Design for the Art of Learning: Defining Challenges for Maker-Driven Design Activities and Design Education in Secondary Schools

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

This thesis reflects on strategies used to facilitate didactic interactions between design research-creation and maker experiences in a secondary school. The author uses *maker-driven design activity* as a hybrid term to define educational activities that integrate critical making, sustainable action, and creative uses of technology. Two projects are described to exemplify the challenges and qualities of this didactic approach. The careful use of design constraints and observations of patterns of concern, such as process avoidance, are essential in understanding the qualities necessary for a meaningful design experience in the context of school. The author uses observations of maker-driven design activity situated in a school Fab Lab to inform guideposts for future research-creation infusing creative-technical learning with design literacy. This thesis is intended for designers, teachers, and researchers interested in creative and interdisciplinary learning experiences in what is broadly labelled as design for the art of learning.

KEYWORDS

maker-driven design activity / didactic experimentation / process avoidance / design literacy / design & technology / STEAM / MYP / design thinking / design education / constructionism / makerspaces / Fab Labs / sustainable action / creative uses of technology / critical making / microworlds

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LIST OF ACRONYMS

CAD	*Computer-aided design*
CAM	*Computer-aided machining*
DP	*Diploma Programme (IB)*
D&T	*Design and Technology (UK, or IB)*
Fab Lab	*Fabrication Laboratory*
IB	*International Baccalaureate*
IDEO	*Global design & innovation company and leaders in design thinking*
K-12	*Kindergarten to grade 12*
MDes	*Master of Design*
MYP	*Middle Years Programme (IB)*
SDG	*Sustainable Development Goals*
STEM	*Science, Technology, Engineering, and Math*
STEAM	*Science, Technology, Engineering, Art, and Math*
UK	*United Kingdom*
UN	*United Nations*

LIST OF FIGURES

1 INTRODUCTION

This thesis reflects on strategies used to facilitate didactic interactions between design research-creation and maker experiences in a secondary school. Working in a school as a designer has fueled my interest in seeing education as a creative space for design practice. It stems from a belief that, when done effectively, making and design thinking in creative-technical learning environments like Fab Labs and makerspaces can help build essential pathways and 21st-century competencies for many high school students, just as it does for design practitioners. In all its forms, design education has the potential to activate innovative mindsets and create awareness between subjects, technologies, and actions. Design deals with human factors and gives context to emerging patterns that can train minds and make surprising connections that tackle complexity with creativity and optimism. We can enact the massive change (Mau, 2004) needed for more sustainable futures, but this also requires an understanding of the nature of design, and it is unclear if school systems are effectively arming future generations with the mental habits this requires. Future lawyers, politicians, entrepreneurs, and people of all interests should be exposed to the thinking needed to understand how ideas and actions are connected to technologies and materials. Through inquiry and creative problem solving, a critical awareness of a "designed world" emerges and, with this, a greater understanding of the "things" that influence our behaviour in this world. Simply put, what is designed and learned can be explored as one instead of being treated as separate processes. My excitement for this topic should not be confused with over-optimism. Design education is not a catch-all nor a topic that will excite all students. Rather, it is an underrepresented topic in secondary education which requires translation and further research.

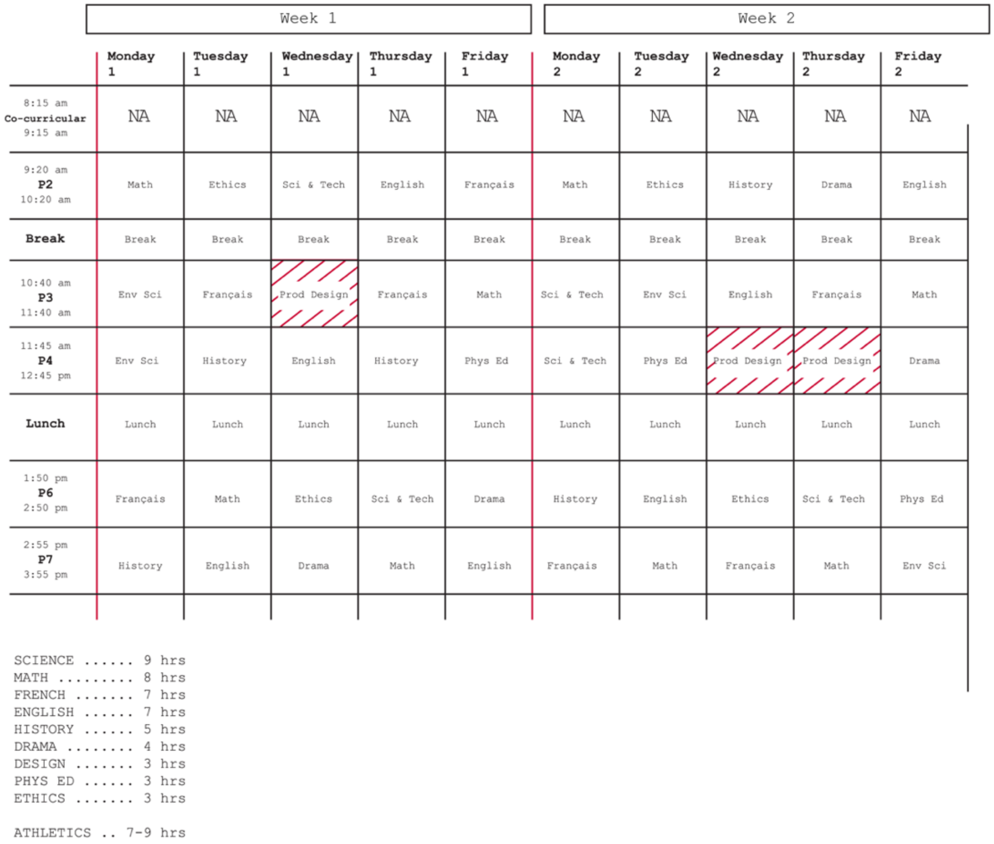
The opinions reflected in this thesis express perspectives that have evolved over seven years of experience building and integrating a design program around a Fab Lab (digital fabrication lab) at a private English school in Montréal, Québec. In addition to maintaining the standards of the Québec Education Program as set out by the Ministry of Education, the school where this work is situated also follows the internationally recognized curriculum of the International Baccalaureate (IB). The IB recognizes design as one of its distinctive subjects in its holistic approach to education (International Baccalaureate, 2016, 2019). Though the IB has helped introduce design education at different levels and introduced it to many more students, it has not influenced the design experience shared in this work. Instead, this work had to fit into an IB framework. Still, it has benefited from the IB's impact on raising the profile of design education which is not formally classified in the government's curriculum as an area of learning despite the term "design" used throughout Québec Education Program guides (MEES, n.d.-b, n.d.-a). This work has also received lots of support because of its context in a private school where there is a capacity, and the interest, to invest in the human resources needed to facilitate experimentation and exploration of innovative programs. I have been free to explore the aesthetic qualities of maker-driven experiences and observe interactions with new approaches to design education. I have introduced design concepts and maker experiences to teachers who are asked to teach product design classes for the first time or encouraged to bring students into the Fab Lab for project-based learning. While situationally different than what might be observed in other private, public, or alternative schools, many conditions influencing this work reflect the same constraints that one might see in different educational contexts. They boil down to the availability of time for learning, teacher readiness, and the amount of community interest in, or understanding of, design and maker activities.

In observing student and teacher approaches to learning in a school Fab Lab over the years, behavioural patterns emerge and speak to broader issues related to creative-technical confidence, curiosity, autonomy, and critical thinking that must be addressed further. In my experience, most teachers and many students are regularly discouraged by the time it takes to develop the creative-technical skills needed to work iteratively and autonomously in a Fab Lab. They also tend to make assumptions about technology and shy away from the extra steps to consider the impact of their creative activity. Like any skill or competency, this type of learning takes time, and when time is not available or the work is not deemed worthy of more time, the opportunity to learn from it is lost. Such sentiment is amplified against a fast-paced educational system, expectations of grades, and an orientation toward just-in-time learning. The result is behaviour that cuts corners and seeks simple projects that require less forethought, context, or testing. A healthy learning environment should be one where students and teachers are motivated and support each other through the fun of learning and the creative and technical challenges that follow. There are still many students who love this kind of work, but as the IB programs may increase the number of students learning about the design process, leveraging the creative benefits of a Fab Lab becomes more complex. Seymour Papert (2002) once wrote, "…everyone likes hard, challenging things to do. But they have to be the right things matched to the individual and the culture of the times" (p. 1). If we take this statement to heart, it suggests accepting different approaches to learning without trivializing our interactions with technology and the learning environment.

This work highlights a design practice aimed at facilitating better interactions between people and what will be defined later as *maker-driven design activities*. It aims to create an understanding of what can be accomplished while making objects that catalyze learning as a core function of the creative process. I use these strategies to make creative-technical design experiences more salient in an educational context. It is done with tacit knowledge of the design process and the systems and interactions that make up the learning environment. For example, the influence on student learning experiences due to academic expectations and the organizational complexity found in pedagogy translates into a sprinkling of subjects divided into hourly blocks. Such structuring indicates the inherent challenges of managing prerequisites and teacher workloads against carefully allocated measures of time per subject (Figure 1). The impact of this on learning is a stratification of ideas and a system for prioritizing what is deemed more time-worthy.

Figure 1

Grade 10 Student Schedule



	Week 1					Week 2				
	Monday 1	**Tuesday 1**	**Wednesday 1**	**Thursday 1**	**Friday 1**	**Monday 2**	**Tuesday 2**	**Wednesday 2**	**Thursday 2**	**Friday 2**
8:15 am **Co-curricular** 9:15 am	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9:20 am **P2** 10:20 am	Math	Ethics	Sci & Tech	English	Français	Math	Ethics	History	Drama	English
Break	Break	Break	Break	Break	Break	Break	Break	Break	Break	Break
10:40 am **P3** 11:40 am	Env Sci	Français	Prod Design	Français	Math	Sci & Tech	Env Sci	English	Français	Math
11:45 am **P4** 12:45 pm	Env Sci	History	English	History	Phys Ed	Sci & Tech	Phys Ed	Prod Design	Prod Design	Drama
Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch
1:50 pm **P6** 2:50 pm	Français	Math	Ethics	Sci & Tech	Drama	History	English	Ethics	Sci & Tech	Phys Ed
2:55 pm **P7** 3:55 pm	History	English	Drama	Math	English	Français	Math	Français	Math	Env Sci

SCIENCE	9 hrs
MATH	8 hrs
FRENCH	7 hrs
ENGLISH	7 hrs
HISTORY	5 hrs
DRAMA	4 hrs
DESIGN	3 hrs
PHYS ED	3 hrs
ETHICS	3 hrs
ATHLETICS	7-9 hrs

As far as it relates to this work, I aim to present a broader understanding of design's reach, hoping to express a greater appreciation for the nature of design education. All this is to preface that the work proposed in this thesis must fit within the periodic offerings of a student schedule and expectations that only sometimes mesh with the ongoing, iterative, creative-technical, and solution-oriented learning encouraged by the design process.

In this thesis, I highlight two purposes of my research, which will later be described in more detail as *didactic experimentation*. One goal of this research is to track the learning process in creative practice. The second goal tracks interactions between students and teachers in maker-driven design activity. The dual purpose of this approach should provide an exchange between design research-creation and experiential learning in support of the following research question:

Can the design process inform learning strategies that generate more opportunities for critical making, sustainable action, and creative use of technologies in schools?

The specific reason for choosing critical making, sustainable action, and creative uses of technology as essential in this process is linked to a professional awareness gained by developing design experiences for middle and high school students while learning about design research in higher education. Although design research and K-12 educational circles share an interest in critical thinking, sustainability, creativity, and digital literacy, my experiences suggest that these qualities are lacking in student experiences where technology is concerned. The Québec curriculum makes sure that students are introduced to educational technology that supports broad campaigns in STEM, media, or innovation. They are also introduced to some critical issues through ethics and digital citizenship. However, there have been many missed opportunities to encourage a relationship with tools and techniques that give agency over technology. The questions being asked in this thesis will only get more complicated as we unearth the infinite potential of AI technology. When a student can take any whim or idea and prompt AI to make images, videos, and objects, what impact will this have on reasons to learn from the act of making and the associated challenges that feed curiosity and resilience? Indirectly, this includes creative uses of technology that address sustainable action. Sustainable action can be expressed by learning to make more and consume less. This notion of action is also linked to the choices of materials and processes we use to make things. If we exercise action alongside thinking, we can perpetuate awareness of "things" that influence our behaviours. On the surface, this affects how students and teachers approach technology and craft. As an ethos, this encourages mindsets supporting the creative-technical learning needed to tackle complexity. Design research-creation can help address such issues while raising awareness of these qualities in educational contexts.

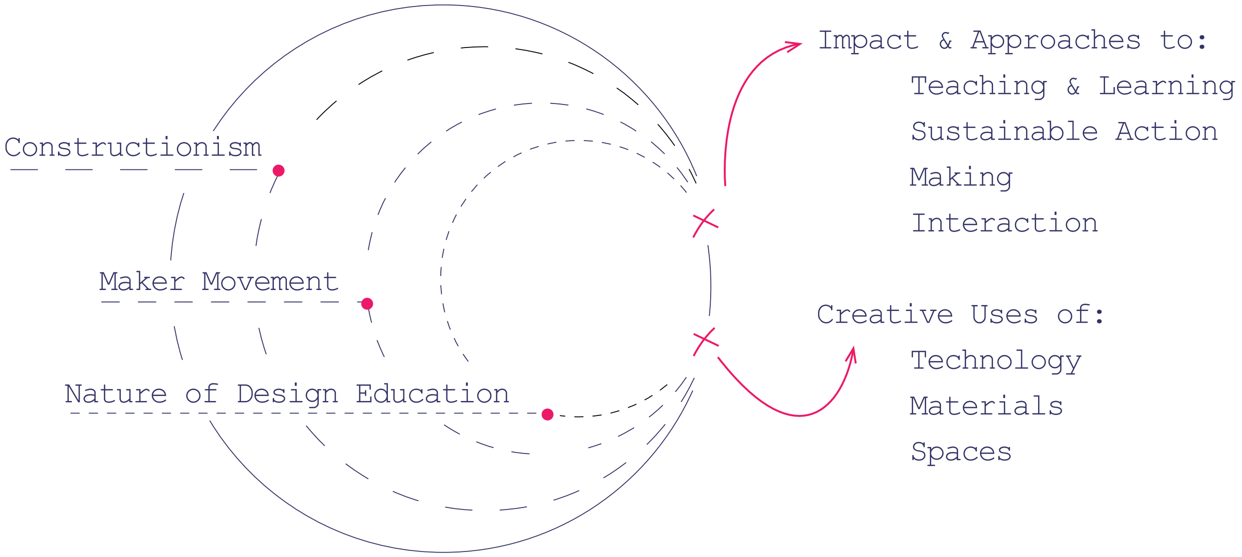
While there are plenty of examples to support design education and making in schools and lots of academic discussion about the challenges that face this type of learning, this thesis does not present formal research methods designed to gather data. Instead, it classifies observations of maker experiences and design activity in a school setting. The following chapter highlights essential theories and applications that link design and maker principles with the nature of learning, situating this work among different communities of practice surrounding design activity in schools. Chapter 3 presents a methodology based on constructionist principles that will be used to define the approach to research-creation in this work and the types of evidence used to capture impressions of student interactions within maker-driven design activity. Chapter 4 presents two projects that fuse these ideas in action blending critical thinking with making, digital fabrication, and knowledge of design studies. Chapter 5 discusses the outcomes of these projects and organizes key observations that should influence future research into maker-driven design activity, which is discussed in Chapter 6. While this thesis does not measure the efficacy of this technique or if maker education or design thinking improves understanding, it does provide an approach to assess the essential qualities of design education in secondary school leading to new questions concerning the use of digital fabrication and design literacy. In theory, it implicates research-creation as a mode of learning. In practice, it aims to formulate a creative process to help organize labs, devise techniques for content delivery, and construct design thinking tools for students that will be effective in a school setting. This thesis is used to help define more broadly what has evolved into a creative practice in *design for the art of learning*.

2 LITERATURE REVIEW

The interdisciplinary nature of this inquiry speaks to a broad and complex relationship between learning and design activity. Three threads of understanding concerning the concept of *learning through design* emerged in forming an awareness of the theories and contexts that position this work. The first thread situates this work through *constructionism* which places interactions with technology as meaningful learning experiences. The second thread provides context and understanding of the broader implications found in the *maker movement* and its impact on supporting creative-technical activity in schools. The third thread reflects the evolution and shifting views on the *nature of design education* as a point of direction for design thinking and design activity in schools. Each thread is also explored through intersecting topics: (1) impact and approaches to teaching and learning, sustainable action, making, and interactions; (2) creative uses of technology, materials, and spaces. The crossover between "approaches to" and "creative uses of" has helped form a view of converging fields of interest (Figure 2) in design education and how it manifests in schools.

Figure 2

Fields of Interest



2.1 Situating Learning by Doing

As the concept of *learning* is identified in the title of this thesis, it is necessary to define its use in this work. On a more neutral level, learning can be defined as acquiring new skills and understanding (S. K. Robinson, 2022, p. 39), but it is harder to measure in practice. There are different theories of learning such as behavioural, cognitive, and constructivist which we can draw from. According to education scholars, Peggy Ertmer and Timothy Newby (2013), instructional designers should understand different learning theories to make the best design choices based on the situations surrounding the instruction. While this is true, the nature of this study is very much linked to the experiential. Cedric Cullingford (1990), former professor and author of the book, *Nature of Learning: Children, Teachers, and the Curriculum,* suggests that learning is influenced by our moods, operates at various levels, and is constructed through interactions with the physical world. Analyzing outcomes in this work is linked to observations in the school environment and impressions of learning exhibited through evidence of design and maker activity. As such, the stance in this work is largely centred on constructivist epistemologies in that learning occurs through interactions and experiences in the world (Ertmer & Newby, 2013). This is not to suggest that other theories are excluded but that the learning discussed here is largely centred around the individual and cognition which is a flavour of constructivist thinking often attributed to Jean Piaget (Sjøberg, 2007). Whereas Lev Vygofsky, another constructivist with an interest in stages of learning, believed in a more social dynamic in that learning occurs through social interactions with adults and peers and guidance from others, Piaget's interest lies more in how meaning is constructed by the individual in their own experiences. Piaget argued against collective buy-in to perceived truths or dogma and supported the idea that education should build creative and critical individuals who could work out their own ideas (Lourenço, 2012). Piaget (1964) distinguished the difference between the process of learning and intuitive knowledge. One requires provocation through psychological factors or external situations, the other can be integrated, transferred, acted upon, and re-interpreted. Loosely translated, this represents the mental actions that differentiate seeing from knowing. According to Piaget, “To know an object is to act on it. To know is to modify, to transform the object, and to understand the process of this transformation, and as a consequence to understand how the object is constructed.” (p. 176)

Another interesting figure in education from whom this work draws is philosopher John Dewey who is referenced in design and constructionist literature for his pragmatic view of education, which was based on principles of learning by doing that came with project-based, problem-based activity (Santos Arias, 2021; Sikandar, 2015). Dewey (1938) argued that humankind thinks in terms of extremes, which remains especially visible in the debate between traditional vs. progressive education. Dewey's views on learning formed the basis of many learner-centred approaches. He saw learning as a social activity that should be closely linked to experiences that students can relate to (Dewey, 1938; Williams, 2017). Another useful concept is the idea of growth and “concern for what students are wanting, thinking, feeling, and actually doing as they tackle difficult learning tasks” (Dweck, 2015, p. 243). Psychologist Carol Dweck (1986) believes that motivation in learning is affected by the type of goals learners are given. *Learning goals* encourage ongoing effort and resilience by prioritizing the experience. In contrast, she describes *performance goals*—like those that praise success or high achievement—as having an alternate effect on motivation. Edith Ackerman (1996), another psychologist who was interested in learning and interactions, suggests that we must step away from an object and observe it from other perspectives before diving back in and building on the knowledge gained. Ackerman's perspective represents a form of *situated knowledge* where learning is contextual and experiential (J. S. Brown et al., 1989). It is like learning to speak a language by being immersed in the culture that speaks it (Papert, 1993, p. 64). These views are posited against behaviourist models of learning that view instruction as the dominant mode of teaching and learning (Murphy, 1997). Seymour Papert (1996) proposed the term *mathetics* to signify the importance of establishing *the art of learning* as a counterbalance to pedagogy. Papert (1993), who studied under Piaget, argued for more concrete and individualized approaches and suggested we move away from *instructionism* and towards *constructionism*.

> Traditional education codifies what it thinks citizens need to know and sets out to feed children this "fish." Constructionism is built on the assumption that children will do best by finding ("fishing") for themselves the specific knowledge they need; organized or informal education can help most by making sure they are supported morally, psychologically, materially, and intellectually in their efforts. (Papert, 1993, p. 139)

Here we see Papert linking the conditions for learning to the support that the individual has in discovering the learning experience. Similarly, American philosopher and advocate of the design process Donald Schön brings up an important consideration regarding the exploratory nature of design activity. He argues that novices need to learn by doing*,* but as novices, they are not yet able to do anything; thus, it is essential to establish the right conditions for discovery (L. J. Waks, 2001). Similarly, French philosopher Jacques Rancière (1991) makes an argument suggesting that the master of knowledge should not "explicate" (p.13) but allow students to use their intelligence to guide their learning. In reference to higher education, Rancière's proposal for the "emancipation of the master" (p.12), or the separation between the professor and the student's own will to learn, is presented as necessary for meaningful educational experiences. Papert's view of the teacher as a guide to self-directed activity complements Donald Schön's notion of the student as a "self-educator" (1987, p. 84) and the studio master as a coach. The constructivist perspectives presented here are qualitative and recognize one's natural ability for inquiry and creativity. Kids naturally approach learning this way, but these characteristics often get lost as they move through school (Resnick, 2007; K. Robinson & Aronica, 2016). It is a constructivist perspective that learning “operates on culture as opposed to control” (Alkove & McCarty, 1992, p. 18).

2.2 Constructionism and Tinkering as a Design Process

Whereas Piaget's constructivist (emphasis on 'tivism') theory represents the construction of knowledge in one's mind in reaction to interactions in the world, Seymour Papert's *constructionism* (emphasis on 'tionism') finds meaning in the projection of what is in one's mind through the use of media. Piaget's constructivism focuses on internal cognitive processes of constructing knowledge, and Papert's constructionism highlights external manifestations of one's ideas and understanding. Making something offers opportunities for growth when internal feelings are projected into projects that get shared and interpreted by others. The iterative cycle of making, sharing, and reflecting provides learning opportunities that help sharpen ideas (Ackerman, 2001). Noss and Hoyles (2017) point out that “constructionism involves choosing or designing representations, engaging artifacts and suitably oriented pedagogies that together can bring about a fundamental change in how to learn and, if successful, will ultimately change what is learned” (p. 31). Richard Kimbell, a design professor involved in the establishment of Design and Technology in the British curriculum, describes design activity as starting “with an idea (in the head) and immediately externalize it through discussion, sketching or modelling, and this allows us to see the idea more clearly and think more deeply about it” (Bohemia et al., 2015, p. 5). Without direct reference to constructionism, this statement illustrates similar principles discussed by constructionists. In *Designerly Ways of Knowing*, Nigel Cross (2006) emphasizes the importance of design education because it acts on a third domain of knowledge which relies on nonverbal, non-numerical, modes of communication that are expressed in the creation of artifacts. Again, no specific mention of constructionism but along the same lines and supporting the view that designerly knowledge and making express learning in ways that are not well understood in traditional educational environments.

In his book Mindstorms: children, computers, and powerful ideas, Papert used the term “microworld” to suggest a design approach for learning that can act as an incubator for complex ideas by allowing children—or novices—to gain awareness of essential principles in a meaningful way. He gives the example of the “Logo Turtle” - used in the Logo programming language - as an example of a microworld for learning math (Papert, 1980, Chapter 5). Although the view of constructionism as a methodology for design activity is less apparent, Papert’s ideas are referenced in design literature. For example, Schön suggests that designers construct their design worlds and "instantiate a particular set of things to think with" (Schön, 1988, p. 138). According to Schön (1992a), "the designer constructs the design world within which he/she sets the dimensions of his/her problem space and invents the moves by which he/she attempts to find solutions" (p. 11). It appears that Schön saw Papert’s ideas as suitable examples for designerly knowledge:

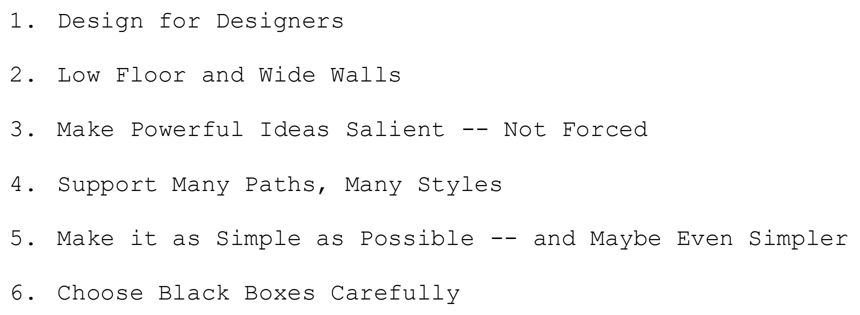
> A designer's knowledge is not only in his ideas or actions but in the things with which he deals. The objects of a design world are, in Seymour Papert’s phrase, 'things to think with’ (Schön, 1988, p. 183).

Like Papert, Schön also saw potential in defining the art of learning through design activity. For Schön (1992a), the design process reveals itself through iterative conversations with sketches, materials, and prototypes only as the designer engages with them. His view of design activity is similar to *tinkering,* which is “a playful, experimental, iterative style of engagement, in which makers are continually reassessing their goals, exploring new paths, and imagining new possibilities” (Resnick & Rosenbaum, 2013, p. 163). Design activity and tinkering both require thinking on one's feet and framing problems based on an inquiry into the materials of the situation (Cross, 2011; Mader et al., 2016; Schön, 1992b; Wilkinson & Petrich, 2013). Wilkinson & Petrich (2013), directors of the Tinkering Studio at the San Francisco Exploratorium, argue the importance of getting stuck and unstuck as central to this theme of learning by doing and learning through making mistakes.

