design and printing is a time consuming and unrealistic task as per the findings of Nemorin and Selwyn (2017).

Training should focus on how to weave the *teaching tool* of 3D printing and design technology into the core curriculum which educators will undoubtedly be teaching. Creating the resources which weave ADST curriculum with core subjects, and training educators to use them, bridge a developing divide between the need for STEM training while preserving the teaching of traditionally core knowledge. In short, resources and training for 3D design and print should be grounded in core subjects instead of ADST curriculum.

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