In 1972, Seymour Papert and Cynthia Solomon published a paper through the MIT Artificial Intelligence Lab titled *Twenty Things to Do with a Computer* (1972) which offers an early example of constructionist thinking exhibited through experiments with the Logo programming language. It provided a simple guide to interactions with machines. The work serves as an early example of creative computing and is being revisited from new artistic and creative perspectives, albeit in the context of learning (Bull et al., 2022). These intersections of design and constructionism are evident throughout the work emanating from the MIT Media Lab. It should be noted that the MIT Media Lab features both the Center for Bits and Atoms—the birthplace of Fab Labs—and the Lifelong Kindergarten Group—a constructionist research group. Literature from these communities presents a shared interest in learning through creative uses of technology, which has had a foundational effect on the maker movement by democratizing access to tools for design activity and learning (Gershenfeld, 2012; Laprade & Lassiter, 2021; Martinez & Stager, 2019; Resnick, 2018). Cohen et al. (2017) acknowledge the importance of Papert's constructionist approaches to learning and their representation in the maker movement and cite research that supports the view that this type of learning increases student "motivation, engagement, development, learning, performance, and psychological well-being" (p.12). Many papers highlight constructionist perspectives as relevant in situating the literature on the maker movement and activities in makerspaces and Fab Labs (Blikstein, 2018; Khan & Winters, 2020; Laprade & Lassiter, 2021; Smith et al., 2015; Stager, 2017). This suggests a renewed interest in Papert’s ideas despite his influential theories on education and interactions with computers remaining invisible in schools (Ames, 2018).

Using constructionist literature, we can find examples of design principles for creative-technical learning. Setting up the conditions for optimal experience and intrinsic motivation comes from formalizing boundaries that help learners balance challenging situations with enjoyment and feedback (Csikszentmihalyi, 2014a; Dweck, 1986). Constructionist designers, Mitchell Resnick & Brian Silverman (2005) share a list of essential guideposts to consider. This list (Figure 3) is helpful from a design perspective in addressing best practices to achieve meaningful interactions with construction kits and the “affordances” (Ackermann, 1996; Norman, 1999) that these learning technologies provide.

Figure 3
Resnick & Silverman's 10 Principles for Designing Construction Kits



1. Design for Designers
2. Low Floor and Wide Walls
3. Make Powerful Ideas Salient -- Not Forced
4. Support Many Paths, Many Styles
5. Make it as Simple as Possible -- and Maybe Even Simpler
6. Choose Black Boxes Carefully

7. A Little Bit of Programming Goes a Long Way
8. Give People What They Want -- Not What They Ask For
9. Invent Things That You Would Want to Use Yourself
10. Iterate, Iterate — then Iterate Again

In devising a design process through which students learn how to exercise creativity and iteration, Resnick (2007, 2018) proposes a creative learning spiral featuring five creative process stages that build upon each other as one progresses. We start by imagining, then followed by creating, playing and sharing, and ending with reflection. Once we have reflected, we start a new spiral building on what was just learned and can now imagine new things with new knowledge and experience. Resnick's spiral concept relies heavily on the notion of play and imagination and sharing central to the *Lifelong Kindergarten Groups'* constructionist design philosophy used in technologies like the Scratch programming environment. These ideas are based on observations of how kindergarten kids express their creativity in learning. However, it should be noted that this approach is not limited to children and that it catalyzes learning and builds creative and technical confidence for all ages. While the iterative component of Resnick's learning spiral is similar to design thinking processes (T. Brown & Barry, 2011; Cross, 2011; Verplank, 2009), Resnick's proposal lacks the client-focused origins and terminology of corporate culture and instead stresses the importance of sharing personally meaningful activities within a community engaged in the learning experience.

2.3 Making and Creative Uses of Technology

Opportunities for learning through making and creative uses of technology are widely discussed. Despite challenges, there are many examples of schools and informal learning spaces integrating principles of design and maker activity that support more progressive ideals for learning (Cohen et al., 2017; Davidson & Price, 2018; Halverson & Sheridan, 2014; Papavlasopoulou et al., 2017; Sang & Simpson, 2019; B. Taylor, 2016). In their book *Design, Make, Play: Growing the Next Generation of STEM Innovators*, Honey and Kanter (2013) describe a *maker sensibility* as someone who experiences "a deep sense of engagement with content, experimentation, exploration, problem-solving, collaboration, and learning to learn" (p.4). Dale Dougherty (2013), the founder of Make Media and Maker Faires, posits that transforming education is the biggest challenge and opportunity in the maker movement. He describes a community of makers as having a strong sense "of what they can do and what they can learn to do" (p. 7). The potential of a Maker education has also been examined. A comprehensive literature review by Schad & Jones (2019) highlights a few key conclusions. First, they identify the potential for maker-centred learning activities in K-12 educational environments. Second, they report a significant lack of quantitative research with measurable outcomes to determine how successful maker activities are integrated into K-12 learning (p. 68). They also highlight abundant literature on teacher uses of technology but very little on integrating maker technology into teacher practices (p. 74). It is also understood in the literature that the kind of learning experienced through making and design thinking is more progressive and works against dominant models for learning in schools (Bevan et al., 2015; Godhe et al., 2019; Quinn & Bell, 2013).

Paulo Blikstein (2018), professor of education and founder of the FabLearn research initiative, notes the historical trends contributing to the movement's growth in education systems. The first trend relates to accepting more progressive and constructivist ideas for education (p. 422). The second trend reflects a desire for innovation-based economies (p. 423). The third trend is linked to the democratization of making with technology through outreach initiatives like the Fab Lab network, Maker Faires and *Code.org*. The fourth trend is a dramatic cost reduction in digital fabrication equipment, making it possible for more people to design and produce technologies (p. 424). Lastly, Blikstein presents a fifth trend that reflects better tools for academic labs where more informed research-creation can support the design of better tools for creative uses of technology in schools and informal learning communities (p. 426). Making is process-driven and requires new ways of evaluating and assessing the benefits of this type of learning without running the risk of diluting these experiences through traditional methods that fail to see its value (Valente & Blikstein, 2019). Many of the challenges described facing the integration of creative uses of technology in schools demonstrate friction with the "grammar of schooling" (Cuban & Tyack, 1995, p. 9), which is a term used to describe the educational structures that remain dominant in school systems.

In facilitating meaningful learning through design activity with machinery in makerspaces and fab labs, researchers recognize a need for mediation and coaching to help build the scaffolding to address the inherent complexity involved (Blikstein et al., 2017; Valente & Blikstein, 2019). Assessing the quality of learning in such situations requires understanding the affective qualities of the experiences they offer (Gelmez & Bagli, 2018; Picard et al., 2004), especially where creativity, technology, and complexity are concerned. To be compelling in an age where measuring academic success is prioritized, even at the expense of learning (Biesta, 2009), making a case to increase student-centred design or maker education in schools will require tools for formal assessment and quantitative research (Blikstein et al., 2017; Christensen et al., 2016). Using the *Beyond Rubrics Toolkit* (Maker Ed, n.d.; MIT Playful Journey Lab, 2021), Rosenheck et al. (2021) have successfully collected different types of evidence through student reflection, peer review, and collaborative assessment that work well in the context of maker activity. This method helped to identify six unifying qualities communicated across the different types of evidence in the artifacts students make (1) *alignment* between the project and the outcomes, (2) *actions* taken by students, (3) *specificity* in describing the actions, (4) *articulation* in explaining the situation surrounding the artifact, (5) *abstraction* of thinking that conveys reflection about intangible elements, and (6) *coherence* across projects and experiences (p. 179).

Teacher and institutional readiness are crucial in determining the successful integration of educational technology (Petko et al., 2018). Paulo Blikstein (2013, 2018) warns of the trivialization of fabrication technology in education. He describes "keychain syndrome" (Blikstein, 2013, p. 8) as the desire to create accessible experiences promptly using the impressively capable tools of a Fab Lab without much thought to their educational benefits. The other concern in prioritizing trivial projects based on convenience is that it risks teaching students how to avoid complexity (Blikstein et al., 2017). Blikstein and Valente (2019) summarize the main issues in disseminating the creative-technical experiences discussed here. They note:

> The fast dissemination of makerspaces in pre-college education is one of the most noteworthy events in the history of educational technologies – comparable to teaching machines, educational television, and the Logo language. It brings familiar issues and dilemmas that have concerned educators and designers for decades: How much open-endedness should we allow in schools? How to integrate these new spaces within the current school infrastructure? How to do assessment? How to prepare teachers to use those technologies? What learning goals can be uniquely achieved within these novel environments? (p. 268)

Learning technologies should encourage a low floor, wide wall, and high ceiling approach in their design (Resnick & Silverman, 2005). Amongst the discussions of learning and making, there is much emphasis on creative experimentation with electronics and computation to help make them more accessible (Bdeir, 2008; Hanning, 2018; Legault, 2015; Qi et al., 2018). Others explore simplifying digital fabrication, making cardboard machine kits, and learner-friendly CAD tools (Bhaduri et al., 2021; Peek et al., 2017). Jay Silver (2014), one of the designers behind *Makey Makey*, sees the world as a construction kit. He describes construction kits as having three components: “1) Parts (especially loose parts); 2) Tools (for combining and reconfiguring loose parts); 3) Stage (a substrate or place where the creative action is situated and may live on)” (p. 43). Silver argues that if one of the three components is removed, users of the kit must consider alternatives in the world around them, requiring creative problem-solving. In this example, designing with electronics is simplified, and concepts relating to electricity, computation, interaction design, and material science become more easily understood.

The literature supports the view that while makerspaces and Fab Labs contribute meaningful learning opportunities in schools, their integration into schools highlights critical areas for improvement, especially when concerning more sustainable, diverse, and inclusive educational experiences (Dew & Rosner, 2019; Kohtala, 2017, 2016; Lachney & Foster, 2020; Millard et al., 2018; Wolf et al., 2022). Gilbert (2017) suggests that makerspaces do not provide better learning, nor are they future-focused unless they are supporting learners with access to “powerful ideas” (Papert, 1980) and the skills needed to address “wicked problems” (Rittel & Webber, 1973). On a more positive note, Kohtala (2017, 2016) presents a favourable view of the global Fab Lab network as an ecosystem for sustainable action and a model for change toward a more circular economy due to a strong interest in repair, material reuse, and distributed manufacturing which are more favourable in the circular economy. These links are being made outside the context of school.

The literature discussed in this review highlights an understanding of technology's role in shaping society. However, the study of technology is commonly taken up by STEM subjects or Science, Technology and Society (Bijker, 1995; S. Waks, 1997). With STEM, “design” is often presented as a verb (MEES, n.d.-c) in deciding how to make technology rather than seeing it as a creative domain for academic research and inquiry. The call for more critical thinking around making and technology can be found in the literature referencing critical making (Godhe et al., 2019; Kohtala, 2016; Ratto, 2011; Ratto et al., 2018). Matt Ratto (2011), professor in the Faculty of Information at the University of Toronto, defines critical making as creative uses of technology around critique and expression. He borrows three concepts from Seymour Papert: the affective qualities of interacting with technology, projecting oneself in the abstraction of objects and using computers as material, and the importance of messing about with technology. He describes critical making as "design-oriented research" (p.254), centring around creating objects to facilitate reflection. Ratto's vision is to use critical making to change people's relationship with technology, which is complex and under-explored. Although it is not related to maker literature, Ursula Franklin (1999), a metallurgist, researcher, professor, and author of *The Real World of Technology*, provides a clear description of two principal uses of technology, *work-related* and *control-related*. These definitions help to shape an understanding of the design of technology which is a key ingredient in critical making. Critical making is a form of design research-creation. Research-creation can be described as having the capacity to blur lines between academic disciplines and social discourse (Loveless, 2015). Critical making can also be useful in terms of using maker experiences to develop design literacy. Research emerging from the FabLearn Project (*FabLearn: Research*, n.d.) supports this view that we should imbue making, where education and technology are concerned, with design literacy (Christensen et al., 2019; Turakhia et al., 2022). Christensen et al. (2016) describe design literacy as "students' stances towards inquiry" and the ability to "reflectively engage with and make inquiries when confronting wicked problems" (p. 132), which they argue is a necessary 21st-century skill that should be available in general education. Design scholar and educator Sharon Helmer Poggenpohl (2008) suggests that design literacy is "understanding the cultural shifts that push design to re-evaluate and re-think its position" (p.217).

2.4 The Shifting Nature of Design and Design Education

Design exists to "disrupt, contest, invent, direct, coordinate, respond, provoke, and project" (Rodgers & Bremner, 2017, p. 28). Design Scholar Richard Buchanan (2001) describes four orders of design and suggests different approaches are needed in its study. The four orders include the first order of *symbols* (graphic design), the second order of *things* (industrial design), the third order of *action* (interaction design), and the fourth order of *thought* (environmental design). Whereas design theory and education in the early-mid twentieth century focused on foundations, symbols and things, the focus now is more on thought and action. "The focus is no longer on material systems-systems of "things"—but on human systems, the integration of information, physical artifacts, and interactions in environments of living, working, playing, and learning" (p. 12).

Concern for design's reach was previously expressed by Victor Papanek in his novel *Design for the Real World: Human Ecology and Social Change* who labelled design—industrial design mainly—as fundamentally dangerous in its ignorance of the more significant problems it can cause (Meyer & Norman, 2020; Papanek, 1985). A sentiment which is now echoed by more contemporary perspectives. Tony Fry (2009; 2003) proposes that design be viewed more as a redirective practice requiring a new set of educational guidelines to take on the monumental and complex task of redesigning the world. In expressing reproach for design's unsustainable and exclusive practices, other diverse voices contribute to its shifting nature, many from fields outside of design. The study and concern for design are being joined by more contemporary, participatory, and inclusive 21st-century perspectives (Bennett, 2004; Costanza-Chock, 2020b; Dunne & Raby, 2013; Latour, 2008; Tonkinwise, 2014; Willis, 2006).

The boundaries between design, science, art and engineering are fuzzy and entangled where creative uses of materials and technologies are concerned (Oxman, 2016). As society shifts from "atoms to bits," (Negroponte, 1995, p. 4) so does the nature of how we behave in the world. We are also in a time of technological agency, such as democratizing digital fabrication and its capacity “to turn data into things and things into data" (Gershenfeld, 2012, p. 1). Design research is increasingly concerned with the impact of systems thinking, which exposes complex and paradoxical truths that are invisible in their totality but emerge as patterns in our experiences and interactions (Buchanan, 2001; Nelson & Stolterman, 2012). Several authors attempt to capture these shifting and the blurring lines between technology and design as a means to understand how design thinking and design activity shape human behaviour in today's complex world (Friedman, 2012; Maeda, 2020; Moggridge, 2007; Negroponte, 1995; Norman, 2010; Ratto, 2011; Verplank, 2009). Rodgers and Bremmer (2017) propose that the expansion and digital hybridization of design has moved it beyond traditional disciplines like industrial design. They posit that design has moved toward “an “alternative disciplinarity” — an “alterplinarity” that does not rely on historical disciplines of design as the boundaries of our understanding has been superseded” (p.23). The expansion of design’s scope is also expressed by Latour who questions what it means to make something when the challenges are so complex.

> The expanding concept of design indicates a deep shift in our emotional makeup: at the very moment when the scale of what has to be remade has become infinitely larger (no political revolutionary committed to challenging capitalist modes of production has ever considered redesigning the earth's climate), what means to "make" something is also being deeply modified. (Latour, 2008, p. 3)

Based on similar expanding views and shifts in its practice and study, Friedman (2008) calls for a general theory of design education that can be explored through many domains. Some authors worry that design’s reliance on other academic fields threatens its value as a field of study (Clemente et al., 2020; Dorst, 2016; Meyer & Norman, 2020). Design is permanently linked to the contexts in which it is practiced forcing researchers to review regularly, and question design education’s impact as these contexts change (Redström, 2020).

One of the more compelling arguments for academic research in design is to view it from an ontological perspective (Hartnett, 2021). Professors of Information and Decision Sciences, Arkalgud Ramaprasad and Papagari Sridhar (2009) define ontologies as "cognitive maps of complex, ill-structured, and plastic problems” (p. 1). Design theorist Anne-Marie Willis (2006) refers to the act of designing as a "double movement," suggesting that "we design our world, while our world acts back on us and designs us" (p. 80). The literature reciprocates these descriptions, forming a view that designs form habits and influences our experiences in a designed world. In return, these habits define the impact of design (Tonkinwise, 2014). It is even suggested that sometimes the best act of a designer is "not-designing" (p. 198). Like the literature on critical making, the use of the design process can also be used to form critique. Design scholars Anthony Dunne and Fiona Raby (2013) propose using design activity as a mode of debate and critical inquiry through speculation into possible, plausible, or probable futures. Costanza Chock (2020b, 2020c, 2020a) is another voice for new directions, proposing a radical shift in teaching design. Their effort in forwarding the cause of *Design Justice* is also a critique of the dominating forces that design represents in the world, including the design of systems and technologies that embed prejudices and cause more harm than good. They propose guideposts for more equitable, transparent, and open access to diverse voices in design.

It is upon schools of design to ensure that people training in the subject are prepared for the new realities of the profession (Friedman, 2012; Norman, 2010). Buchanan (2001) suggests that first-year students should focus on *projects* and *problems* that expose students to the human experience in design and only then progress toward learning about materials, tools, and techniques. In arguing for a change in how design is taught, theorist, scholar, and practitioner Don Norman (2010) describes designers today as "applied behavioural scientists”; he also acknowledges that “they are woefully undereducated for the task" (p. 1). Notions and interpretations of design, and what should be the content of design research and education, are continually being questioned as it expands with increasing complexity. According to professor and designer Johan Redström (2020), what is particular about design is its uncertainty. Therefore, any design curriculum should be focused on establishing trajectories that allow for this uncertainty of what design is rather than finding a fixed position like “product design” and sticking to it. Redström suggests:

> To offer a curriculum based on the idea of a trajectory rather than a position implies that the educational structure would embody a constant transformation of making. This can be used to counteract tendencies to stabilize the notion that “this is design and this is how you do it,” and instead build the notion that design is actually inherently unstable into a program’s movement through courses and projects (p. 95).

To Redström’s knowledge, there are few design curricula based on trajectories, but this will change as design evolves (p. 94).

2.5 Formal Design Programs in Secondary School

Much of the literature on design education focuses mainly on its implementation in higher education. Literature about design in secondary schooling is found in different communities of practice—for example, those relating to Design and Technology or STEAM education. Design-like experiences can also be found woven into the government's curriculum. For example, the Québec curriculum features broad areas of learning meant to bring about experiences that raise awareness for critical 21st-century skills for future citizens, such as entrepreneurship, sustainability, media literacy, and well-being. Critical thinking and interdepartmental project-based learning are also built-in through a focus on interdisciplinarity (MEES, n.d.-a, n.d.-b). There is also a *Digital Action Plan* to support digital literacy and an awareness of new technologies (MEES, 2018). These elements support many of the qualities one might expect of design education. However, as noted by education scholars from the Université de Sherbrooke, the mandated interdisciplinary in the Québec curriculum is often poorly integrated, and teachers are not trained effectively to understand how to synthesize knowledge across disciplines in a meaningful cross-curricular project (Hasni et al., 2015). There appears to be very little in the literature researched about a governmental stance on design education in Québec secondary curriculum. Instead, it is integrated or designed into the curriculum without distinction.

To understand more about the history of secondary school design education, we can look more closely at other examples, specifically in the UK. In the late '70s and early '80s, British design scholars began to examine the benefits of defining design in general education (Archer et al., 2005). In describing student interactions with design Ken Baynes (1985) had this to say:

> A child’s encounter with it is likely to be incoherent and wrapped up in the preconceptions of subject areas principally concerned with other matters. But more importantly it is because we have at last come to recognize the true scope, scale and significance of design as a critical area of experience and learning in the contemporary world (p. 237).

Other British design scholars expressed this view that there should be generalized K-12 design education. Bruce Archer's view of Design—presented with a capital D—was that it was a discipline which belonged in a third domain of knowledge next to literacy and numeracy and was of equal value as the sciences and humanities (Archer, 1979; Archer et al., 1992, 2005). Ken

Baynes defined design intelligence as closely linked to children's experiences (p. 20). Phil Roberts saw the intended outcomes of making artifacts as less important than a change in the student's understanding of things (p. 25). Supported by industry and a culture of appreciation for the trades, Archer, Baynes, and Roberts helped lay the rationale for establishing Design and Technology education in the UK as a core element offered to all students (Atkinson, 1990). However, regardless of support from industry and a consortium of people fighting to prove the subject's relevance in education, it is widely misunderstood and misrepresented, resulting in a sharp decline (Bell et al., 2019; Page & Thorsteinsson, 2018; Spendlove, 2022; Tuckett, 2022).

> Whether defined as a discipline, interdiscipline or multidisciplinary subject, design and technology is both complex and difficult, and like an awkward child it refuses to sit in one place. Coupled with a divergence of opinion surrounding what should be taught, this lack of clarity only serves to divide those working within design and technology, and in so doing, if indeed it ever had one, design and technology has lost its identity (Irving-Bell et al., 2017, p. 16).

Outside the UK, design education is also formally recognized by the International Baccalaureate (IB), which places the subject within its rigorous academic framework across two programmes, the Diploma Programme (DP) in grades 11 and 12 and the Middle Years Programme (MYP) from grades 6 to 10. In the IB Diploma Programme, design technology is situated within the sciences, requiring all students to be familiar with standard level topics linked to product design such as *human factors and ergonomics*, *resource management and sustainable production*, *modelling*, *raw material to final product, innovation and design*, and *classic design* (International Baccalaureate, 2018). Acting as a platform for all students to acquire some of the design competencies that could eventually lead a student to study design technology in grades 11 and 12, the Middle Years Programme positions design as one of eight core subject areas (Figure 4).

Figure 4

Middle Years Programme Subject Areasd

Language Acquisition
Language and Literature
Individuals and Society
Mathematics
Design
Arts
Sciences
Physical and Health Education

(*Middle Years Programme Design Guide*, 2014, p. 2)

In the Middle Years Programme, schools can offer courses on product design, digital design, or a combination of the two. Teachers are asked to follow the IB's design cycle, featuring sixteen strands (Figure 5) which are to be assessed twice a year. Unlike the pre-determined curriculum Diploma Programme, the Middle Years Programme is open to teacher interpretation and is intended to introduce students (ages 13-15) to problem-based learning. According to the IB, the nature of design is process-oriented, accessible by all, human-centred, sustainably responsible, empathetic, technological, creative, and organized through a design cycle that, like other design processes, is marked by inquiry, problem-solving, development of ideas, creation, and evaluation (International Baccalaureate, 2014).

The IB's perspective on design supports standard features of a design process which can be perceived as encouraging moments of insightful creativity leading to innovative solutions to problems (Dorst & Cross, 2001). The IB's mission is to "develop inquiring, knowledgeable and caring young people who help to create a better and more peaceful world through intercultural understanding and respect" (International Baccalaureate, 2014, p. 6). The organization sees design education as a critical component of this. Surprisingly, in both program guides for the subject of design in the IB, there is but one reference to design thinkers referenced in this thesis (Victor Papanek). The IB perspective on the nature of design favours product development, with some reference to the UK's Design and Technology Association and manufacturing culture. The relevance and impact of design is discussed but within the context of more scientific inquiry and analysis.

Figure 5

16 Strands of the MYP Design Cycle

A INQUIRING AND ANALYZING

- Ai Explain and justify the need.
- Aii Identify and prioritize the research.
- Aiii Analyze existing products.
- Aiv Develop a design brief.

B DEVELOPING IDEAS

- Bi Develop a design specification.
- Bii Develop design ideas.
- Biii Present the chosen idea.
- Biv Develop planning drawings/diagrams.

C CREATING

- Ci Construct a logical plan.
- Cii Demonstrate technical skills.
- Ciii Follow the plan to make the solution.
- Civ Justify the changes made to the design.

D EVALUATING

- Di Design testing methods
- Dii Evaluate the success of the solution.
- Diii Explain how the solution could be improved.
- Div Explain the impact of the solution.

The strands presented above are typically represented in a circle.
(*Middle Years Programme Design Guide*, 2014, p. 12)

2.6 STEAM & Design Thinking

Design thinking has become a popular method for problem-based learning in 21st-century education (Davis & Littlejohn, 2017; Goldman & Kabayadondo, 2017; Hubbard & Datnow, 2020; Panke, 2019; Rauth et al., 2010; Smith et al., 2015). Features that strengthen a designer's resolve to deal with unknown situations or to make future-forward assumptions have led to the rise of design thinking in education (T. Brown & Barry, 2011; Dorst, 2010; Koh et al., 2015; Verganti et al., 2021). The Hasso Plattner Institute of Design (d.school) at Stanford University has, under the guidance of IDEO founder David Kelly been instrumental in spreading design thinking in schools (Banerjee & Gibbs, 2016; McCarthy, 2020). The d.school offers a variety of tools aimed at design thinking for educators. “We teach teachers in the ways they are now being asked to teach – in immersive real-world projects and experiences where creative problem-solving matters most” (*K12 Lab*, n.d.). The value added by offering design thinking in schools is linked to a cultural interest in innovation (Goldman & Kabayadondo, 2017). Still, others note that, despite its popularity beyond its communities of practice, design thinking has not yet met its promise (Kimbell, 2011; Verganti et al., 2021).

Design thinking is often linked to STEAM education and offers a natural structure for creative and scientific inquiry supported by an interest in real-world, project and problem-based learning (Graham, 2020; Henriksen, 2017). John Maeda, entrepreneur and former director of the Rhode Island School of Design has made propositions that STEAM education raises the profile of design and art as central to economic success in the 21st century (2013, 2019). However, there exists a critique of the legitimacy of STEAM when it is not appropriately addressed in the curriculum. Understanding its interdisciplinarity requires time and professional development, where art is an equal partner and not a secondary add-on (Catterall, 2017; Colucci-Gray et al., 2017; Milara et al., 2019). There is also concern that proponents of STEAM end up marginalizing the value of artistic expression when design thinking is seen as a more practical application for creativity (Graham, 2020; Thomson & Maloy, 2022). Graham (2020) offers a sentiment of concern for STEAM and design thinking in schools suggesting they promote economic perspectives which are complicit in environmental destruction (p. 40). Regardless of such concern, STEAM is also an important entry point in education for inquiry into the interdisciplinary nature of UN Sustainable Development Goals (SDG) and supporting student motivation for change (Hsiao & Su, 2021; Rieckmann, 2017; P. Taylor & Taylor, 2019).

2.7 Alternative Schools with a Focus on Design

Many educational institutions and types of schools may provide project-based learning similar to what we consider design education. Schools may also choose to be independent or non-accredited, which offers some freedom from government curriculum but at a cost to parents through tuition or extra support for students to achieve the necessary prerequisites to get a high school degree. All schools can offer unique programs with impressive facilities that embed design and experiential learning with STEM, STEAM or that feature Fab Labs and makerspaces. Some parents might choose to homeschool and prefer to send their kids into informal programs that are more tailored to their interests. This review investigates schools with a specific nod to design education or inquiry-based learning.

French alternative public schools in Québec do emphasize inquiry-based learning. In 2012 there were 31 designated alternative schools but only 3 were at the secondary level (Weeks, 2012). As of this writing, this number has since grown to 48 according to the RÉPAQ (Réseau des écoles publiques alternative du Québec) website, a support network for alternative public schools in Québec. These schools may focus on the IB, arts, sports, or special needs and often times they are instigated by parents who are unhappy with the regular school options (Arsenault, 2015). Alternative schools emphasize learner-driven experiences and regularly focus on personal and collaborative projects in STEM, entrepreneurship, or community service (Pallascio & Beaudry, 2001; REPAQ, n.d.). Still, there is little research on Québec schools with a distinction for design and few public alternative English schools in Québec with a focus on inquiry or project-based learning. In the United States, there is a growing trend to start micro-schools, which tend to be classified as small and bespoke offerings which may cater to financially secure families, homeschoolers, and those who have found some freedom to substitute mandated curriculum with unique experiences (Cohen, 2017; Horn, 2015). Examples of this can be found in some privately owned schools, like those born from the start-up culture of Silicon Valley, like the AltSchool. Customization of educational experiences can also be found in US charter schools, like High Tech High, which provides innovative learning that models design-led practices through problem-based and project-based learning (Neumann, 2008). Of course, there remain impressive schools around the world like the Green School that take experiential learning seriously and often surround this with projects and design activities (The Green School, n.d.).

Few examples of design-specific alternative schools at a secondary level were found in this literature review and very little in terms of academic research on secondary design education to note outside of Design Thinking, STEAM, the IB, or Design & Technology (UK). However, one unique example is Nuvu School of Innovation, a non-accredited micro-school linked more directly to design research. In his doctoral thesis, *More Seeing in Learning*, NuVu founder Saeed Arida (2011) cites Donald Schön's reflections on learning through project-based and problem-based activity in the architectural studio. Arida highlights *critique culture*, *reflection*, and *custom evaluations* as critical factors in establishing a creative atmosphere for learning he has set up for the NuVu School platform. NuVu has expanded its offerings as a framework available to other schools in the form of NuVuX platform with the goal of spreading studio-based learning to other sectors (NuVu The Innovation School, n.d.). Another innovative example of design education emerging from MIT is the Fab Academy, a distributed educational model based on the university-level course *How to Make Almost Anything* (Ylioja et al., 2019). Some schools with highly integrated Fab Labs, like Charlotte Latin School in North Carolina, may invite students to participate in the Fab Academy (Charlotte Latin Fab Lab, n.d.). However, it is not advertised on their website likely due to the rigours of the program not being suitable for all students (Charlotte Latin School, n.d.). Other members of the Fab Lab education network are forming initiatives to integrate better opportunities for teacher training in digital fabrication reimagining the Fab Academy model to be more effective in schools (Whitewolf, 2023). One author likened the Fab Academy, and Fab Labs, to work emerging through the Bauhaus; only in this world what is designed are the algorithms and repository of design files—CAD/CAM and coding—for machines (Santos Arias, 2021).

2.8 Summarizing the Literature

The focus of this literature review was to highlight what is known about design and maker activity in secondary education. As literature was collected based on the three threads introduced at the beginning of this section—constructionism, the maker movement, and the nature of design education—the proximity between different stances toward learning in maker-driven design activity was examined. The literature chosen for this review represents only a fraction of what might be available in each thread. This limitation has had an advantage in narrowing the scope of this work to literature about design and maker experiences in schools linked to activity in Fab Labs, and makerspaces. However, further insight and interest in this study could be found in the literature related to other domains such as STEM, cognitive science, art education, instructional design, interaction design, computer science, educational technology, arts and crafts, art therapy, and more.

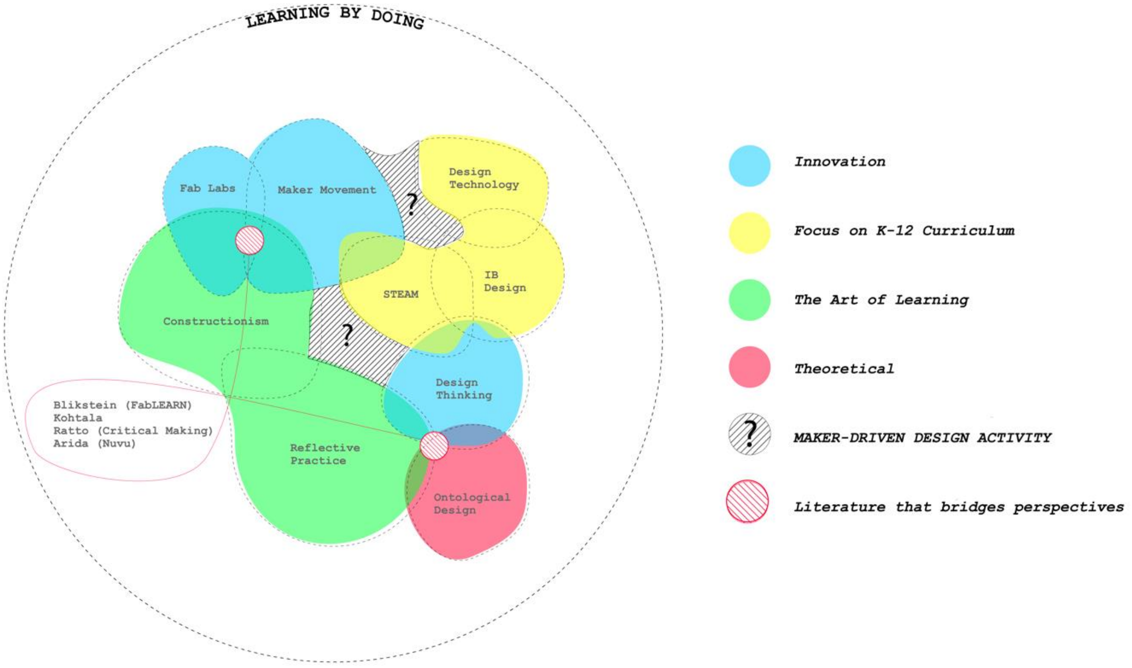
The selection of readings that were examined provided enough sense of the academic and practical territory that situates this work and helps assess the boundaries between communities of practice, the individuals involved, and the institutions that support their work. Inquiry into shared and differentiated terminology helped to determine how keywords are defined in different communities. For example, how is “design” used in constructionist and maker literature? Are there links to “constructionism” in design literature? How are “Fab Labs” or the “maker movement” referenced in Design and Technology literature? Is the design research community discussing K-12 education? What, if any, reference to “ontological design,” “critical making,” or “systems” and “interactions” are being made concerning secondary education? In this regard, the selection of literature reviewed provided enough evidence to come up with conclusions about the state of knowledge in design and maker education in secondary schools, where several of the foundational ideas referenced in this thesis have emerged.

Although it was not explicitly described in the literature, it can be inferred that the design process also be viewed as a learning process, and it supports ways of thinking that are not expressed in other subject areas. The literature supports the view that design and maker experiences offer unique 21st-century learning opportunities and strengthen mindsets that support meaningful introductions to creative uses of technology, sustainable action, and critical making. Still, there are significant challenges facing this kind of activity in secondary schools, such as teacher training, biases toward other subjects, and lack of time. Makerspaces and Fab Labs are valuable sites for this type of learning, but more effective research methods are needed to validate them as significant spaces for formal education. Design and technology in the UK, the IB programs, and alternative schools are of interest because they place design processes as an essential element in the curriculum. Outside of concern for declining interest in British schools offering design and making through a General Certificate of Secondary Education, the literature supports these activities as popular add-ons to an educational experience. Meanwhile, little evidence from design research communities is available to suggest a progression of learning through design from secondary to higher education beyond those initial scholars pushing for the subject in general education in the UK (Archer et al., 1992, 2005; Baynes, 1985). There was also little discussion relating to design research in the literature focused on communities interested in design thinking and making in secondary education. This omission suggests that current concerns of design research may not be entering the discourse of those who introduce design activity in secondary education.

The literature reviewed points to a possible gap in how different voices on design, constructionism, and maker education share their view of what design should look like when it is meant to express learning. Figure 6 presents a conceptual map of the literature reviewed and helps to visualize two zones where relevant connections between the communities were not described.

Figure 6

Gaps Between Communities of Practice



The map reveals how the theoretical interests linked to design research communities do not interact much with communities that support innovation and creative use of technology in schools. Of the literature reviewed, design communities invested in the subject as it stands in traditional school settings—like the IB, Design & Technology Association (UK), and organizations with a general interest in STEAM education—rarely referenced constructionist thinking despite sharing an interest in maker experiences. Alternatively, the intersecting perspectives between Papert's constructionism and Schön's reflective practice support more pragmatic, experiential, and learner-centred views.

This diagram presents a general overview and highlights possible limits within the reviewed literature. The apparent gaps found at the intersections of this research provide information on where opportunities for further research-creation present themselves. There is an interest among the different communities explored to express a notion of design for the art of learning. Most communities believe in the promise of design and maker experiences to support critical thinking and expose students to alternative ways of seeing, including developing student sensibility for sustainability and innovation. The stance being made in this thesis is that new guideposts for design in K-12 education can be achieved by defining activity at the intersections of these academic communities. While there is new research interest in bridging perspectives between maker and design communities, there appears to be an opportunity to uncover new approaches to learning that support critical making, sustainable action, and creative uses of technology in schools. Despite the many challenges facing this type of education, the literature reveals possible interest in forming more educator-designer perspectives in support of design literacy and teacher readiness in maker environments. The following table revisits the different sections of the literature reviewed and reflects on how they relate to the research question.

Table 1.
Summary of the Literature with Reflection in Relation to the Research Question

<table>
<tr><td colspan="2">2.1 Situating Learning by Doing
Constructivist thinking supports experiential learning and situational design activity and encourages individual reflection in the process of creation. Teachers should be seen as guides or coaches in self-directed learning where goal-oriented motivation is seen as a factor for success. The constructivist approach to learning is more akin to promoting the art of learning rather than the science of teaching.</td></tr>
<tr><td>Critical Making</td><td>Choosing the right approach to learning can affect how project-based, problem-based learning is implemented. The constructivist lens supports “learning by doing” and the potential for critical making which is process-driven and requires reflection based on experiences with technology and craft.</td></tr>
<tr><td>Sustainable Action</td><td>Engaging students in real-world and experiential learning provide avenues for a deeper understanding of sustainable issues. The reflective component in situated learning encourages a hands-on approach that provides context and room to reframe activity toward sustainability.</td></tr>
<tr><td>Creative Uses of Technology</td><td>A learner-centred culture promotes trial and error and supports opportunities to learn from serendipity. The mental models we create in our heads about technology need to be confronted by real-world experiences forcing us to rethink our understanding of it.</td></tr>
<tr><td colspan="2">2.2 Constructionism and Tinkering as Design Process
Tinkering with materials and technology is a feature of designerly processes and constructionist approaches to learning. Though, they represent different communities of practice and do not share terminology. The literature has enough cross-over references to support the view that constructionist perspectives can be used as a design methodology. Both constructionist and design literature emphasize the importance of learning through an iterative process, microworld experiences, and communicating and sharing ideas through sketches and projects.</td></tr>
<tr><td>Critical Making</td><td>Both constructionist and design literature present the potential for growth and the sharpening of ideas through making, sharing, and reflecting. Ideas are embedded in artifacts as nonverbal evidence of learning and critique of the process and the purpose of the objects being made.</td></tr>
<tr><td>Sustainable Action</td><td>The texts mention the importance of design choices, their impact, and the need to reflect on the process used to make them. The constant desire to reimagine the way things are done can be used to emphasize sustainable action and discussion relating to making in an environmentally conscious way.</td></tr>
</table>

Creative Uses of Technology	Constructionism emphasizes the value of tinkering, debugging, and playing with technology which can lead to novel ways of learning and generating design ideas that are used to optimize learning experiences with technology

2.3 Making and Creative Uses of Technology

The maker movement has promoted the study and interest in design and technology in more diverse ways. The ability to conduct research and design technology for maker experiences is improving with the rise of digital fabrication and an interest in innovation. Fab Labs provide resources for communities and schools to engage in sustainable action and creative problem solving which can be valuable tools for learning. Design literacy can support more meaningful interactions with technology in Fab Labs provided it is done effectively.

Critical Making	Critical making can be seen as a form of design-oriented research that involves creative uses of technology for critique and expression. It shares views on the transfer of knowledge through project-based activity with constructionist thinking. It uses technology and a maker's sensibility to construct statements about design.
Sustainable Action	The inclusion of design literacy is called to help strengthen meaning in the maker process and to help guide activity toward sustainability, such as through repair, material use, and distributed manufacturing.
Creative Uses of Technology	Creative experimentation with electronics, digital fabrication, CAD, and computation helps make them more accessible. Tools that demystify complexity in order to focus on creativity are valuable in building confidence in learning environments. Teacher and institution readiness is critical to avoid the trivialization of technology.

2.4 The Shifting Nature of Design Education

Design research is becoming more ontological in nature and is moving away from simplistic views of design practice. Design research is concerned with its social and environmental impact and pulling from different fields of study. Several papers describe a need to shift toward more pluralistic views of design, accepting it as inherently unstable or difficult to define. Designers need to learn more skills across domains to be relevant in a future where interactions are increasingly obscured, and systems are redefining the notion of a product and impacting society in invisible ways. Some authors call for redesigning design education to focus on trajectories rather than the fixed understanding of design skills such as graphic, industrial, or interaction design.

Critical Making	Design is increasingly used as a method to speculate and infer ideas about where technology is being used and how it is informing behaviour. Critical making is a vehicle to investigate the shifting of design practice and its impact on society.
Sustainable Action	The environmental impact of design activity is central to design studies and increasingly embedded in practice. Using making and technology to generate less waste is central to design experiences. Designers are expected to act on sustainability rather than just reference it.

Creative Uses of Technology	Designers are increasingly polymathic and versed in diverse forms of technology. Creative exploration at the intersections of technologies, materials, systems, and interactions is central to the kinds of experiences occurring through design in a Fab Lab.

2.5 Formal Design in School Curriculum

The study of design occurs in secondary education in various ways and is usually defined by different communities of practice. Design that is embedded in Québec government curriculum is distributed and lacks definition. Dedicated design programs in schools can be found through an IB education and through a General Certificate of Education in the UK. Papers emerging from the UK are more likely to promote design in general education as it is more culturally accepted. However, a decline in interest in offering Design and Technology education is also questioning its relevance in the general education. Despite accepting designerly thinking as unique and relevant, research on the IB and Design and Technology in the UK neglect more ontological and shifting perspectives of design emerging in higher education. Formal design programs in schools seem linked to a more practical and definable immovable impression design as a viable economic activity rather than as an evolving form of inquiry, critical thinking, and broader creative-technical skillsets.

Critical Making	The influences of the maker movement, or critical making, were not found in the literature relating to formal design education in secondary schools. However, the MYP framework is flexible enough to include more diverse perspectives provided there is some translation.
Sustainable Action	Sustainability and the nature of design's role in the development of environmentally friendly products is important in the language used in literature in design education in schools but these are linked more to industry perspective. Sustainable action in how students of design is not properly defined.
Creative Uses of Technology	The MYP focuses on a plan-first approach, and it needs to be clarified where creative uses of technology are encouraged. D&T offers more contact with craft and creative technology uses like digital fabrication but focuses on more traditional industrial design practices. There needs to be more evidence in these communities relating to the potential of tinkering and experimentation with technology that is more exemplified in the literature on making and in Fab Labs, where there is more experimentation with blending tools, materials, and processes.

2.6 STEAM and Design Thinking

There is plenty of literature pertaining to the use of Design Thinking in secondary education or activity relating to STEAM (science, technology, engineering, art, and mathematics) as a way to divert more attention to the critical role of creativity in education which tends to favour STEM (science, technology, engineering, mathematics). While the study of design can be wrapped into these experiences, there is concern over teacher readiness to effectively synthesize the interdisciplinarity of a STEAM experience. There is also a tendency to tokenize art or creativity when sprinkled onto traditional activities or to assume that design is a higher form of art due to its perceived practicality. Design thinking is widely used to spark creativity and innovation. In education, it is more often an add-on to other activities and may not always represent design's best interests or it may also bring with it a bias toward corporate interests in design.

Critical Making	Although it is not referenced in the literature, critical making can give meaning to STEAM and design thinking activities in schools. It offers an effective way to address 21st-century concerns expressed in the literature.
Sustainable Action	STEAM offers a transdisciplinary approach to the subject of sustainable development while problem-solving skills exercised in design thinking activity can also help motivate students and educational communities to address UN SDGs. The challenge is moving from a thinking-oriented to action-oriented activity.
Creative Uses of Technology	STEAM can blend science and technology with creativity, but examples often default toward STEM for inspiration in this domain. Design thinking, on the other hand, prioritizes cardboard and sticky notes. Creative use of technology in STEAM would require technology as an active agent in transdisciplinary inquiry.

2.7 Alternative Schools with a Focus on Design

Alternative schools come in various formats but often prioritize learning experiences unavailable through general education. Alternative schools may be public, private, independent, or uncredited. They often explore project-based learning, which may include design-like experiences. The NuVu Innovation School and evolving partner program (NuVuX) stand out as one example of a school with a design focus aligning with design research. Although not categorized as a school, the Fab Academy addresses design-like experiences in Fab Labs. It provides a rigorous learning experience influencing programs entering schools through informal initiatives emerging from the Fab Lab network.

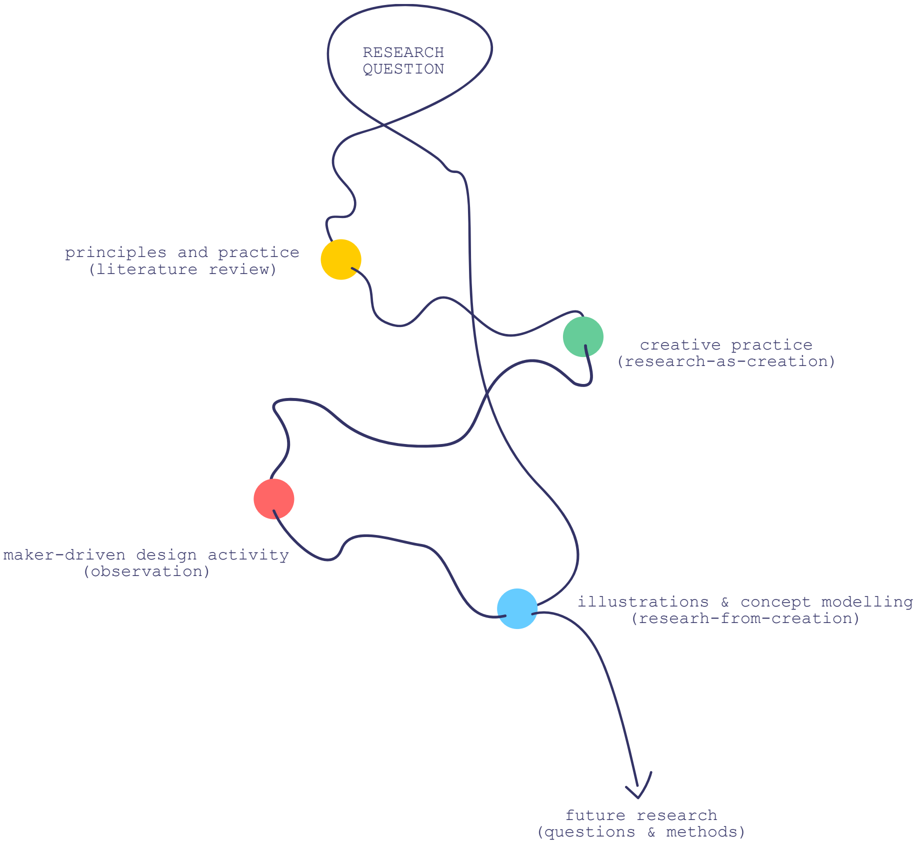
Critical Making	Critical Making can be addressed in alternative schools that explore interdisciplinary projects but require educators with interest in using maker experiences as a strategy for debate or dialogue within the project.
Sustainable Action	Alternative schools can address sustainable action by giving students time to engage in community-oriented projects where they are actively engaged in implementing sustainable projects or within the materials and processes used in project-based learning.
Creative Uses of Technology	Alternative schools are more likely to offer students alternative experiences with technology due to freedom in allocating time to project-based learning. It should be identified as a feature in their creative approach to differentiate from general education. Creative uses of technology imply a freedom to experiment, tinker, and find atypical uses of technology in learner-centered educational experiences.

3 METHODOLOGY

This study aims to describe a creative practice that encourages qualities that enhance critical making, sustainable action, and creative uses of technology and to see what happens when these qualities are applied in a school setting in what will be defined as a *maker-driven design activity*. The methods represented propose a mixture of research-creation informed by observation followed by communication strategies that employ concept modelling and illustration. Combining these methods provides the tools to map out and express guideposts for maker-driven design activity in secondary education. Figure 7 illustrates an overview of the methods as a thread-like loop which tethers ideas expressed in the literature with creative practice and educational activity. The outcome of one loop should inform opportunities for future research.

Figure 7

Methodology



Two types of research-creation have been exercised in the methods described—*creation-as-research* and *research-from-creation* (Chapman & Sawchuk, 2012). Creation-as-research describes the efforts to generate creative works that exercise powerful ideas and reveal new design opportunities throughout the process. Chapman describes creation-as-research as a "form of directed exploration through creative processes that include experimentation, but also analysis, critique, and a profound engagement with theory and questions of method" (p. 19). As described in this work, creative practice is linked to critical making. It need not be for any specific outcome other than personal enjoyment, artistic expression, or experimentation with new ways of thinking and doing. This practice aims to learn from the process and discuss the topics being explored critically. Informing methods with similar constraints found in educational contexts helps establish new techniques, tools, kits, and experiential elements while emphasizing design strategies for educational activities in schools. Research-from-creation is "iterative design or testing that involves the participation of individuals or groups who may be an intended audience" (Chapman & Sawchuk, 2012, p. 16). In this case, the audience refers to students and teachers. It constitutes efforts to understand better how maker-driven design activities contribute to engagement and learning in a classroom or Fab Lab. The combined efforts in this research-creation form meaningful translation points between creative practice and facilitating learning experiences.

Illustration and concept modelling are used to present the observations emerging from research-from-creation. This method helps to unpack the new knowledge arising out of this work in a fashion that can be communicated playfully and efficiently to others. Because this work is situated in zones that bridge different principles and practices, as expressed in the literature review, it becomes relevant that these methods lead to communication strategies that educators and designers can interpret. Combining research-creation, illustration, and concept modelling helps define research-creation and reflect on the nature of design, the nature of learning, and the contexts in which these two categories collide.

The outcomes of this work will include strategies to identify opportunities and challenges in maker-driven design activity and the broader context of design and maker education. Two projects are being examined as examples that will highlight these methods. But first, it is essential to define what constitutes a maker-driven design activity and the kind of evidence that informs opinions relating to the impact of these methods.

3.1 Defining Maker-Driven Design Activity

In the context of this work, the verb "designing" suggests an iterative and creative process used to "convert utility into behaviour" (Oxman, 2016, p. 5), and the term "making" is defined as a process of construction, whether by physical or digital means (Dougherty, 2013; Honey & Kanter, 2013; Martinez & Stager, 2019). These distinctions are fuzzy, but they share an iterative and creative-technical process. Tonally, “designing” is concept-oriented, outward-facing, and scalable, and “making” can be interpreted as more inward-facing, technical, and personally meaningful. Maker-driven design activity is proposed as an easily understood hybrid term. It defines goal-oriented educational activities involving designing (devising ways to inform thoughtful behaviour) and making (constructing) something using hands, computers, and machines. The idea is similar to critical making, and both support inquiry and critical discussion about the social and environmental impact of design, especially where technology is concerned. However, the intent behind maker-driven design activity is to playfully engage with powerful ideas (e.g., Papert, 1980, Chapter 6) and find links to design research in a way that is more aligned with secondary education.

A powerful idea offers “ways of thinking that afford the learner access to concepts and strategies that confront and build on intuitive knowledge” (Noss & Hoyles, 2017, p. 30). We *think in action* (Schön, 1987) with tools, materials, peers, teachers, and coaches towards some desired end. Students learn to debug and make mistakes by exploring opportunities that reveal themselves through action. What is known is made visible in the output of a design process. What can be exhibited in the object being made (physical or digital) is evidence of learning by doing. This evidence is presented through creative uses of technology and applied in critical, sustainable, and interdisciplinary thinking. More specifically, maker-driven design activity is a neutral way to define creative-technical experiences familiar to the different communities that may find themselves working in learning environments such as Fab Labs and makerspaces. Maker-driven design activity can be used to design and make physical objects, digital media, installations, or expressions of an inquiry into a topic, material, or technique. Rather than thinking about design as a client-facing activity helpful in building entrepreneurial or innovative thinking in schools, the outcome of a maker-driven design activity should be seen as a product of creative-technical learning.

Seymour Papert’s description of the “art of learning” is central to the methods being explored, which aim to establish a “*mathetic”* (1996, p. 2) design process. In other words, this work seeks to exercise the art of learning as applied to design research-creation. Rather than layering design activity onto existing structures to develop specific skills, the methods employed seek to embed design literacy into maker experiences to engage students in inquiry-based learning (Christensen et al., 2019). As a term, design literacy has helped to describe an ability to recognize the multimodal and increasingly complex ways designed things impact and sustain life. Such critical understanding should be accessible to all students, not just those interested in design disciplines. Lutnæs (2021) proposes the following definition of design literacy:

> Being design literate in a context of critical innovation means to be aware of both positive and negative impacts of design on people and the planet, approaching real-world problems as complex, voicing change through design processes, and judging the viability of any design ideas in terms of how they support a transition towards more sustainable ways of living. (p. 10)

Maker education introduces students to ill-defined problems (Davidson & Price, 2018) and offers a fun way to exercise 21st-century competencies (OECD, 2018). Finding more opportunities to imbue this activity with design literacy and toward critical making aims to help sensitize learners to the concerns captured by the shifting nature of design, including an understanding of ontological design (e.g., Willis, 2006), design justice (e.g., Costanza-Chock, 2020b), and ideals of sustainable action (*United Nations: Sustainable Development Goals*, n.d.). Maker-driven design activity can be defined by how it blends design theory with maker experiences that support student inquiry and discovering an art to learning relevant within the educational contexts in which it takes place.

3.2 Context of Research-Creation

This work stems from ongoing observations as a design teacher and facilitator of maker experiences. It has evolved within a high school environment where maker-driven design activities are practiced. It supports a more "discovery-oriented" and naturalistic inquiry (Patton, 2002, p. 99) into creative and technical learning phenomena. Open access to student and teacher interactions has provided many informal opportunities to assess design activity and adjust approaches to teaching and learning. A design practice centred on generating maker-driven design experiences in schools must understand the conditions imposed on the process due to the grammar of schooling. As an outsider to the core curriculum and because it represents an alternative and creative way of learning paced differently, raising the profile of design and maker education can be likened to working in an indeterminate zone of practice. Schön (2001) describes indeterminate zones of practice as:

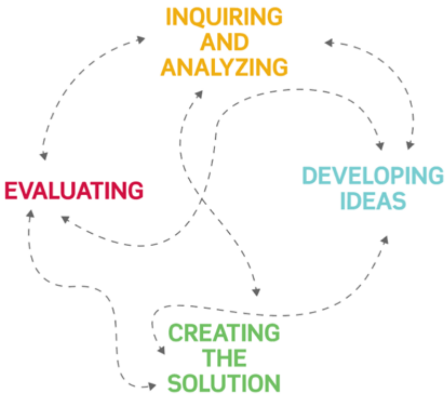
> … situations of complexity and uncertainty, the unique cases that require artistry, the elusive task of problem-setting, the multiplicity of professional identities. (p.4)

For designers of maker activities, tools, and technologies, it is essential to prototype and make changes once patterns of frustration reveal themselves (Resnick & Silverman, 2005).

The information gathered in this work took place in the context of an IB school that has adopted the Middle Years Programme (MYP). While the problem-based learning approach taken by the MYP framework is characteristic of other problem-solution design processes (Dorst & Cross, 2001), it references a particular way of learning through design which emphasizes research and planning, as evidence of rigour (International Baccalaureate, 2014). Although not intended to be viewed this way, one may confuse the MYP design cycle (see Figure 5) as devaluing the role of tinkering in the design process in favour of other research methods. Tinkering and play are not mentioned in IB documentation but can offer meaningful insight. While setting learning goals and establishing constraints before engaging in maker-driven design activity is crucial, this work examines a design process that follows a “make first” approach. This approach differs slightly from the “specify/plan first” language encountered in the IB’s Middle Years Programme criteria (2014, p. 41). At times, it has been challenging to marry these two approaches unless we reimagine the IB’s design cycle as more fluid in its interpretation of research and creation, and less concerned with overly specific strands, thus allowing for a greater flow between criteria and offering a more blended, neutral, maker-driven design experience (Figure 8).

Figure 8

The MYP Design Cycle Simplified



The work described below will outline a process that encourages directed play with materials, technologies, and ideas in unknown territory. It operates under the assumption that indeterminacy is vital in learning through design. After all, abductive reasoning is a trait of design ability (Cross, 2006, p. 20). More importantly, it demonstrates methods for encouraging serendipity through creative uses of technology. Rigour is shown through a stick-with-it-ness in creative experimentation, tinkering, and iteration. Such playful determination supports necessary 21st-century competencies and builds mindsets which confront complexity with creativity and care.

3.3 Observable Evidence – Forming Opinions

Evaluating whether maker-driven design activity can support successful learning experiences in schools requires evidence of student engagement with concepts beyond what is being asked by the assignment. We need repeatable evidence of interest in applying critical making, sustainable action, and creative uses of technology to know if these elements stick as concepts. If we rely solely on rubrics where performance goals are prioritized, it becomes difficult to know if students practice something simply to achieve marks. Similarly, if teachers do not encourage these concepts as meaningful elements in a design process, there is less chance that students will recognize them.

Evidence of interest can be found in the iterative artifacts generated from student activity, such as physical prototypes, sketches, and media. Artifacts can include design journals where documentation and reflection are submitted for review, or they can be observed in person. Aesthetic quality in the product of design can help assess rigour, but this is not necessarily evidence of an interest in learning. If the intent behind an exercise is to explore visual aesthetics (e.g. straight lines, colour theory, negative space), then the refinement of a project is relevant as evidence of learning. Still, in a mark-driven learning environment, evaluating a student's interest in learning should not be over-influenced by the aesthetics or refinement of a student's project. Taking such a stance is necessary; it is too easy for a teacher to see such attributes and assume a higher level of quality of thinking. Most novices need to learn how to do what they want or be introduced to qualities that constitute refinement over time. Also, it is necessary to realize that some students may be crafty and still dislike what they do. Other students might have external support. If a student chooses to refine the appearance of their products based on feedback or from more independent observations, we can infer that some pride in the creative process was achieved. However, in maker-driven design activity, the mess of learning should be maintained. It should provide evidence of new knowledge as it evolves through iteration, debugging, and experimentation with design processes and ideas.

Furthermore, if ideas and qualities do not evolve throughout an activity, we can infer a lack of change in thinking or approach. A student can submit a beautifully made model of a sustainable home without any evidence of inquiry or creative exploration. Artifacts can also be unpolished and full of mistakes and still represent evidence of learning through design. Standard assessment practice notes the effort to which a student follows an assignment. However, we should also look for markings in student work that provide evidence of their approach to the design process, which might not be explicit. Photos of student work, cardboard prototypes, unfinished work, discarded projects, experiments, and even abuse of materials or tools can suggest whether critical making, sustainable action, or creative use of technology was exercised. For example, suppose a facilitator recovers multiple discarded projects after an activity, like building automata machines, and all the projects show some evidence that glue was used to attach cardboard and random pieces from a scrap bin onto LEGO mechanisms that spin. In that case, this may suggest a few things about the approach students are taking to the design process:

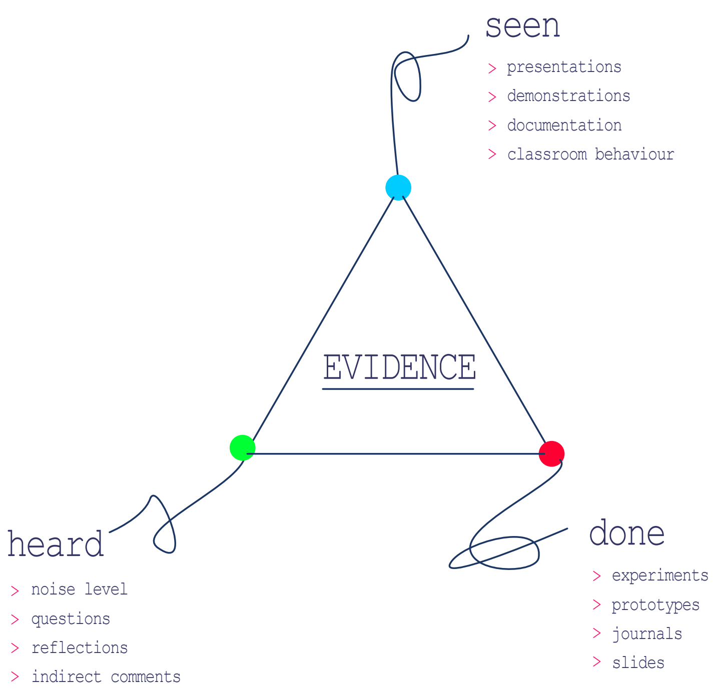
1. It shows a lack of care or due diligence in the design challenge, which would have asked students to think critically about their design choices and consider its impact as a thing to think with.
2. The projects lack evidence of sustainable action in that the students connected compostable materials to a product designed for reuse using glue. The compostable elements are no longer compostable, and the reusable elements are no longer reusable.
3. The project shows little evidence of iteration and experimentation with technology to find alternative ways of connecting parts or communicating a message. The student could have used simple digital fabrication techniques to make custom connectors or experimented with novel ways to use LEGO and paper without glue.

A lot can be learned from this evidence, provided the contexts are known. Evidence of what was done by students has to be weighed against other evidence, such as design journals, teacher instructions, time and availability of resources, or classroom dynamics. Using the automata example above, if a student remarks in their journal that the use of LEGO or scraps constitutes a “more sustainable” approach in their process, it shows a lack of understanding of sustainable action. They cannot be exercising sustainability simply by gluing LEGO parts to scrap material for a one-time exercise destined to be discarded. While materials are being reused for this project, they quickly become obsolete when brute force is used to connect reusable or compostable parts with plastic adhesive. It is essential to triangulate observable and recorded evidence as it will guide future iterations of this activity. We must balance what was done with what has been seen and heard during activities or documentation (Figure 9).

The previous description of discarded student projects was just given as an example of evidence. We can also inform our research based on audible expressions provided we can note them as data. Audible evidence includes what can be heard in classrooms, presentations, or informal discussions. Impressions can be indirect, and a lot can be learned from what is heard when students talk about the state of learning or their interest in the activity. For example, hearing “I’m confused” or “Wait... what?” can suggest students may lack clarity for a task. On the contrary, hearing “Oh my god, how did you do that?” suggests excitement and curiosity. Audible evidence may also include general noise levels and the types of sounds from classroom or lab activities. An active classroom involved in maker-driven design activity should not be quiet, nor should it sound chaotic. Ideally, it sits somewhere in between. Future research might include mapping these different expressions based on student feedback, then finding methods to keep track of what was heard.

Figure 9

Types of Evidence



Lastly, evidence comes in the form of observable behaviour. Watching a class of students work on activities can help to assess the quality of interactions surrounding the activity. How students or teachers address design concepts and creative-technical learning can be investigated through classroom dynamics, body language, and group behaviour. These observations require knowing the differences between active students who are engaged in making and problem-solving, focused and in a state of flow, and students who seem disengaged or who try to mask fidgeting as a creative activity. There is also important information regarding behaviour that should have been informed by instruction. Evidence of this kind can include behaviour that supports desired outcomes, topical knowledge, safety, or transfer skills from other classes. Another area of important observation is in the interactions with materials and tools. How are they being used and misused in the process of creation? The challenge in maker-driven design activity is maintaining student interest in the activity while having time for some iteration and experimentation with ideas, technologies, and techniques followed closely by reflections.

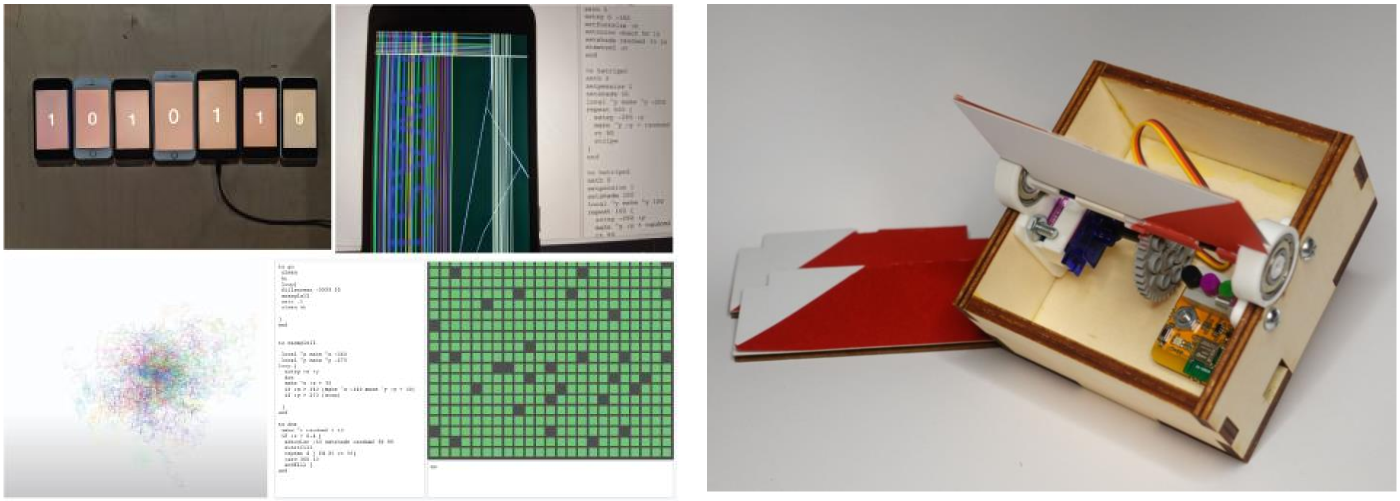
The methods used here represent an epistemology suitable for defining what questions to ask and where more research is needed. In the two example projects to follow, evidence can only support impressions that will inform new methods of researching phenomena related to design(ing) for the art of learning. It is a first step in guiding future efforts to gather data supporting maker-driven design activity in schools under the right conditions and with informed consent by parents and teachers. The opinions reflected in this thesis should be unpacked and repackaged as proposals that include mixed methods to strengthen arguments for this line of research-creation.

4 EXAMPLE PROJECTS

Several explorative projects throughout this work aimed to refine a creative practice that merged digital fabrication and discarded objects with constructionist-inspired educational technologies. Many of these projects focused on making computational art using technology with a low floor, wide walls, and high ceiling design principle (Resnick & Silverman, 2005). For example, experiments with the Logo programming language and modular, easy programmable microcontrollers were used to make objects and explore interactions with physical computing (Figure 10). Due to my students' interest in making non-programmable objects, the two examples analyzed in this thesis veer away from my personal interest in working on more computational projects. Instead, the projects reviewed here favour ideation and making “objects to think with” that explore microworld experiences in digital fabrication. Papert (1980) described the Logo Turtle as “good to think with” (p. 11). It was a tool that children could use to animate, teach, and apply math and logic in making something meaningful with computers (Papert & Solomon, 1972). Like the Logo Turtle, an object can be a good thing to think with if inquiry is baked into its creation. Not only in the way it represents an idea but also in its purpose and the materials and tools used to make it.

Figure 10

Computational Art



`The above images show some of the Logo programming and physical computing experiments.

In the projects described in this thesis, carefully selected constraints are followed, and constructionist design principles help to understand the value of microworld learning experiences. These microworlds can also be viewed as “design worlds,” which Schön described as follows:

> These are environments entered into and inhabited by designers when designing. They contain particular configurations of things, relations and qualities, and they act as holding environments for design knowledge. A designer's knowledge is not only in his ideas or actions but in the things with which he deals. The objects of a design world are, in Seymour Papert's phrase, 'things to think with. ' (Schön, 1988)

Blending Schön and Papert’s ideas provides a helpful backdrop to the research-as-creation employed here, where the object of design is centred around a desire to facilitate learning by seeing, thinking, and doing, followed closely by sharing, observing, and reflecting. As such, the following research-creation will be described from two perspectives: creative practice (creation-as-research) and maker-driven design activity (research-from-creation). The constraints applied to choosing materials, methods, technologies, topics, and design concepts were shared across both perspectives. An essential criterion of the projects explored is to find strategies that force the creator, and the student, to discover alternative ways of seeing. Especially where sustainable action and creative uses of technology are concerned.

4.1 Project #1 - Future Humans

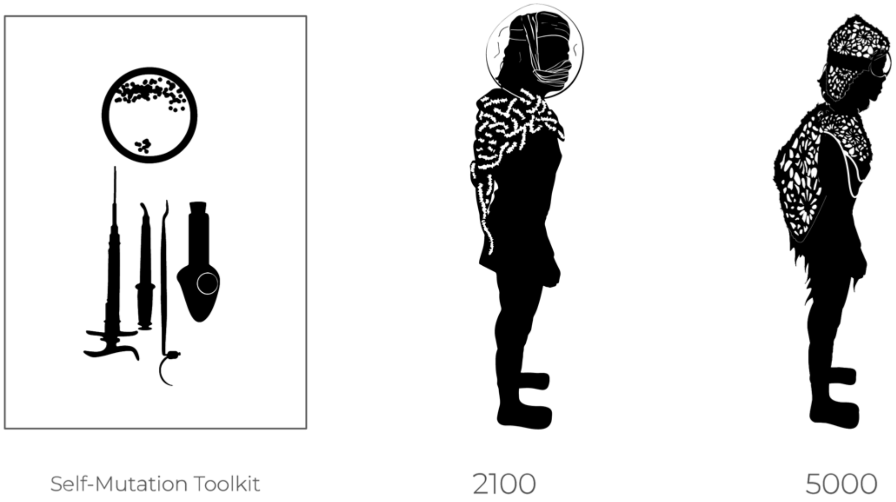
(i) Creative Practice

The idea for the Future Humans project originated from an exercise in speculative design in an Interdisciplinary Practices course as part of my master's degree. Our challenge was conceptualizing a communication strategy that could relay information about the hidden dangers of a buried nuclear waste storage facility to future humans who might lack historical knowledge. Inspired by hieroglyphs, my partner and I chose to communicate a timeline depicting the evolution of humans over thousands of years in two trajectories using illustrations which could be laser etched into rocks. One trajectory proposed an evolution of the human species that might be influenced by organic technologies, the other by computational technologies (see Figures 11 & 12).

Speculating plausible futures presents an exciting learning opportunity to exercise wild ideas backed by a synthesis of research and concept design (Dunne & Raby, 2013). Speculative design requires lateral thinking, considers problem spaces from multiple angles, and brings them to the surface for debate. It encourages imagination, critical thought, and foresight while assessing the potential impact of design. In my experience with high school students, they cannot often see connections between the subjects they study and the things they observe in life which can be spread across different disciplines. This project questions if a speculative design process can help students connect the dots between people, processes, and products, three areas of interest in designerly ways of knowing (Cross, 2006, p. vii). Conceptually, the project examines how time, place, and access to specific products, technologies, and materials influence how humans look and behave. Meanwhile, from a creative-technical standpoint, this project also provided an opportunity to build microworlds around computer-aided design (CAD) and machining (CAM).

Figure 11

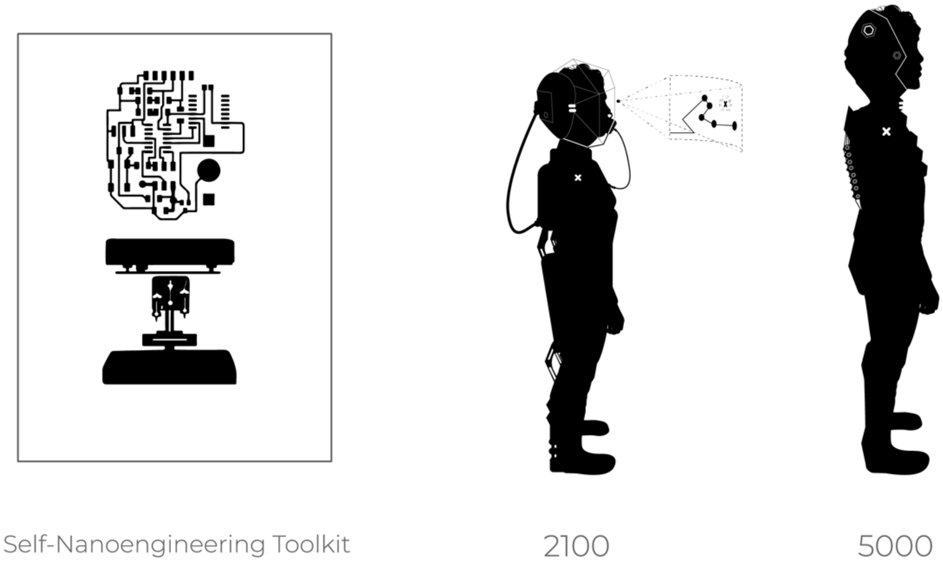
A Message for the Future(A) – MDes Assignment Dart 611



Evolution inspired by organic technology.

Figure 12

A Message for the Future(B) – MDes Assignment Dart 611

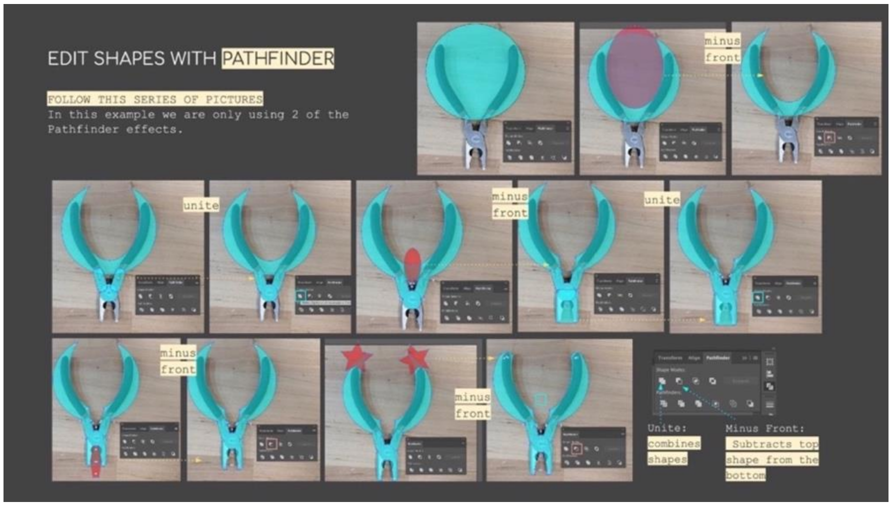


Evolution inspired by computational technology.

Making silhouettes was not novel in this design situation. This technique offers a practical method to help introduce students to vector graphics and to help them learn how to draw for machines. This approach was inspired by numerous experiences sharing strategies with students to make silhouettes and stickers using compound shapes (Figure 13).

Figure 13

Adobe Illustrator Tutorial – Making Silhouettes



EDIT SHAPES WITH PATHFINDER

FOLLOW THIS SERIES OF PICTURES
In this example we are only using 2 of the Pathfinder effects.

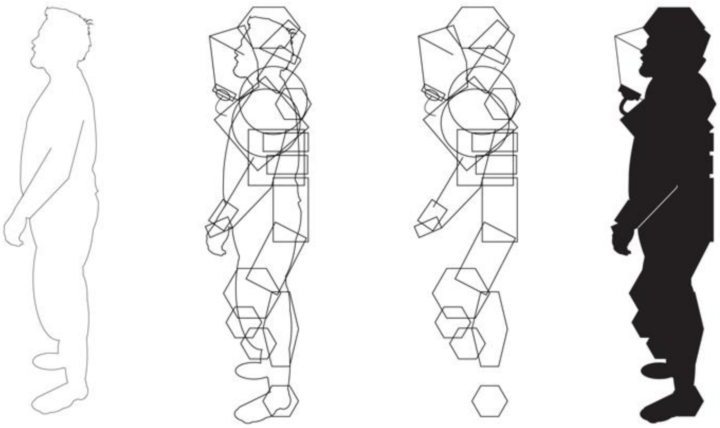
Unite: combines shapes

Minus Front: Subtracts top shape from the bottom

What was of interest in using this technique to design Future Humans, rather than technical objects, was how the featureless format of a silhouette quickly became other-worldly with a little bit of visual tinkering**.** The concept of tinkering brings an element of playfulness to the iterative process that is very useful in learning scenarios (Martinez & Stager, 2019). Simple screenshots can be used to communicate the design process with few words. At the same time, the overall shape of the silhouettes provides enough visual information to illustrate some initial research as a form of science fiction. A few features were discovered during this creative exploration. It was fun to experiment with basic shapes as representations of different materials. Sharp angular edges could look more like metals (Figure 14), and objects with rounded edges could look more like organic or composite materials (see Figure 15). The other feature of this process I discovered was how to approach vector design as a microworld experience. Thinking logically about the sequence of simple shapes and their placement, I experimented with interactions limited to only a few essential vector tools. These essential functions provided enough flexibility to draw complex figures. The process proved that there are easy ways to express the basics of learning how to draw with a computer (low floors), that it supports multiple forms of expression (wide walls), and that it can be scaled in complexity (high ceilings).

Figure 14

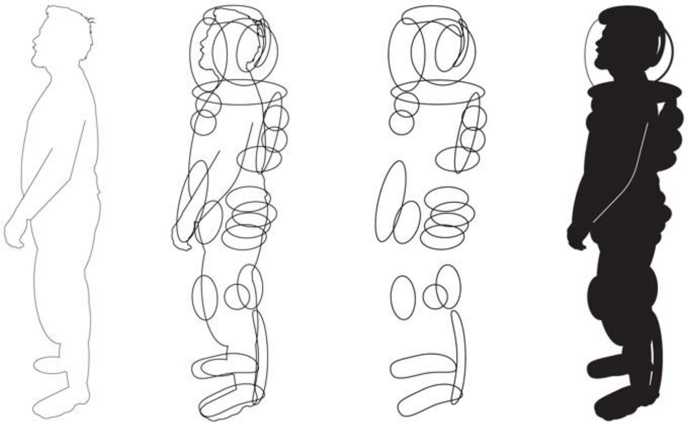
Drawing Future Humans – Tinkering with Angular Shapes



Mixing shapes with sharp edges looks more metallic or using sheet bending manufacturing processes.

Figure 15

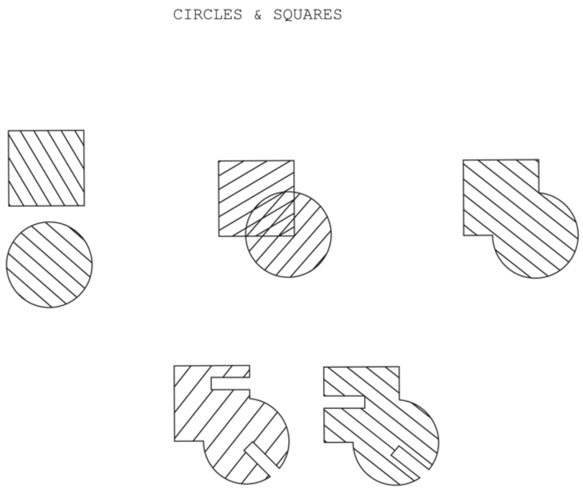
Drawing Future Humans – Tinkering with Rounder Shapes



Compound shapes with curved edges look more organic and formed from moulding, additive manufacturing or bio-based processes.

There is little to be gained in learning digital fabrication without some interactions with computers and CAD. Eventually, teaching students technical drawing may be supplanted by artificial intelligence, which could also be an exciting trajectory for this project. Still, for the moment, learning some basics about drawing with computers (or tablets) is necessary for creative work with machines. Technically, when students are first introduced to vector drawing techniques, they tend to be intimidated by the array of features that confront them. As a result, novices often favour recognizable vector tools, such as the eraser, paintbrush, and pencil tools included in most bitmap and vector graphics applications. These tools are less conducive to drawing for machines unless they are used carefully. Under novice direction, freeform drawing tools introduce extra nodes and hidden features in vector images visible only to machines that may cause them to behave in ways the user hadn't intended. I had previously devised a technique to teach students about essential elements of Boolean operations and compound paths to generate clean vector paths in their drawings and avoid future frustration and waste of precious time and material. These drawing methods were central in the instructions for the Future Humans project as they support CAD techniques that work in other contexts, such as 3D modelling and more complex CAD (see Figure 16). The experience introduces novices that the shapes of things can be understood through combinations of basic geometries, states, or relationships. Once it is understood that computers take control of the relationships between straight lines, angles, and radii, the process becomes much less daunting, especially for those who do not think they are good at drawing.

Figure 16
Compound Shapes - Combining Circles and Squares



Another realization during this project presented itself through an opportunity to make some version of a cardboard drawing machine. The initial inspiration came from early architecture machines, conceived as learning tools that could democratize access to architectural engineering (Negroponte, 1975). Using recycled cardboard, a plotter, a Makey Makey, and some bolts, it was possible to make a simple interactive object inspired by design for disassembly and creative reuse that could mimic a computer. A Makey Makey microcontroller was tastefully embedded into the body of the cardboard console, with symbols designed and drawn onto the surface using a pen plotter. This object represented some fundamental concepts of critical making, sustainable action, and creative uses of technology using a method that could be easily understood and adapted. Electronics were made visible, and the cardboard drawing machine was a creative object to think with that presented the critical design principles I hope to share with others (see Figures 17 & 18). Further, it highlighted the simplicity of a microworld drawing experience in two-dimensional CAD and turned it into an interaction design exercise. Such a drawing machine could live in a school hallway, providing a playful and more tangible way to explore digital processes while sharing imaginative ways of seeing.

Figure 17
Drawing Machine – Installation

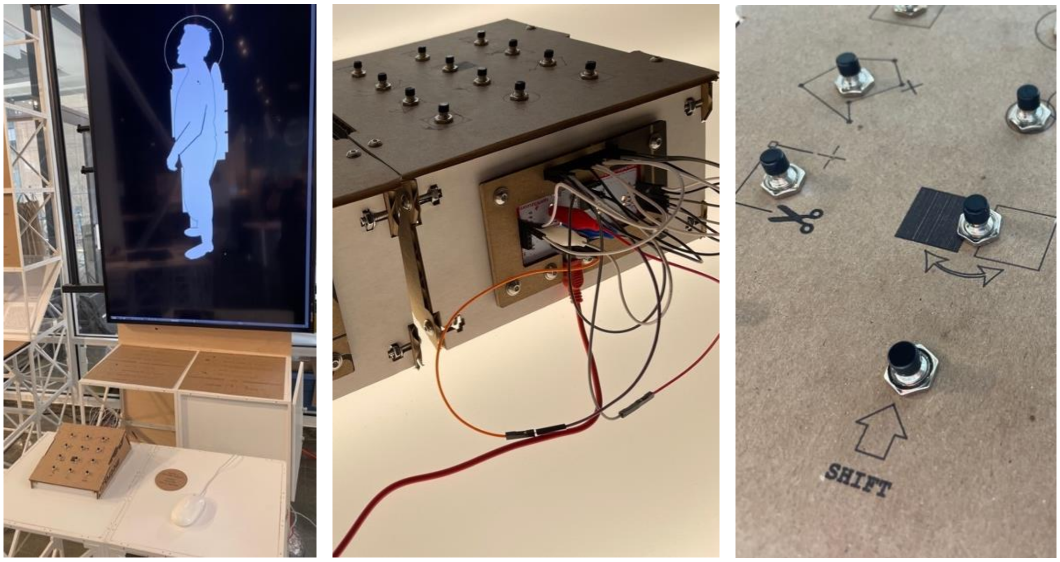


Figure 18
Drawing Machine – Essential Functions.

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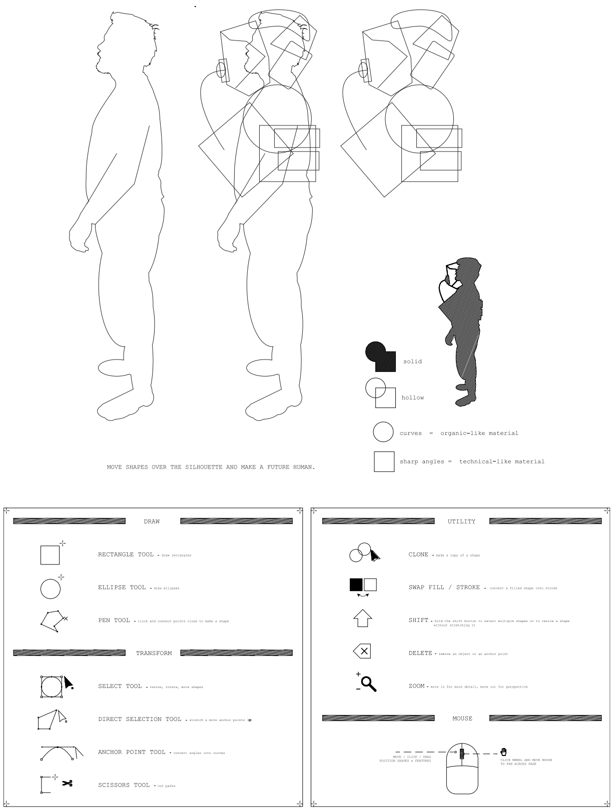


curves = organic-like material

sharp angles = technical-like material

MOVE SHAPES OVER THE SILHOUETTE AND MAKE A FUTURE HUMAN.

DRAW

RECTANGLE TOOL - draw rectangles

ELLIPSE TOOL - draw ellipses

PEN TOOL - click and connect points close to make a shape

TRANSFORM

SELECT TOOL - resize, rotate, move shapes

DIRECT SELECTION TOOL - stretch & move anchor points (▣)

ANCHOR POINT TOOL - convert angles into curves

SCISSORS TOOL - cut paths

UTILITY

CLONE - make a copy of a shape

SWAP FILL / STROKE - convert a filled shape into stroke

SHIFT - hold the shift button to select multiple shapes or to resize a shape without stretching it

DELETE - remove an object or an anchor point

ZOOM - move in for more detail, move out for perspective

MOUSE

MOVE / CLICK / DRAG
POSITION SHAPES & FEATURES

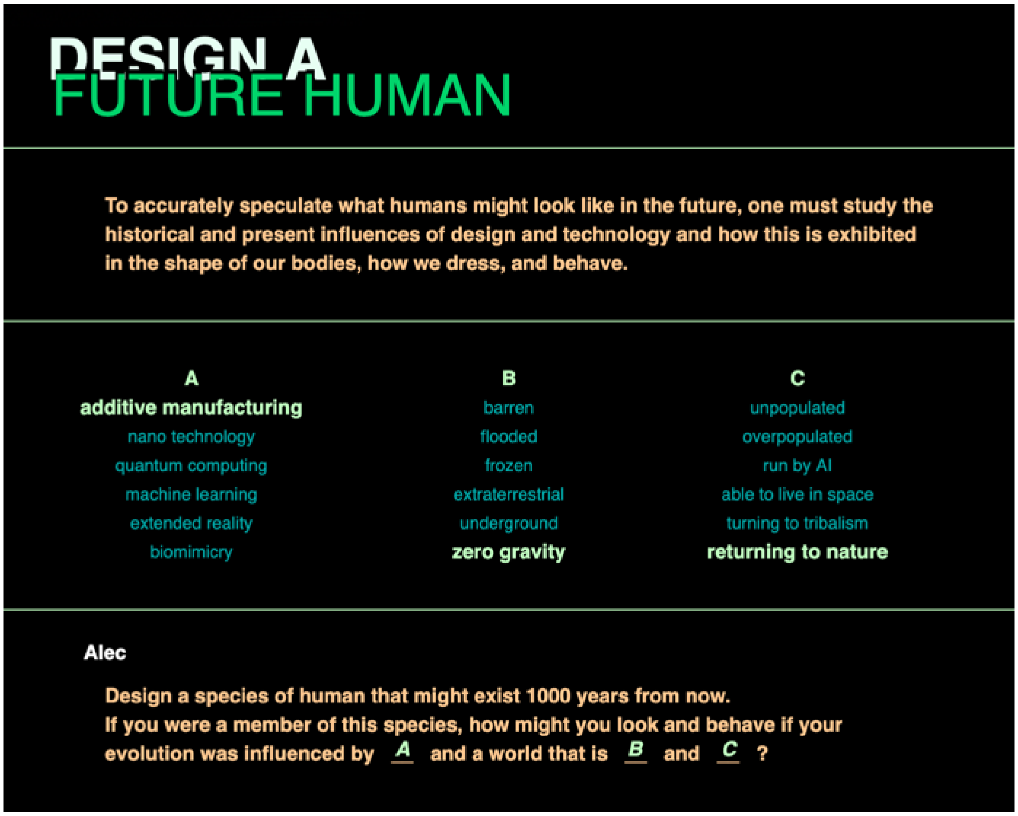
CLICK WHEEL AND MOVE MOUSE
TO PAN ACROSS PAGE

(i) Maker-Driven Design Activity

The Future Humans project provided a fun and engaging platform for 10th-grade students to be introduced to CAD and digital fabrication while exercising research skills in their IB Middle Years Programme product design class. However, one of the most significant challenges in this maker-driven design activity is not learning to use the tools but using the design process to tell a good story. As part of their assignment, students were asked to make a vector-drawn silhouette of themselves which they would then alter using the visual tinkering technique discovered during creative practice. They were then asked to transform their silhouette into a future human (+1000 years) using research to justify their ideas. In designing their future humans, students were given three randomly selected prompts based on a specific list of possibilities to encourage speculative thinking (Figure 19).

Figure 19

Design Prompts – Teacher Sample



DESIGN A
FUTURE HUMAN

To accurately speculate what humans might look like in the future, one must study the historical and present influences of design and technology and how this is exhibited in the shape of our bodies, how we dress, and behave.

A	B	C
additive manufacturing	barren	unpopulated
nano technology	flooded	overpopulated
quantum computing	frozen	run by AI
machine learning	extraterrestrial	able to live in space
extended reality	underground	turning to tribalism
biomimicry	**zero gravity**	**returning to nature**

Alec

Design a species of human that might exist 1000 years from now.
If you were a member of this species, how might you look and behave if your evolution was influenced by _A_ and a world that is _B_ and _C_ ?

Students received one technological, environmental, and societal factor to inform their research and create a story that situates their character in a time and place. Once a final future human was settled on, students were asked to name the species and include a couple descriptive paragraphs (Figure 20).

Figure 20

Future Human Journal - Teacher Sample

LAGRANGIAN

Lagrangians live across 2 space colonies located at Lagrange points L4 and L5 approximately 400 000 km from Earth in the Earth-Moon system. These stations represent critical points in the early colonization of space where craft can be refueled and scientific experiments take place. The science being conducted relates to experiments in artificial gravity, self-sustaining ecosystem, and space mining and manufacturing.

Due to the rise of artificial intelligence in the 21st-22nd century human could evolve more rapidly allowing necessary modifications needed to support extended stays in low-no gravity environments. Biomaterials could be designed and custom fit for each Lagrangian which would provide necessary monitoring and assistance for the high radiation in space. Sensory organs like eyes and ears are retrofitted with implants to help deal with radiation and zero gravity that exists in space.

Langrangians are a tall species caused by elongation related to weightlessness. Loss of bone density and elasticity of joints, meant that the Lagrangians had to evolve with the need of a flexible exoskeletons to support joints and improve strength. These unique features also provide the necessary support to visit planets and moons where gravity would pose a risk to their health. This evolution matured over 10 generations of families. There exist over 1000 Lagrangians. They live in condensed spaces with minimal possessions and are motivated by this vision of returning to nature. It is common to see a Langrangian with tattoos of a trees, water, or birds. It is also fashionable to wear their hair in a bun which also keeps their hair neat in low-no gravity situations.

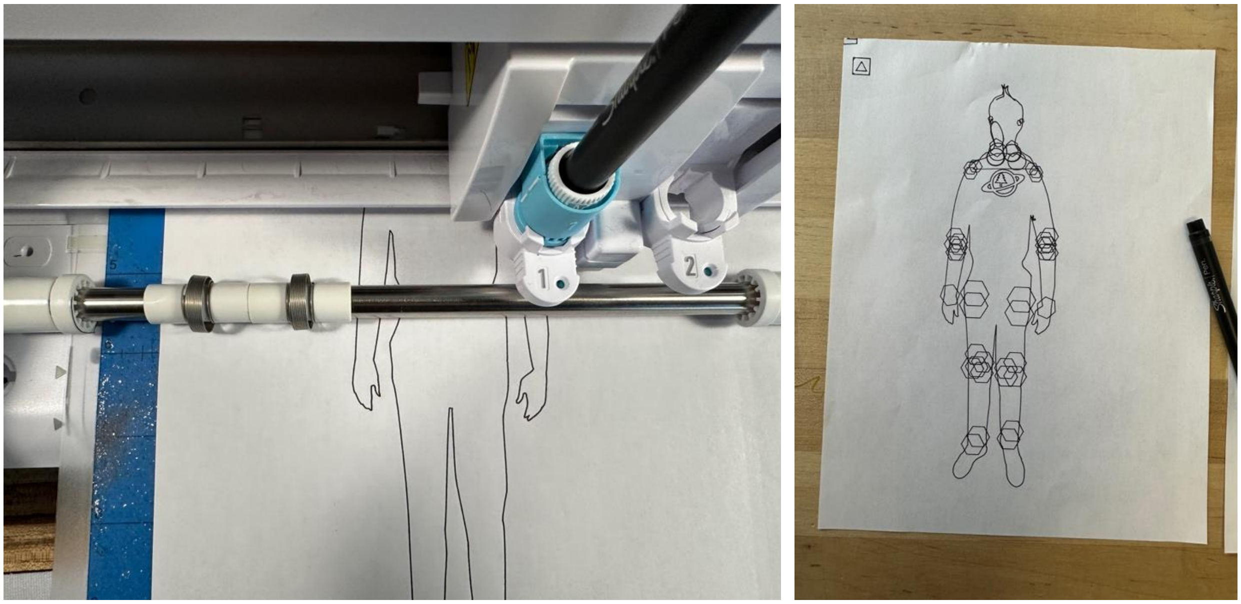
Teacher example slides provided to students of written content.

Original vs modified silhouettes.

Students were also asked to use the vinyl cutters as plotters with sketch pens to transpose their final future humans onto paper (see Figure 21). The advantage of this technique made it possible to use the machine in an atypical way. It helped to focus the student's attention on how vector paths in their drawings are translated into mechanical movements. Any anomalies in the drawings that were not evident in digital form would be revealed on paper. Students were invited to make vinyl stickers if they wanted them, but they were also regularly introduced to the idea of learning to make things without making plastic waste. In other words, students decide if the process is worth the waste. Suppose they are temporary objects, made just for an assignment or "just because," they were encouraged to find alternatives. In this case, the opportunity to draw on paper was an excellent alternative to plastic stickers while maintaining a connection to digital fabrication. All students chose not to cut their silhouettes as vinyl stickers. These decisions could have easily been because it was suggested to them, or perhaps, they were not attached enough to the concept to warrant a decal worth sticking somewhere. However, this activity successfully introduced them to the idea that the vinyl cutter was not simply a sticker-making machine. It is worth investigating whether these techniques supported more sustainable approaches to making and whether or not students were considering the types of materials being processed and the life cycle of the objects being created.

Figure 21

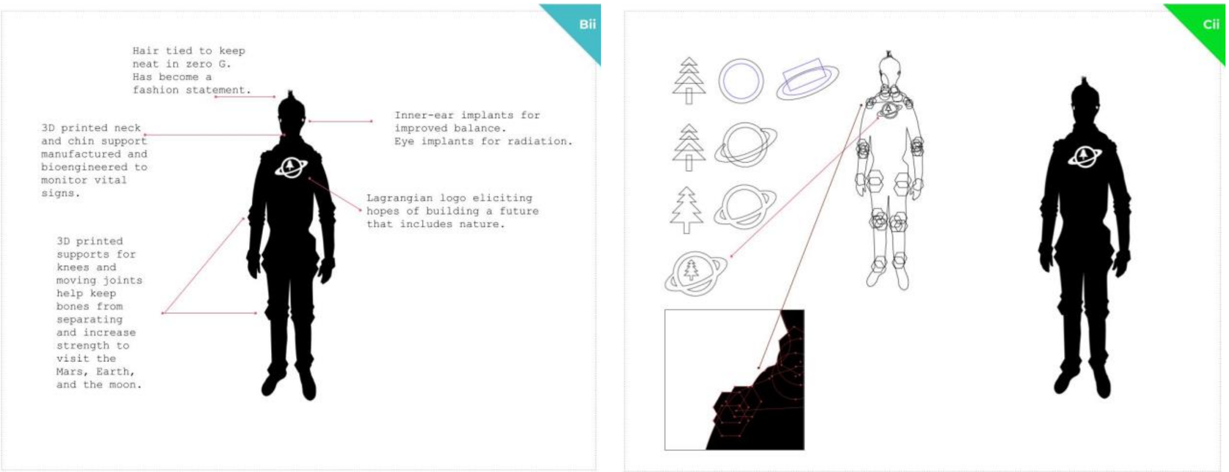
Machine Drawing – Teacher Example



Students are regularly asked to document their process in a design journal, where they include media and reflections. While the scope of student inquiry remained relatively narrow and localized to sources of information easily found, it did force them to consolidate ideas, practice concise but detailed writing, and synthesize information based on the design prompts they were given. The rest of the journal was to include process documentation and links to their design files (see Figure 22). As students produced slides, they were asked to link them to elements in the design cycle. The Future Humans project proved to be a successful maker-driven design activity blending creative-technical learning with some design thinking and speculation, which successfully fit into the Middle Years Programme framework. Technically, the outcomes showed precision and refinement supporting the activity’s effectiveness at disseminating techniques for vector drawing, which were suitable for computer-controlled plotting and should be transferable to other digital fabrication processes based on vector graphics.

Figure 22

Future Human Journal - Teacher Sample



Hair tied to keep
neat in zero G.
Has become a
fashion statement.

3D printed neck
and chin support
manufactured and
bioengineered to
monitor vital
signs.

Inner-ear implants for
improved balance.
Eye implants for radiation.

Lagrangian logo eliciting
hopes of building a future
that includes nature.

3D printed
supports for
knees and
moving joints
help keep
bones from
separating
and increase
strength to
visit the
Mars, Earth,
and the moon.

Example slides provided to students of process documentation using visuals and minimal text.

Due to restrictions on the timing of this project, student samples are not provided in this thesis. Still, the outcomes of student designs showed differentiation, suggesting that using random prompts encouraged alternative perspectives. Students who described wildly impossible scenarios also demonstrated a lack of research to ground their ideas plausibly. Some projects showed refinement in drawing but lacked ideation. Other projects showed the opposite. These examples provided evidence of some student interest in critical making and speculative design, even if they cannot define these qualities. Like the creative practice that it came from, the Future Humans Project appeared to offer a suitable balance between critical thinking and creative-technical learning. Student feedback suggested it was a fun project even though there were frustrations at times, especially in addressing the design prompts, forcing them to consider the impact of design on the environment and how people look and behave more critically.

4.2 Project #2 – Cut. Create. Triangulate

Fab Labs and maker activities generate a lot of material waste (Figure 23). Maker-driven design activity is aimed at encouraging conscious construction, not consumption. When pressed for time or when customization is impossible, schools often acquire kits for use in electronics, coding, or more general STEM-themed activity. There are only so many opportunities for learning that can happen through the use of kits (Davidson & Price, 2018). Such kit designs may encourage creative uses of technology, but they can be wasteful, become obsolete, and work against strategies for more sustainable action and critical making in schools.

Figure 23

Material waste from maker activities.

However, done effectively, kits can also exercise powerful ideas (Resnick & Silverman, 2005). If the design is clever enough, they can offer unlimited possible iterations like LEGO, Knex, or Meccano. These dominant designs are not the kits of interest here, although they have been integrated into the makerspace as a technical material that can be continually reused (Figure 24). LEGO can be interpreted as a raw material that can remain in a technological cycle, integrated into other maker activities and blended with other materials such as cardboard.

Figure 24

Lego as Technical Material.

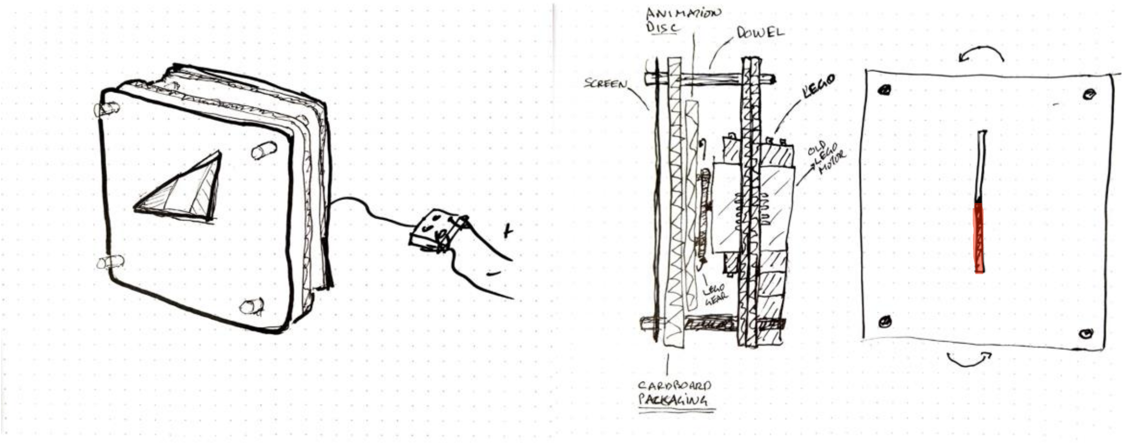
(i) Creative Practice

Cut.Create.Triangulate. is a project designed with two purposes; first, as a form of creative expression exercising interest in making installation art that explores the aesthetic qualities of learning. The second was to use this project as an example of making non “black-boxed” educational technology in a Fab Lab with minimal material waste. It was initiated to explore learning opportunities that would inform maker-driven design experiences in school using the following goals. It had to be a kinetic sculpture, use computer-controlled cutting (vinyl cutter), and be made of paper products and influenced by high school math. The work examines if more points of contact between creative interests, sustainable action, and school curriculum improve opportunities for interdisciplinary design activity that encourage critical making and creative uses of technology. After a stockpile of discarded LEGO Technic motors from obsolete STEM kits were found in school storage, this project shifted toward kit construction. It supported a growing interest in using Fab Labs to address patterns of waste found in the design of STEM kits and educational technology targeting maker activities in schools. Choosing to focus creative practice around discarded technology and scraps of cardboard, paper, and wood, it became possible to use this project as an experiment in making without making waste.

Using the materials and constraints mentioned and artistic interest in the persistence of vision guided this activity toward using the LEGO motor to animate paper. After some time spent tinkering, the idea presented itself as a simple modular object with cut-out features that would cover a spinning disc of partial colour, giving the impression that the cut features were animated as the colour passes under the cut-out feature (Figure 25).

Figure 25

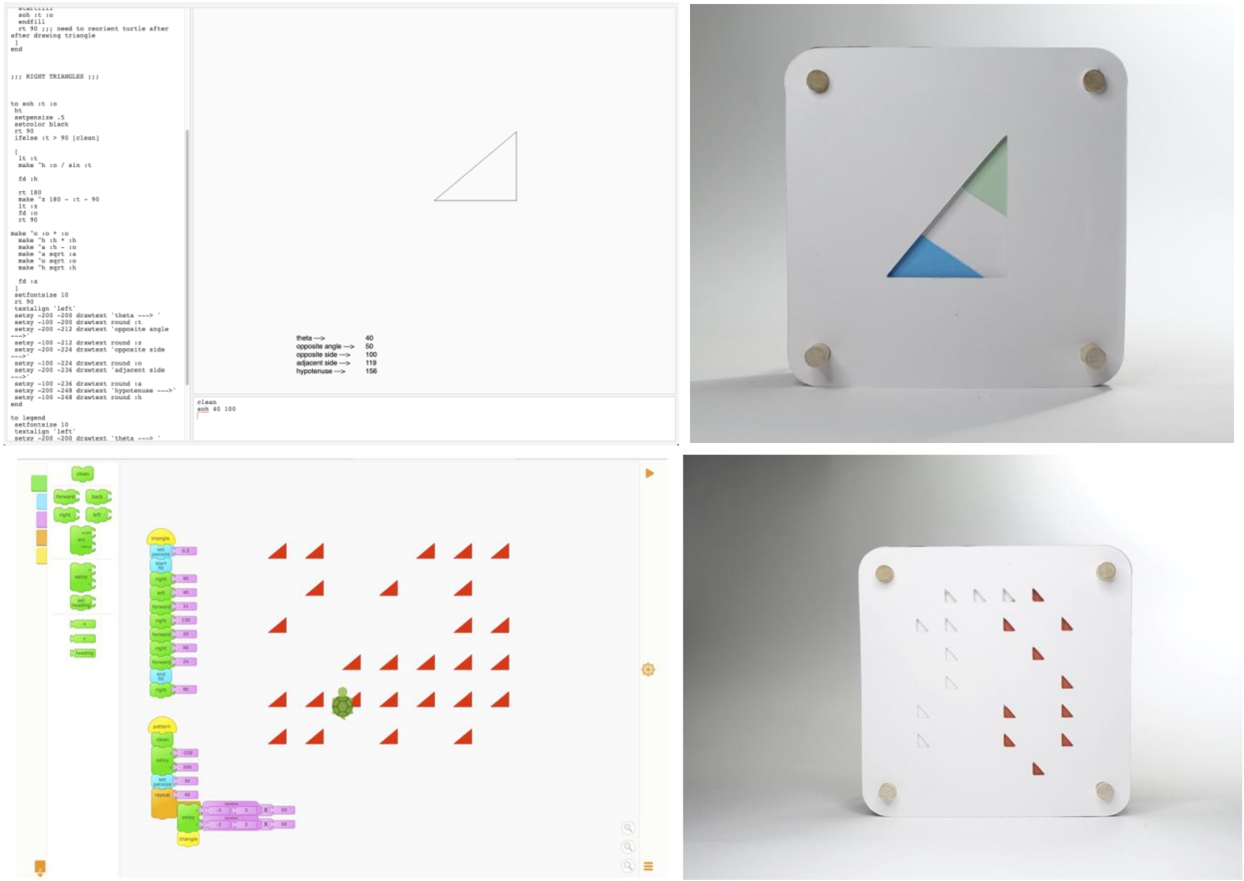
Cut.Create.Triangulate - Initial Concept



Initial experiments used the Logo Programming language and Turtle Art to program shapes for the cut-out features using math and logic (Figure 26). These methods were tested to experiment with computation and math, like making a program to generate patterns with triangles using the Pythagorean theorem (SOHCAHTOA). Using math content central to high school experiences would also be helpful in the creative process and inspire valuable pathways toward applications of trigonometry in future maker-driven design activities.

Figure 26

Programming Shapes



```
  soh :t :o
  endfill
  rt 90 ;;; need to reorient turtle after
after drawing triangle
 ]
end



;;; RIGHT TRIANGLES ;;;



to soh :t :o
 ht
 setpensize .5
 setcolor black
 rt 90
 ifelse :t > 90 [clean]

 [
  lt :t
  make "h :o / sin :t

  fd :h

  rt 180
  make "z 180 - :t - 90
  lt :z
  fd :o
  rt 90

make "o :o * :o
  make "h :h * :h
  make "a :h - :o
  make "a sqrt :a
  make "o sqrt :o
  make "h sqrt :h

  fd :a
 ]
 setfontsize 10
 rt 90
 textalign 'left'
 setxy -200 -200 drawtext 'theta ---> '
 setxy -100 -200 drawtext round :t
 setxy -200 -212 drawtext 'opposite angle
--->'
 setxy -100 -212 drawtext round :z
 setxy -200 -224 drawtext 'opposite side
--->'
 setxy -100 -224 drawtext round :o
 setxy -200 -236 drawtext 'adjacent side
--->'
 setxy -100 -236 drawtext round :a
 setxy -200 -248 drawtext 'hypotenuse --->'
 setxy -100 -248 drawtext round :h
end

to legend
 setfontsize 10
 textalign 'left'
 setxy -200 -200 drawtext 'theta ---> '
```

```
theta --->            40
opposite angle --->   50
opposite side --->    100
adjacent side --->    119
hypotenuse --->       156
```

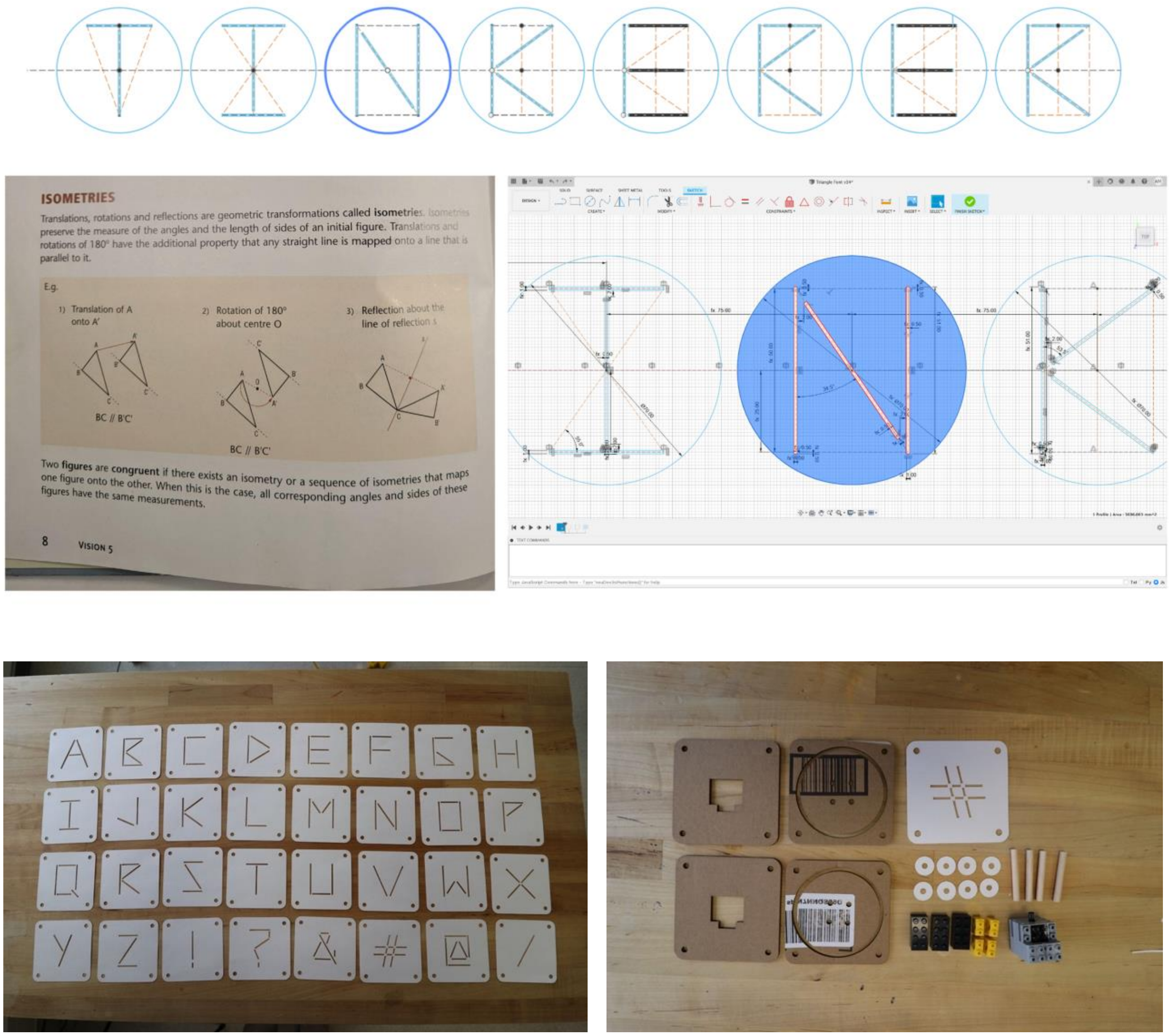
```
clean
soh 40 100
```

Experiments with ArtLogo (a Logo programming environment by Brian Silverman) and TurtleArt block-based logo programming environment by Brian Silverman & Paula Bontá (“Playful Invention Company,” n.d.) *were used to explore applications of math and computational thinking to design features that can be cut out.*

Eventually, after iterative drafts with different shapes and methods, the most effective way to give the impression of paper being animated was to mask a spinning disc with slits as features. I ended up using CAD to experiment with isometric projections and translations. The process revealed an opportunity to explore math and typography as an effective way to address my design constraints (Figures 27 & 28). Language became another theme to tinker with. Modules could be collected to form words. The final object was designed to be disassembled and scalable using nothing but scraps and discarded LEGO.

Figure 27

Isometric-Inspired Font Design



ISOMETRIES

Translations, rotations and reflections are geometric transformations called **isometries**. Isometries preserve the measure of the angles and the length of sides of an initial figure. Translations and rotations of 180° have the additional property that any straight line is mapped onto a line that is parallel to it.

E.g.

1) Translation of A onto A'

BC // B'C'

2) Rotation of 180° about centre O

BC // B'C'

3) Reflection about the line of reflection s

Two **figures** are **congruent** if there exists an isometry or a sequence of isometries that maps one figure onto the other. When this is the case, all corresponding angles and sides of these figures have the same measurements.

8 VISION 5

Figure 28

Module Construction

The result is both a press-fit kit and an object to think with that makes visible what was learned. The number of components required to make an object for each letter of the alphabet soon contributed to another shift in thinking that this object could be used as a classroom activity to encourage tinkering with shapes and alternative forms of creative expression and language. *Cut.Create.Triangulate.* successfully produced meaningful opportunities to explore critical making, sustainable action, and creative uses of technology through microworld interactions. It demonstrated the dual nature of design for the art of learning as a creative practice (Figure 29) and to inform educational activity. It also illustrates the power of designing prompts in maker experiences.

Figure 29

Cut.Create.Triangulate – Interactive Installation

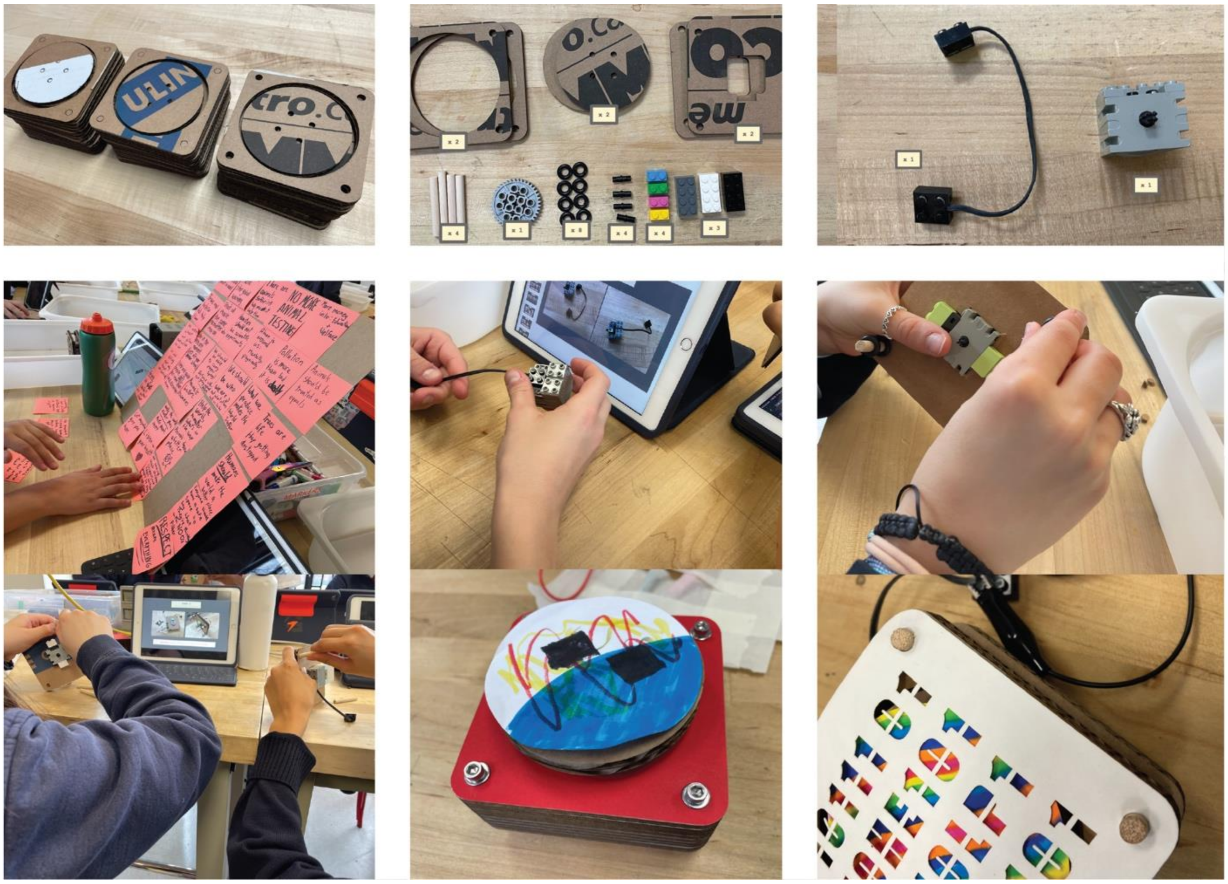
In.Site Exhibition at the 4th Space – Concordia University, September 2022

(ii) Maker-Driven Design Activity

The *TinkerMod* kit was created to implement the ideas explored in creative practice as a maker-driven design activity that can be experienced in a classroom. Collaborating with a middle school English teacher provided an opening to try TinkerMods in a non-design-focused environment using thirty kits which students got to assemble and customize (Figure 30). As the design teacher in a team-teaching role, I discussed the creative-technical elements of the maker-driven design activity as they relate to the concepts the English teacher wanted students to explore. The class had been reading *The Hunger Games,* where the theme of "protest" was being examined. The English teacher would give the context for which to situate student design thinking. TinkerMods presented an opportunity to make objects to think with and explore the impact of symbols as they investigated this topic through their English course.

Figure 30

Students Assembling TinkerMod Paper Animation Kit



The maker-driven design activity was designed to be as easy as possible, removing technical complexity through the kit design, which could be built in half a class. There were two grade 7

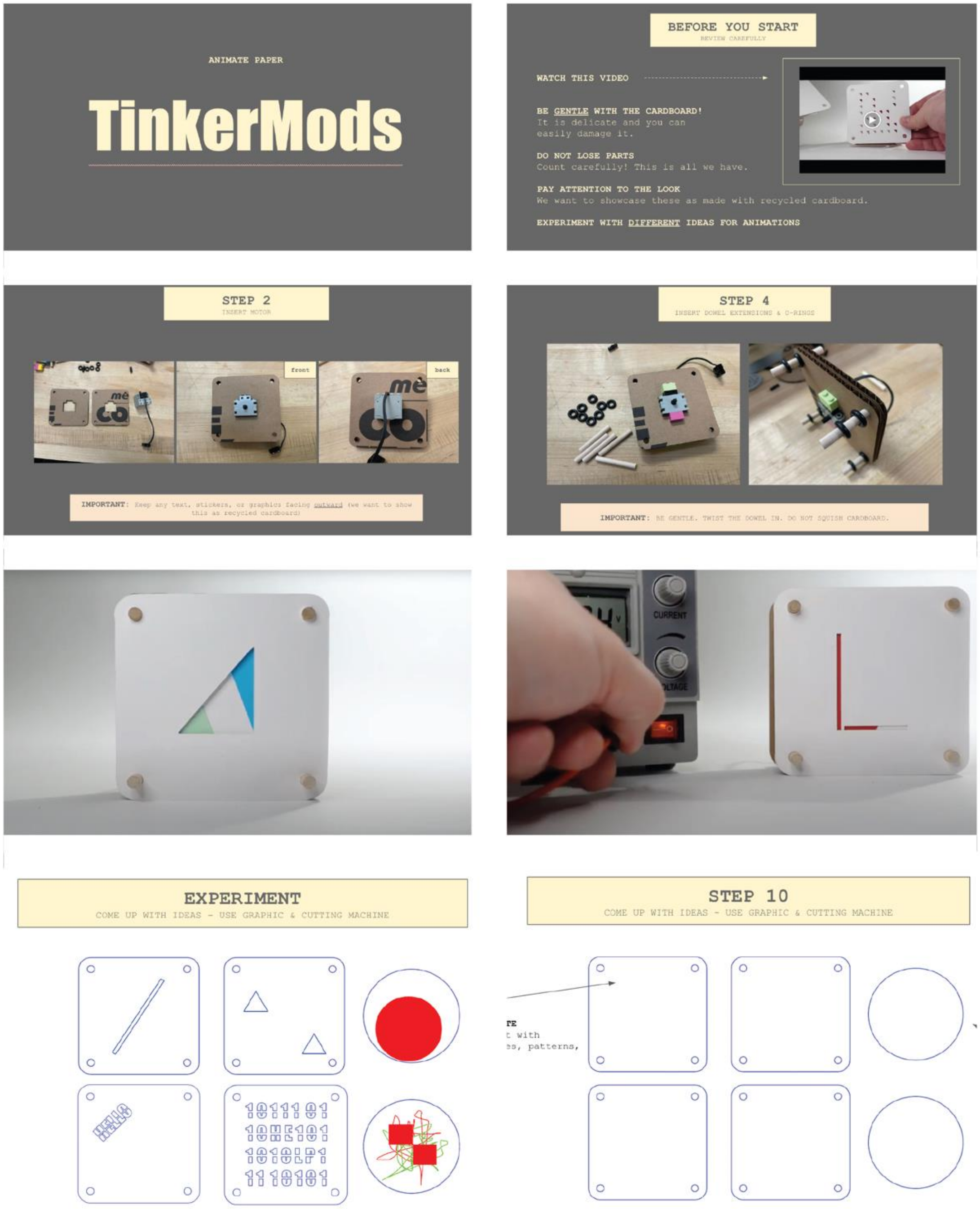
English classes, approximately 17 students in each, who had been visiting the school Fab Lab once a cycle as part of an initiative by their English teacher to offer more tangible opportunities to engage in the topics discussed in her lessons. Because of this teacher's initiative to expand her classroom into the Fab Lab, I had already worked with these students using iPads to draw shapes and cut them out of paper using vinyl cutters. Using the vinyl cutter again provided a chance to reinforce what was already experienced. The challenge in the activity was linked to the creative interpretation of the theme “protest” and using the vinyl cutters to cut out their texts or symbols. This element required more abstract thinking, which posed challenges for some students. Overall, the TinkerMod kits offered a fun, hands-on experience that helped strengthen the meaning behind what was being studied.

Communicating the steps to building the TinkerMod kit without over-explaining was necessary to give space for creative exploration and tinkering. Students could choose how they add colour to spinning discs. Some decided to scribble; others chose to make more concise markings. The next step was to cover the discs with their paper masks featuring the protest symbol or message they produced using the digital fabrication techniques they had previously learned. Our lab technician also developed a practicing mechanism so that students could experiment with colours and shapes before committing to any idea. The total duration of this project should have been four classes or less. A clear, set-by-step presentation was provided to each student (see Figure 31), along with a live demonstration, video documentation, and a reminder that they had seen this object on display for a couple of months in the hallway just outside the class.

It was surprising to witness and hear some students express their confusion. Even with multiple points of contact through instructions, demonstrations, and video documentation. Some students struggled with tasks and sought teacher input even when surrounded by peers successfully embarking on the activity. In these instances, the best tactic was to let them conclude on their own terms that they had access to all the resources to work on this activity autonomously. Students were also given enough time to complete this activity over three periods; one for figuring out a simple way to express their ideas and the remainder for building the kit and testing it out. What was perhaps missing from the activity was the inclusion of personal interest. Even though this had been discussed, it was unclear what the point of making the object was. However, once students started to see the animation effect of the spinning discs of colour under their texts and symbols, they became increasingly excited. As expected of middle school students, there was a range of outcomes. Over half of the students completed the activity despite interruptions to the school schedule (due to the pandemic). Several students wanted to take the objects home, suggesting there was pride in what was completed.

Figure 31

TinkerMod Instructions



ANIMATE PAPER

TinkerMods

BEFORE YOU START

REVIEW CAREFULLY

WATCH THIS VIDEO

BE GENTLE WITH THE CARDBOARD!
It is delicate and you can easily damage it.

DO NOT LOSE PARTS
Count carefully! This is all we have.

PAY ATTENTION TO THE LOOK
We want to showcase these as made with recycled cardboard.

EXPERIMENT WITH DIFFERENT IDEAS FOR ANIMATIONS

STEP 2

INSERT MOTOR

IMPORTANT: Keep any text, stickers, or graphics facing outward (we want to show this as recycled cardboard)

STEP 4

INSERT DOWEL EXTENSIONS & O-RINGS

IMPORTANT: BE GENTLE. TWIST THE DOWEL IN. DO NOT SQUISH CARDBOARD.

EXPERIMENT

COME UP WITH IDEAS - USE GRAPHIC & CUTTING MACHINE

STEP 10

COME UP WITH IDEAS - USE GRAPHIC & CUTTING MACHINE

This activity had partial success. It effectively demonstrated the potential of the design process for promoting sustainable action in a school Fab Lab through a playful exercise using a custom-designed kit. However, as a learning experience, it needed more reflection on the form factor of the modules and the underlying reasoning behind it. The activity failed to establish crucial connections between expression and protest art, suggesting that the thematic link to symbols and memes was unclear. Additionally, due to interruptions, the students could not view all the protest modules exhibited together, missing out on an opportunity for group reflection. While building the modules was intended to provide enjoyment, their impact is much more substantial when presented collectively. A group exhibition and reflection would also act as a necessary exemplar to communicate the meaning of this project to groups of students in future iterations. By bringing them together, the combined voices of the students exploring the theme of protest in their English class would demonstrate the power of words in protest. The goal was also to encourage students to experiment with simplicity and selective language choices. Although the English teacher was enthusiastic about the concept, specific nuances require clarification to enhance its effectiveness. Using the TinkerMod kit to explore a powerful idea in a cross-curricular initiative displayed enough potential to warrant further refinement. It also demonstrates the indeterminate nature of interaction design in schools. More time and feedback are necessary to evaluate the impact of this learning experience thoroughly.

5 OUTCOMES

The objective was to inquire if a design process could inform learning strategies for critical making, sustainable action, and creative uses of technology in schools. First, it is necessary to re-iterate what this thesis means by each of these qualities as it concerns high school education. Critical making suggests that the design process encourages critical thinking and debate about the nature of design, the objects students make, and the technologies and materials used to make them. Sustainable action reflects one's ability to make sustainable choices and act on them in the design process. Creative uses of technology suggest that the design process should support experimentation and atypical use of technology in addressing problems. While this thesis discusses types of evidence that were not formally collected, it did inform opinions which support the arguments made in this thesis. It also suggests a need to define research methods that can be used to collect this evidence as data in future studies.

The strategy used to imbue maker-driven design activity with strategies that encourage critical making, sustainable action, and creative uses of technology was to create a cross-over between creative practice, explored as a designer, and educational activity, explored by students. This iterative process will be described below as *didactic experimentation*. For this strategy to work, creative practice and maker-driven design activity should share the same constraints in materials, technologies, and ideas. It is safe to assume that a creative practice that blends design theory with creative-technical learning and sustainable uses of materials would effectively inform similar strategies in maker-driven design activity. It is hoped that this helped inform meaningful connections between creative activity and the desired outcomes of a learning activity. Using illustrations and concept modelling has helped to analyze the relationships between learning, creative practice, and maker-driven design activity. It is still being determined whether these qualities will stick in a school environment and what elements need further study.

To understand the outcomes of this research-creation and its effectiveness in addressing the research question, we need to examine the intentions behind the process and use observations on what took place to propose new methods that question its validity. The Fab Lab and learning spaces in the school where this work took place were organized to encourage material reuse and circular design thinking. Access to tools and materials was curated for simplicity. These limitations are framed as creative constraints. Students and teachers were introduced to key concepts relating to sustainable action and creative uses of technology. Although critical making was not formally discussed in the same way, the broader scope of design as a redirective practice and its use as a mode of critical inquiry was introduced. One example of how these techniques were encouraged is in how students had to prioritize the use of bolts, magnets, string, tape, or clips, over the use of glue. This supported critical making, sustainable action, and creative use of technology by limiting choice, forcing lateral thinking, and linking to broader concepts that were discussed such as design for disassembly. Scraps, bolts, and alternative connector types were made visible and presented as options. Techniques and examples of how technology can be used to solve problems were introduced through activity and discussion. Glue sticks and wood glue were available, but students had to ask for this material forcing justification of its use. The challenge in this was not making these limitations too difficult to follow and ensuring that teachers who are unfamiliar with such techniques are confident enough to maintain them. The outcomes presented in this section are based on evidence gathered in this environment using such techniques and observing if they elicit new behaviours and understanding of the design process according to critical making, sustainable action, and the creative use of technology. Evidence was collected based on the following capacities:

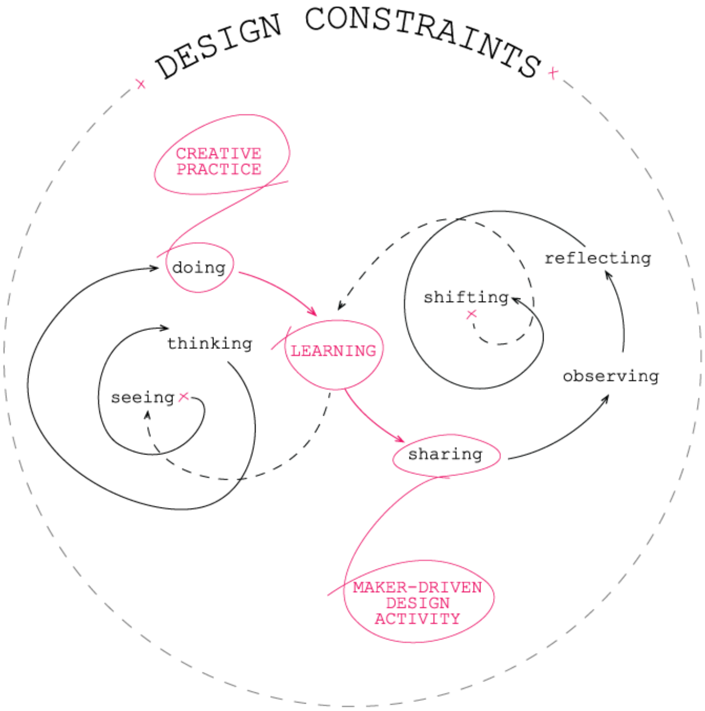
1. As a teacher, co-teacher, or facilitator, evidence of what was done, seen, and heard is gathered from classroom observations during the activity and student discussions or informal presentations. Evidence was also taken from student design journals, prototypes, and experiments. Lastly, evidence was observed through interactions with the space, technologies, and materials. Photos were taken of materials that were wasted, work that was discarded, or elements that had been excluded from student journals.
2. As a Fab Lab Coordinator and design curriculum lead, and not directly involved in the design activity of other teachers, evidence of what was done in other classes was inferred through informal observations, including evidence from discarded projects, materials, and general mess or care of the learning environment. It includes teacher organization and evidence of key concepts, which may or may not be evident in the student work produced or discarded from these classes. Evidence could also come in the form of activity noise or informal statements heard surrounding design activity.

5.1 Didactic Experimentation

Throughout this work, I have reflected on the intersections between my creative practice and maker-driven design activities. A didactic process revealed itself as two intersecting learning spirals interacting with each other through goals and constraints to create microworld experiences (Figure 32). The first learning spiral is more artistic, motivated by curiosity, and driven by professional objectives and broader interests in interactions with designed objects. Making these objects helps establish personal conditions for learning that blend theory, action, purpose, and pleasure. The second learning spiral is behavioural and concerns what happens when others are asked to interact with the ideas and designed objects emerging from the first spiral. Here, we observe, document, and reflect on the outcomes, viewed as behaviours in the learning environment with the tools, materials, and ideas expressed in the maker-driven design activity. Learning opportunities are discovered through creative practice (doing), only to be deconstructed and repackaged as learning experiences to be exercised (shared) with others. This iterative dance between learning spirals and their shared constraints can be described as a form of *didactic experimentation*. They form rules limiting what tools, materials, processes, or topics can be used in creative practice and the maker-driven design activity it inspires.

Figure 32

Didactic Experimentation

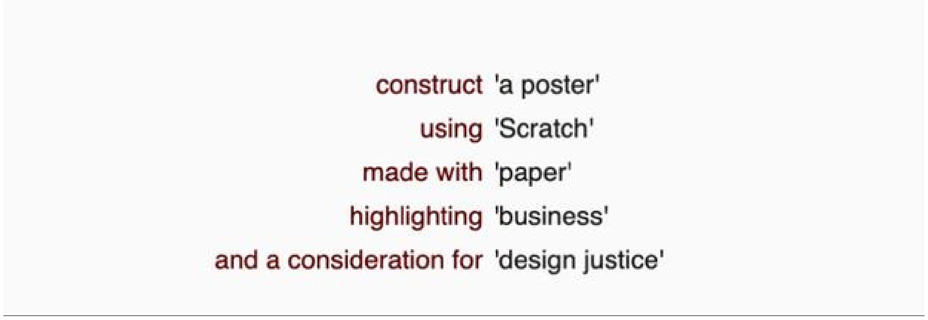


5.2 Creative Constraints

Throughout this work, creative constraints have been used in the projects described to help guide creative practice and maker-driven design activity. Constraints help limit complexity; they encourage creativity, experimentation, and making mistakes, leading to lateral thinking. They force creative uses of technology when solving problems and can be used to promote sustainable action by limiting access to certain materials or processes. Assigning random constraints from a carefully curated list can help students and designers build innovative mindsets while playing with powerful ideas. For example, the power of constraints was tested for a project made during a course taken in this master's degree. A prompt generator was programmed to randomly select items from a curated list. The list was populated with concepts from course readings, personal learning goals, and artistic ambitions (Figure 33). The result helped to pave a path for didactic experimentation.

Figure 33

Randomized Prompts for Creative Practice

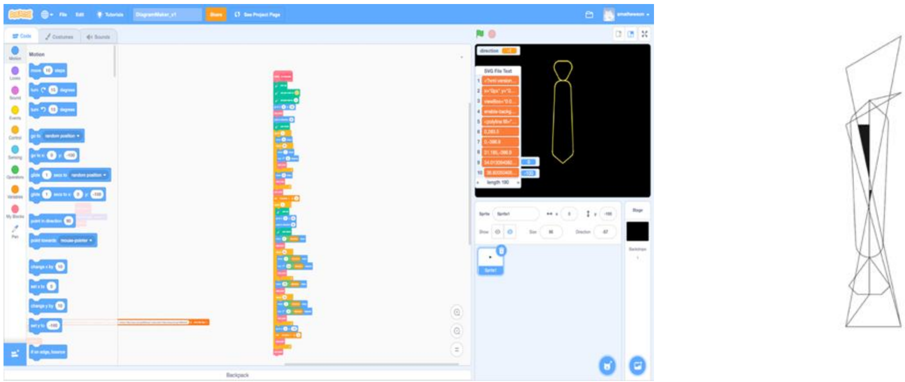


construct	'a poster'
using	'Scratch'
made with	'paper'
highlighting	'business'
and a consideration for	'design justice'

In the example above, how would one construct "a poster" made with "paper," using "Scratch," an educational programming language and digital media platform, while representing the concepts of "business" and "design justice"? While poster and paper match, there are no natural conclusions on how to satisfy the other constraints. The Scratch programming environment is not a tool designed for digital fabrication or drawing; business and design justice could be connected but require more extreme levels of creative interpretation. The constraints imposed by the prompts resulted in new opportunities for learning how to program vector graphics simply by using tools outside of their intended use (see Figure 34). The forced interaction between a material, a technology, a concept, and a subject encouraged chance encounters within the process and helped to conceive a unique object blending ideas with technology.

Figure 34

Vector Drawing with Scratch

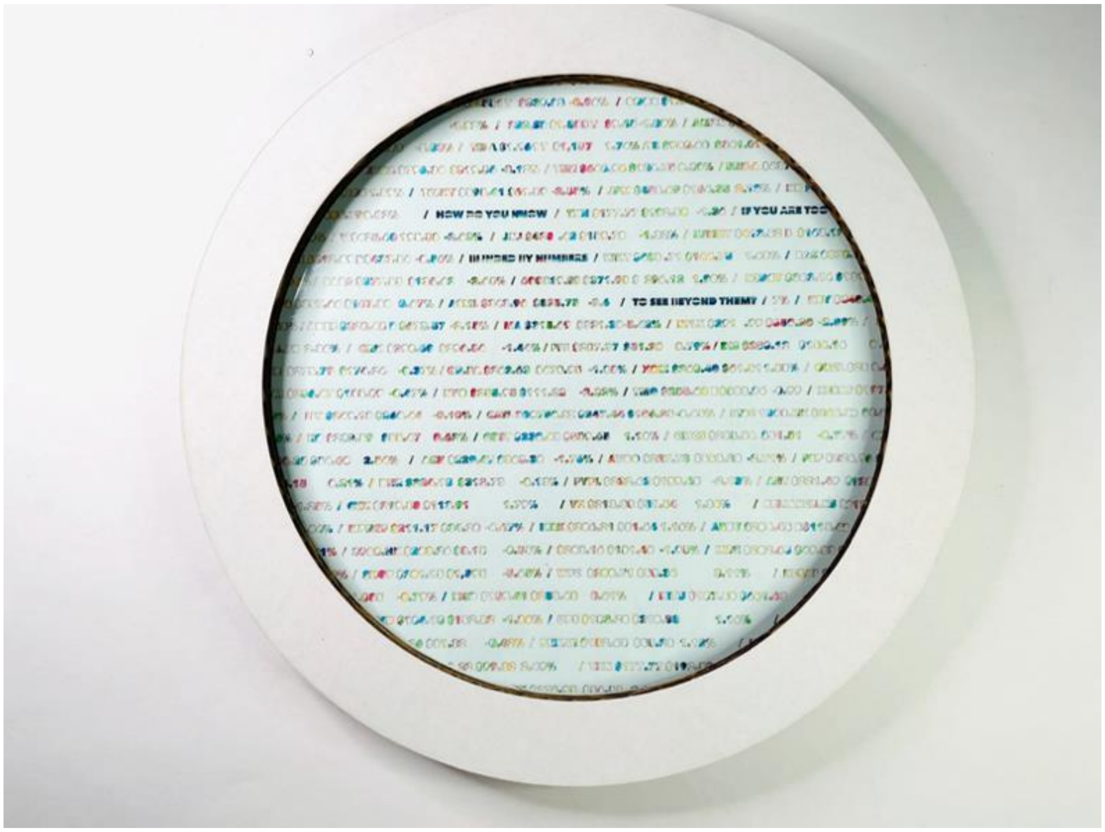


The program on the left shows the intended shape.
The graphic on the right shows the vector output of this program.

The prompts proposed in Figure 34 resulted in final product which featured laser-cut stock market information masking colourful marker drawings made from random vector lines output from Scratch and plotted onto paper using a vinyl cutter. Amidst abstractions of data and colour, one can read the text “How do you know if you are too blinded by numbers to see beyond them?” (see Figure 35). I won’t go into the reasoning leading to these creative choices. However, the unexpected outcome of this project helps to illustrate the power of constraints. Following these particular prompts forced unexpected relationships that made room for serendipity and didactic experiences, while the atypical and creative use of technology contributed to a unique outcome and new knowledge. The final result was nothing like what was expected. Rather than satisfying the constraints imposed by a client, the product of this design was a meaningful learning experience which became a template for learning how to encourage critical making, sustainable action, and creative uses of technology in maker-driven design experiences.

Figure 35

Blinded by Numbers – Creative Results



Made by following the design prompts: a poster, paper, Scratch programming, design justice, business.

The abstract thinking described here is born from many experiences with tools, ideas, and an interest in artistic expression. This process has been expressed from a position of awareness; suffice it to say that allowing oneself to be inspired by constraints in maker-driven design activity can lead to creative-technical growth and strengthen lateral thinking and designerly ways of knowing. This example contributed to the view that the constraints in a maker-driven design activity should be formed using a mixture of prompts for different purposes. Some prompts need to be meaningful to the learner to keep them motivated. For example, this was the approach used with my grade 10 product design class for their major projects. Students had to design a product for the circular economy. They could choose categories based on their interests in design, but their direction was constrained by other prompts randomly selected based on the ideas we had been looking at in the class (see Figure 36).

Figure 36

Grade 10 Product Design Random Prompt Generator – 2022

DESIGN A PRODUCT FOR
THE CIRCULAR ECONOMY

FIELD OF DESIGN
ARCHITECTURE & INTERIOR
FASHION & TEXTILES
APP DESIGN
ENGINEERING
EXHIBITION DESIGN
INDUSTRIAL DESIGN

SKILL TO LEARN
CODING
3D DESIGN
GRAPHIC DESIGN
MODEL MAKING
DIGITAL FABRICATION
SEWING

PERSONAL INTEREST
SPORTS
MUSIC
SCHOOL
TRAVELING
ART
NATURE

YOU MUST USE A ...
3D PRINTER
SEWING MACHINE
EMBROIDERY MACHINE
3D SCANNER
SHAPER ORIGIN
MICROBIT

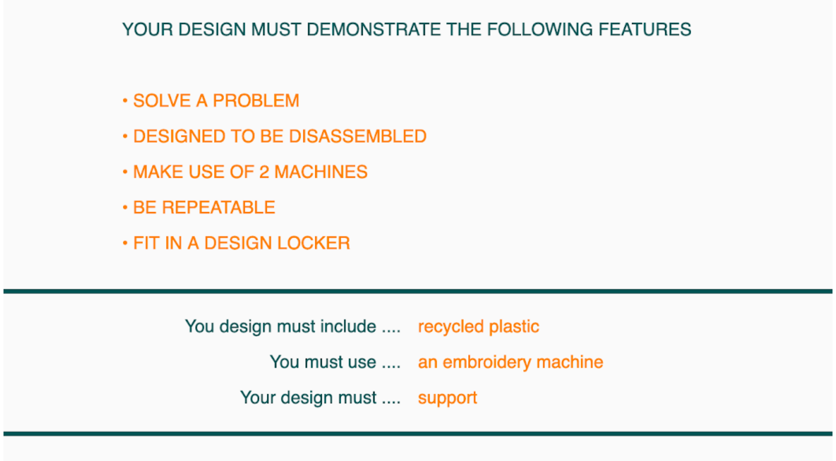
YOU MUST INCLUDE ...
PLASTIC FROM A BAG
RECLAIMED FABRIC
BIO MATERIAL
FAB LAB SCRAPS
ITEM FROM RECYCLING
PAPER

YOU MUST CONSIDER ...
DESIGN FOR DISASSEMBLY
PARTICIPATORY DESIGN
SPECULATIVE DESIGN
SLOW DESIGN
CRADLE TO CRADLE
BIOMIMICRY

This method successfully promoted creative uses of technology, encouraged sustainable action, and asked students to think critically about the impact of design. However, it leaned a bit too challenging for the time they had to complete it. A later version simplifies the prompts. Students were still encouraged to make a product of their choosing but were given fewer prompts (Figure 37) and more time to finish it.

Figure 37

Grade 10 Product Design Random Prompt Generator – 2023



YOUR DESIGN MUST DEMONSTRATE THE FOLLOWING FEATURES

- SOLVE A PROBLEM
- DESIGNED TO BE DISASSEMBLED
- MAKE USE OF 2 MACHINES
- BE REPEATABLE
- FIT IN A DESIGN LOCKER

You design must include .... recycled plastic
You must use .... an embroidery machine
Your design must .... support

Using randomly generated prompts in a non-design-related class was also tested. The same English teacher who had been bringing students into the Fab Lab to do the TinkerMod activity discussed earlier wanted to do another maker-driven design activity over four periods with her grade eight students. Students were reading the book *Of Mice and Men* and asked to relate to what it might have been like to live during the Great Depression. The English teacher and I devised a series of random prompts that would outline the characteristics of different fictional individuals (Figure 38). The class was divided into four groups, each receiving a set of traits for their random character. The students had to empathize with their random personalities and design an object (a low-resolution cardboard prototype) that represented something meaningful to the character. Students then had to communicate how their design related to the prompts and carefully consider the constraints imposed on the people during the Great Depression. Students also had to design their objects for disassembly and consider the amount of material added. As a group, we discussed the creativity and resourcefulness needed during challenging times.

Figure 38

Prompts for Maker-Driven Design Activity - Middle School

your age	6-10
your status in life	dependent
your strengths	curious
your weaknesses	easily distracted

You must include .... a wire

YOUR DESIGN CHALLENGE (40 pts)

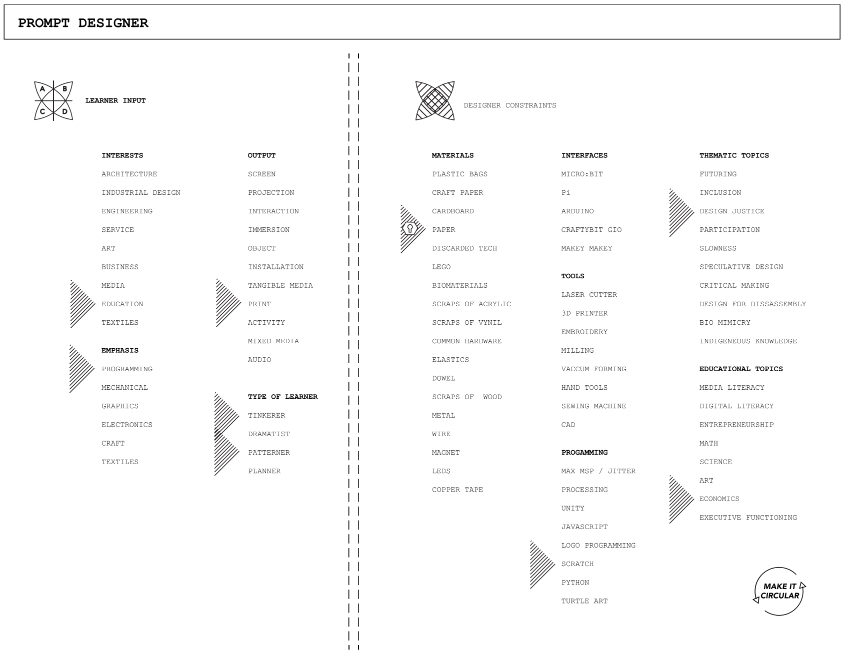
- fits in a project bin (5 pts)
- designed to be dissembled (15 pts)
- only 1 piece of cardboard (10 pts)
- only 1 glue stick (10 pts)

The prompts pictured above resulted in a low-resolution cardboard prototype of a portable and multipurpose game that could offer distraction and entertainment for a curious young character.

The examples just given resulted in experiences that highlight the potential of using prompts in guiding maker-driven design activity. Collectively, these prompts do a few things. First, they support differentiation between projects. This method ensures that all design ideas work on slightly different threads of thought, although they must be connected to the ideas expressed in the activity. Second, the random prompt generator helps motivate students and can encourage a state of flow. A randomizer can gamify and excite students with a design challenge. This method proves even more popular when a big blue button triggers the randomizer. Third, using prompts has proven to increase the potential for critical making, sustainable action, and creative uses of technology. A material prompt mixed with a sustainable design process encourages sustainable action. Asking students to explore the meaning behind what they have made in response to a design prompt linked to a powerful idea facilitates critical making. Asking students to consider at least one technology forces them to translate their ideas in ways that may be atypical. Linking an activity to the curriculum adds incentive and more points of contact with the subjects found in school. Just as engineering prompts relate to working effectively with large language model artificial intelligence, prompt design may offer ways of adjusting learner behaviour in Fab Labs and makerspaces in schools and an opportunity for future research in maker-driven design activity (Figure 39).

Figure 39

Prompt Designer – Concept Sketch



A tool to generate prompts in maker-driven design activity

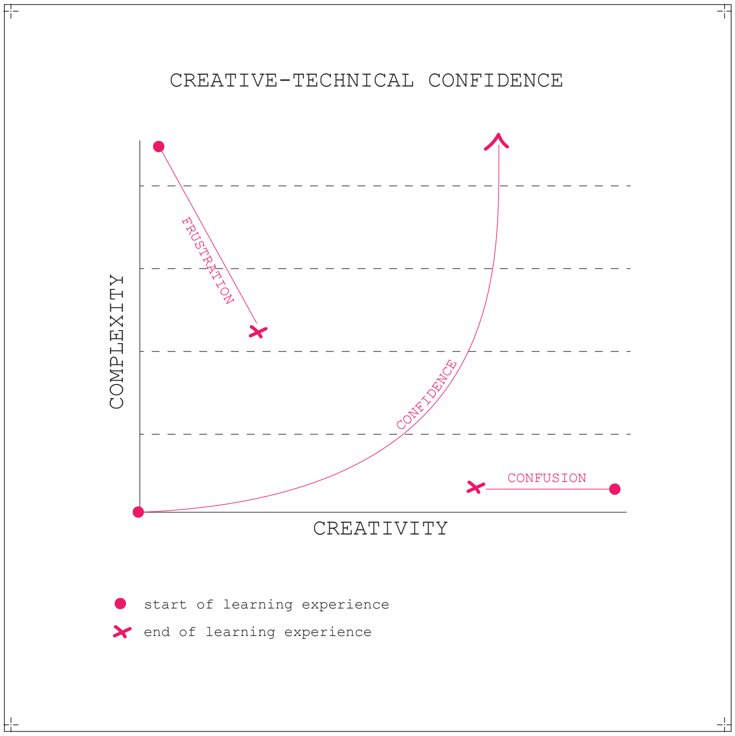
5.3 A Hard Fun Principle

Understanding people's interaction with technology is central to constructionist learning, and it is here where successful mapping of maker-driven design experiences begins. One key trait that makes the didactic experimentation described in this thesis possible is the confidence needed to tinker with technology and the acceptance that there are unknown outcomes from creative action. In other words, the faith required to play with tools, ideas, and processes supersedes their perceived complexity. There are different thresholds to what individuals will deem as complex or not. Therefore, using design principles that allow for creative-technical growth while respecting these thresholds is essential.

While studying the essence of constructionist thinking and its potential as a design process, many instances were observed while working with students and teachers where a perceived complexity gets in the way of meaningful experiences with technology and design processes. Figure 40 shows how creative-technical confidence has been understood in this work.

Figure 40

Creativity vs Complexity



If we consider the ability to deal with complexity as being linked to one’s ability to think creatively, then confidence becomes a factor that should affect both. If a person has creative confidence, the ability to make more complex connections grows. The same should be exhibited in the opposite direction. If one has confidence in dealing with complex issues, creativity will likely grow as new problems are encountered. This interrelationship is especially evident where creative uses of technology are concerned. Creative confidence is difficult to achieve if an activity is too complex, and students will express frustration. We can observe this from what students say, how they behave, or the lack of evidence of any product in an activity. On the other hand, if an activity requires too much creativity, as it asks students to think abstractly about a problem before they can understand the question, you will see more confusion. As was noted in the TinkerMod activity with the grade 7 English class (see Figure 30), students might express confusion as frustration or vice versa. Still, knowing what part of the experience is informing this behaviour is helpful. If multiple students start to express confusion or frustration, there is likely an issue with the communication strategies or content related to the activity. Distraction issues may be unrelated to the activity if this evidence appears as an isolated instance among one or two students. Why students get distracted requires sensitivity and attention, especially where neurodiversity and inclusion are concerned, but it is not necessarily linked to a design flaw in the activity. Where the TinkerMod activity failed was the lack of time for reflection and discussion needed to give it meaning and to be able to assess the impressions of those who completed the activity. The challenges facing the TinkerMod activity have further strengthened the views here that it is vital to understand the relationship between creative-technical confidence with available time and the given constraints.

As a comparison, the Future Humans project had more evidence to suggest that creative-technical confidence was achieved. Almost all of the grade 10 product design students completed the multiple steps required in this activity. Student ideas were differentiated. Students provided evidence of iteration, research, and documentation. The tasks were followed and creatively diverted, and complexity was evident in many of the designs. There was no evidence of bottlenecking in the creative-technical process, which showed a balance in the availability of resources and time. Lastly, students were working until the final due date, suggesting a certain amount of stick-with-it-ness. A class feedback form further supported the view that students enjoyed the experience and that it was the right amount of challenge for the time given to complete it. These observations were consistent across the two sections of this activity, one of which I was not the teacher. Here we see the mix of evidence that supports an increase in creative-technical confidence linked to an activity that asked students to use speculative design thinking and to consider the impact of design on the world. It was hard and fun enough to maintain interest and grow confidence.

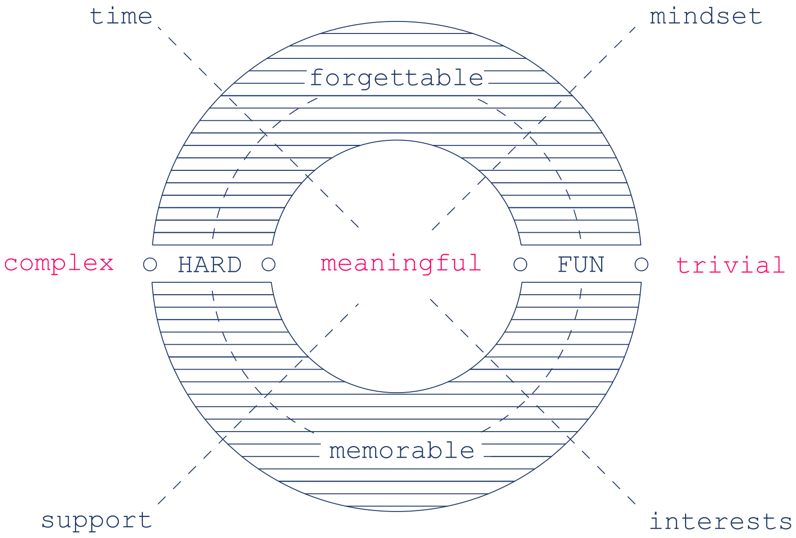
The Future Humans project was an excellent example of how craft and creative use of technology blend with the conceptual dimension of this work. It exemplifies the challenges required in maker-driven design activity to balance expectations between complexity and playfulness. Seymour Papert (2002) coined the term “*hard fun,”* referencing the expressions observed while children were learning the Logo programming language, one of Papert's most recognizable contributions to the world of education (Solomon et al., 2020). Papert's interest lies in how "we learn to construct objects and play with powerful ideas to the point that we own these ideas as our knowledge" (Harel, 2016). We can attribute the phenomenon of hard fun to understanding how people engage in challenging forms of learning. The idea that an opportunity for growth would not be “fun” if it weren't “hard” presents a way to measure the scope of a maker-driven design activity. It can be helpful as a guide toward having "an experience" (Dewey, 1934, p. 37) that is meaningful enough to establish new knowledge.

Observing students and teachers engage in maker activities in the Fab Lab has cemented this notion that finding the threshold between challenging and fun things to do is the difference between giving up and sticking around long enough to benefit from the experience. If it is too complex, students lose interest. If we enter too far into the “fun” zone, students lose an opportunity to engage in powerful ideas—like critical making, sustainable action, and creative uses of technology. These rules may seem simple, but they are also easily forgotten when faced with challenges imposed by schedules, prerequisites, and preconceived assumptions surrounding design education.

The proposed model for a *hard fun principle* (see Figure 41) was inspired by Charles Hartshorne's diagram of aesthetic values (Spuybroek, 2012) and Mihaly Csikszentmihalyi's model of the flow state (Csikszentmihalyi, 2014b), which help identify an aesthetic experience and the intrinsic motivation in an activity. Combining the benefits of both models helps to visualize a design principle which focuses on the aesthetic experience of learning. In maker-driven design activity, meaningful learning experiences occur through a careful balance between four influences: (i) available time, (ii) the learner's mindset, (iii) technical support, and (iv) personal interest in the activity. If all four elements are satisfied, meaning should be established. If any aspect outweighs the other, the experience risks being too complex or trivial. There is an ongoing push and pull between a learner’s desire for fun and pedagogically imposed rigour which tends to colour the learning experience with complexity. This thesis illustrates how the hard fun principle was used as a strategy for didactic experimentation in my creative practice, which then informed decisions in maker-driven design activity.

Figure 41

Hard Fun Principle

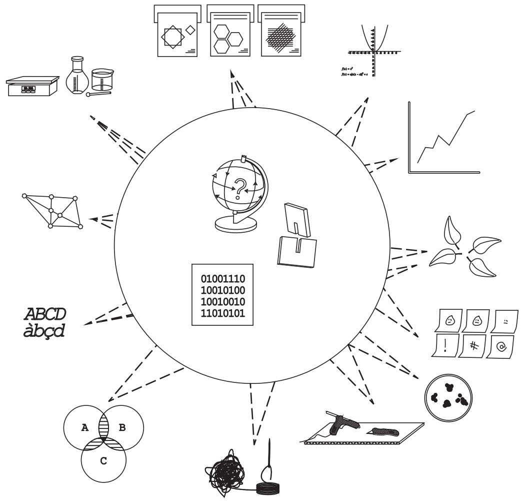


The challenge for meaningful maker-driven design activity is to calibrate between student and designer expectations in finding this balance between complex and trivial. Teachers are aware of classroom dynamics and how they shift over time and with the different typologies of students in a cohort. For example, some students who like to study and get good grades might find the ambiguity of an ill-defined problem challenging. Other students might need help with iteration and working toward a solution. Some students might need help following technical instructions, while others need more research skills to be autonomous. Some students lean toward the arts, others toward the sciences. Some feel that optional subjects hold less educational value, while others wish the "important" ones could be more like the options. Some students can connect the dots between subjects, while many fail to recognize the links that can be made between maker-driven activities and other subjects. Any of these details can tilt the experience. Facilitating maker-driven design activity requires finding a willingness in most students to be challenged by the activity. A class represents a mixture of diverse interests, backgrounds, learning styles, and abilities that are hard to measure. It becomes relatively easy to misalign an activity with its participants because of such factors. Microworlds offer one method to help us scaffold these experiences (see Figure 42). They help to limit our ability to wander, get confused, or be intimidated and allow us to find the ingredients needed for a "hard" yet "fun" experience.

Figure 42

Microworlds – Poster

MICROWORLDS



"Pick one collection of things and do it well."

- Brian Silverman (personal communication, August 9, 2021)

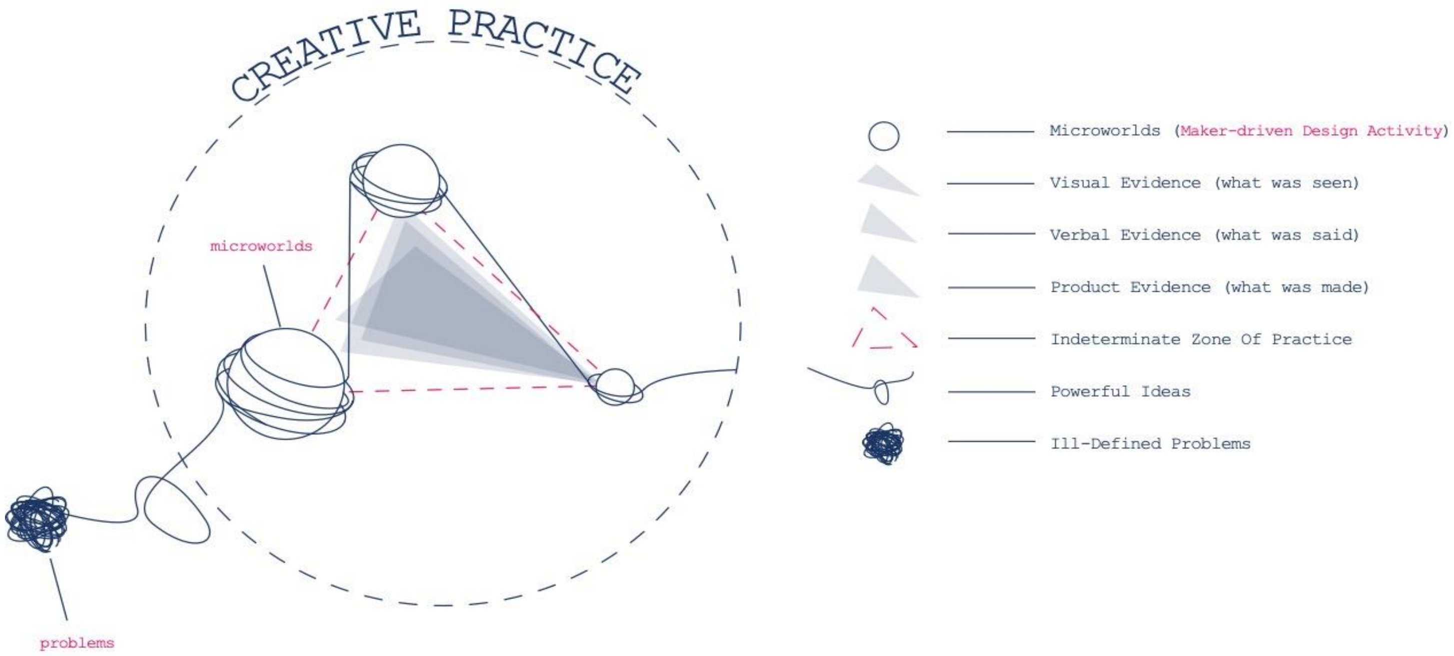
It is important not to assume these concepts are simple to understand or to manifest. For example, when trying to encourage sustainable action in maker activity by introducing principles of disassembly, it can be challenging for students to seek alternatives for fastening materials with glue. Using bolts, elastics, or other reusable components will not come naturally without prior effort to facilitate this new understanding. A teacher encouraging sustainable action in a maker-driven activity should understand these design principles and how to take advantage of the microworld concept to empower students with the confidence to experiment with these powerful ideas. The activity needs to include time for creative discovery and tinkering.

> … a successful microworld is both an epistemological and an emotional universe, a place where powerful (mathematical, or scientific, or artistic) ideas can be explored; but explored "in safety", acting as an incubator both in the sense of fostering conceptual growth and a place where it is safe to make mistakes and show ignorance. (Noss & Hoyles, 2017)

The creative practice explored in this work follows a “hard fun” principle to inspire microworld thinking. Such an approach is a reminder to make creative decisions that balance rigour and play in maker-driven design activity. The tools, processes, and ideas experimented with in a creative practice will be the same as the ones introduced into school experiences. The difference is that creative practice builds on previous experiences, allowing for more complexity. In a school context, different levels of confidence are encountered. Some students can deal with complexity, while others lack the experience to feel comfortable with certain activities. Microworld experiences help triage and encourage the scaffolding necessary to untangle these different levels of complexity and convert them into meaningful interactions.

Figure 43

Untangling Complexity



Each microworld experience produces the rules of creative practice and maker-driven design activity, which help untangle powerful ideas and are calibrated to be functional at various levels (see Figure 43). When triangulating evidence from these microworld experiences, valuable information on how we practice design for the art of learning is exposed as new opportunities.

5.4 Mapping Patterns of Concern

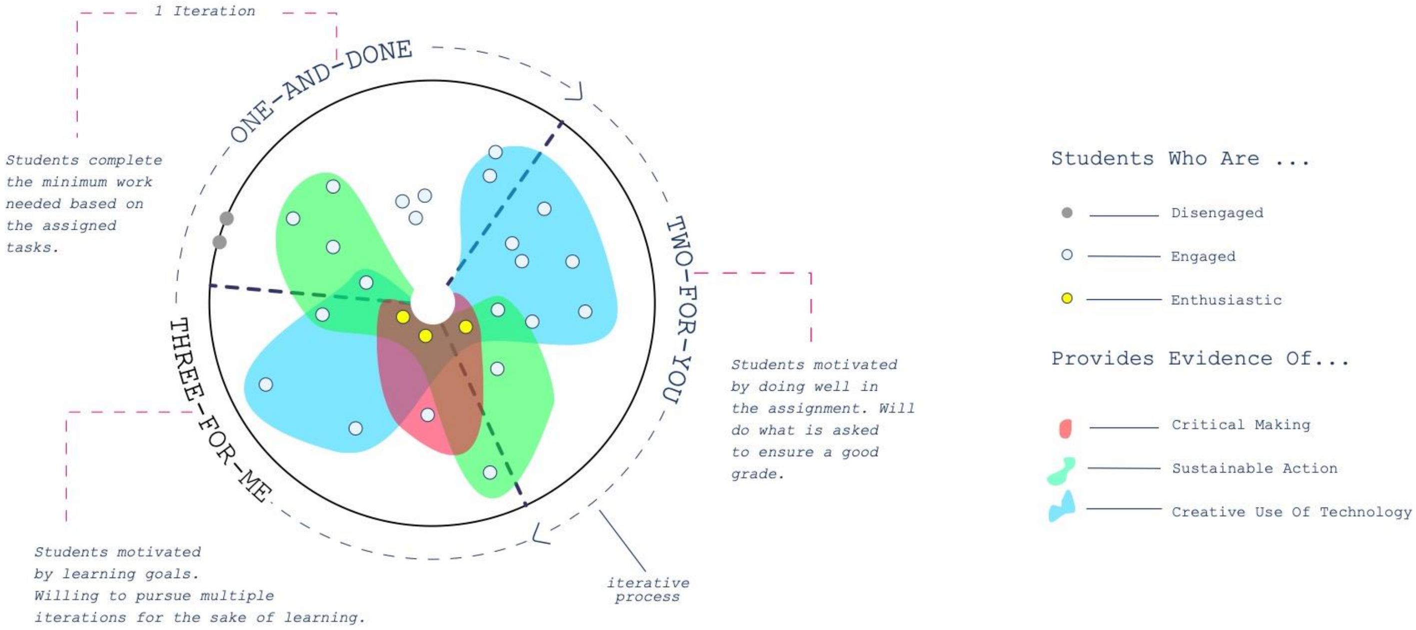
The different activities that I facilitated as a design teacher, co-teacher, Fab Lab coordinator, or through my work as curriculum lead provided me with several points of contact to observe interactions during activities, including student behaviour with tools, materials, ideas, and creative-technical spaces. These observations have helped reveal *patterns of concern* that may affect the strategies used to promote critical making, sustainable action, and creative uses of technology. A pattern of concern is any behavioural trait that is repeated among learners that complicates or contradicts the intentions of the learning experience. We can revisit Blikstein's (2013) depiction of a "keychain syndrome" (p. 8) as an example of this.

> … digital fabrication is a type of Trojan horse: it introduces in schools a "genre" of tools that have the very special property of easily generating aesthetically pleasing, almost magical products. Therefore, for the student-creator, there is a conflicting incentive: (i) obfuscate the simplicity of the process ("I used this laser cutter machine, it's science fiction, it's really complicated"), and enhance the value of the product to others, or (ii) make the process transparent ("I used the laser cutter, it's actually not so hard to do keychains, the machine did most of the work!"), and reveal the triviality of the product.

Patterns of concern can be broad and complex or isolated and relatively minor. They can be linked to how people think or how they approach making. They need to be addressed as they impede the transfer of essential concepts, or they can limit interactions, encourage improper techniques with tools, and impact safety. The dilemma for facilitators or teachers in these situations is how to efficiently add layers of control or complexity of thought without losing student interest in the maker-driven design activity. Borrowing from Verplank's (2009) description of designing interactions for people, we need to be able to ask questions about how students *do* these activities, how they *feel* about them, and how they *know* what to do when they approach them. It was important in this situation to find strategies to communicate the evidence that supports what was observed through student interactions. Figure 44 introduces a playful petri dish-styled map used to visualize some impressions of maker-driven design activity concerning the research question posed in this work. Students are mapped onto the dish as dots based on their willingness to iterate—a vital ingredient of a healthy design process. Most students are seen as engaged, some are enthusiastic, and there will always be one or two who seem absent and not participating. Some students hang out in groups, some in pairs, and some on their own.

Figure 44

Mapping Student Interactions



Students tend to gravitate toward and repel each other, which can be displayed by the proximity of dots. Colours are used to suggest which students have provided evidence of critical making, sustainable action, or creative uses of technology based on what has been seen, heard, and done in maker-driven design activity. If students pose questions about the nature and impact of what they are making, they are surrounded by red. If they question their choice of materials, they are surrounded by green. If they experiment with new ways of engaging with technology, they are surrounded by blue. If they express any combination of the above, they are placed at the intersections of these colours. The overall effect looks like a petri dish of colours and dots interacting. Ideally, you want to have as many students as possible exhibiting all three qualities in their work and how they express their thinking.

The dish-like shape of this map is divided into three zones representing student engagement in the process. In my observations, most students will fit in zones one and two. In zone one, “one-and-done,” we find students who do the minimum of what is asked and show little intention for further iteration after a first effort. Zone two, “two-for-you,” is where we find most students who want to do well; they may be grade-focused and work on multiple iterations based on what they feel the teacher is asking. This behaviour is typical in a school setting where grades are seen as a priority over the experience itself. Zone three, “three for me,” is where students find themselves when they are motivated by the learning goals. Zone three is where you locate the students who are taken by the desire to create and work on as many iterations as possible. Enthusiastic students who exhibit a high degree of design literacy will be the kind of students who identify as makers or may choose to continue using design processes in their work. Although this mapping example was backward designed from previous observations, it does provide an idea for a visualization method that can be used in future research. It would be interesting to see how these elements shift over time, providing interesting information about the efficacy and evolution of a design program.

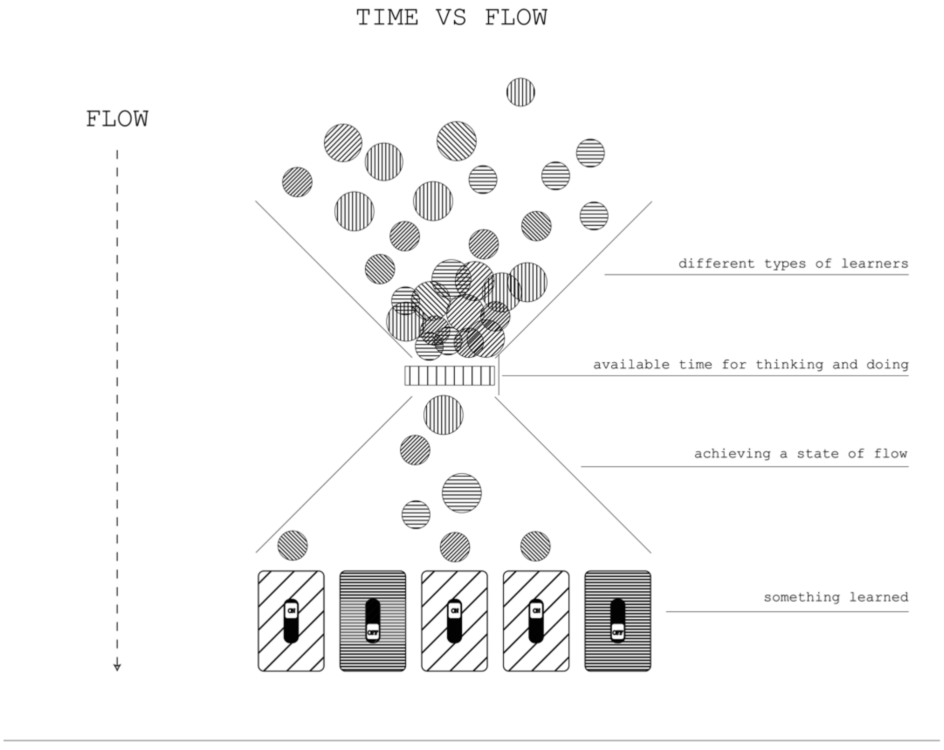
5.5 Process Avoidance

John Maeda (2006) identifies a central issue with learning new ways of doing things in that "the problem with taking time to learn a task is that you often feel you are wasting time" (p. 33). Time, or lack of it, is essential in how students and teachers approach more progressive approaches to learning (Cuban, 2020; Kohn, 2008; K. Robinson & Aronica, 2016). Time must be carefully considered and mapped onto the hourly blocks of a school schedule which is not representative of the time it takes to experience flow (Csikszentmihalyi, 2014b) in creative-technical work. There may be time to “think,” and there may be some time to “do,” but rarely is there enough time to “think, do, and reflect.” A maker-driven design activity needs to be programmed around 60-minute blocks of time, which are more like 30 minutes after taking attendance, setting up the activity, getting into a state of flow, and then taking the time to clean up (see Figure 45). Such timing constraints train teachers and students to approach learning in a way which is not always conducive to creativity (K. Robinson & Aronica, 2016), and it poses challenges for maker-driven design activities. In all my experiences working in a school and developing a design program focused on making and digital fabrication, *process avoidance* is one observation that stands out among the rest.

Process avoidance can be described as the steps a student, or teacher, takes to cut corners and bypass best practices, instructions, challenging factors, or creative suggestions. It is the effort that goes into avoiding the design process. This is problematic if the value of design education is communicated through the design process. Surprisingly, students may spend more energy avoiding this process than it would take to give it a try. For example, as was done with the Future Humans project, we asked students to make silhouettes using a technique that requires forming compound shapes and adjusting the vector paths to follow the outline of an image. We take the time to express that this is just one method. Still, it has been tested as a strategy that effectively avoids annoying and time-consuming mistakes with machines later in the process—assuming this process involves digital fabrication. Still, we find students who choose to ignore this less-than-familiar method only to find complications when they take their designs to a machine that is not reacting well to the hidden defects found in their drawings.

Figure 45

Flow in Maker-Driven Design Activity – Poster

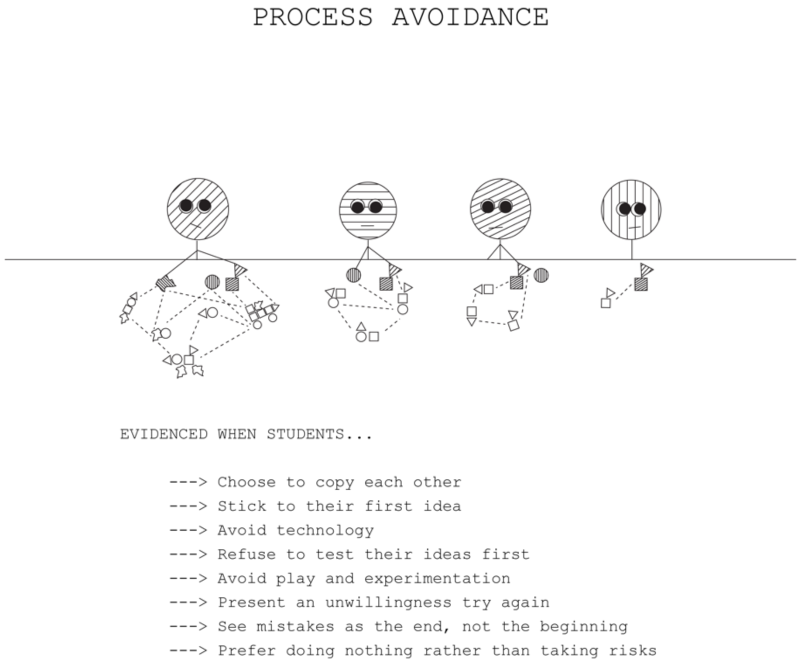


How many students experience a flow state in a 60-minute design period?
[~40 minutes after settling in, taking attendance, and cleaning up]

Process avoidance can be exhibited in several ways, but it points to an aversion to tasks that may seem like a waste of time. First, it encourages a lack of iteration or experimenting with materials and technologies before making design decisions. Design thinking seeks differentiation refines itself over time and encourages mistake-making as a key to unlocking creativity (T. Brown & Barry, 2011). Process avoidance can be observed as repetition without differentiation, copycat behaviour (copying solutions that others find first) or concluding that the first idea is the only idea (Figure 46). Students may express frustration with redoing, reframing, or repositioning their activity. These observations need to be noted as they oppose designerly processes which promote alternative ways of seeing (Cross, 2006, 2011). With only one iteration and little experimentation, the potential return of some form of creative discovery and the confidence this brings is diminished.

Figure 46

Process Avoidance – Poster



PROCESS AVOIDANCE

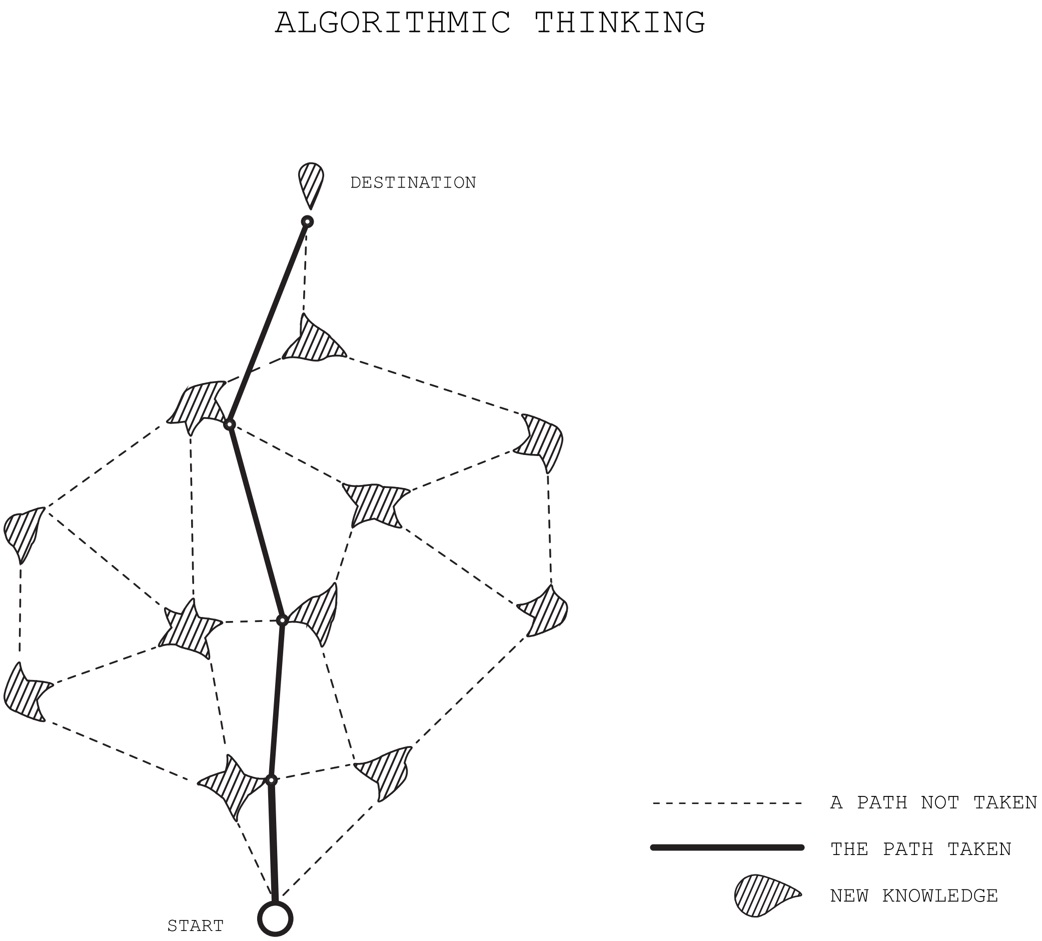
EVIDENCED WHEN STUDENTS...

---> Choose to copy each other
---> Stick to their first idea
---> Avoid technology
---> Refuse to test their ideas first
---> Avoid play and experimentation
---> Present an unwillingness try again
---> See mistakes as the end, not the beginning
---> Prefer doing nothing rather than taking risks

It has been noted regularly during the observations that led up to this research-creation project that some students avoid seeking information and have limited patience for creative uses of technology. Rather than "messing about” with technology and ideas (Ratto, 2011), many students tended to ask for step-by-step guidance, regardless of provided instructions, peer support, or the potential for simple online inquiry. A lack of student autonomy poses a significant challenge for managing classroom dynamics and scaling creative uses of technology within a school environment. The teacher cannot be the only solution in learning how to move beyond creative-technical hurtles. It became clear during this research-creation that other forces are at play and worthy of further research. For example, how many of these observations are linked to school culture? How many of these observations are influenced by the evolving reality of “just-in-time” access to information? How will these behaviours change with increased exposure to artificial intelligence technology? More research is needed, and more tools should be designed to support changing interests and trends in how students approach learning through design and making (Figure 47). In a world of information-on-demand, why should students care about learning how things work if an algorithm can do it for them?

Figure 47

Algorithmic Thinking – Poster



Students must demonstrate process avoidance in other subjects, and this phenomenon cannot be specific to maker-driven design activity or the like. However, we should recognize that in other instances, such as math or science, these courses have the advantage of having their learning processes reinforced yearly from kindergarten to grade 12, with many more hours in the schedule, and are culturally supported as necessary for preparing students for society. Process avoidance can be equally evident in the work of teachers as well. There is a process for setting up an effective maker-driven design activity so that elements fall into place. If a teacher avoids this process, it becomes harder to ensure that critical making, sustainable action, or creative uses of technology will be meaningfully experienced. It means that these activities and responsibilities can't just be handed over to teachers who have not been trained to know what it is like to exercise them. It takes time to learn how to use digital fabrication equipment or to code, and it requires time for students to absorb the material. It takes time to ensure that concepts like sustainable action are embedded, not just discussed. Most importantly, it takes time to learn how to scaffold this way of doing things in an environment that is not designed to support it.

Maker-driven design activity brings these unique learning situations to the forefront, where they are apparent and can be studied. We are asking students to learn and teachers to teach in a way that is atypical of other school subjects. It is also atypical of our experience with technology as we have grown accustomed to bite-sized information and the use of apps to make learning easy. The rise of AI in learning might bring about new reasons to include design in the curriculum. The tools and the methods will and should change, but the process remains. We could be training students and teachers to embrace this process and the inherent challenges associated with critical making, creative uses of technology, and sustainable action. It is an effective agent in becoming more observant, taking risks, being determined to work toward a solution, and using challenging material as a creative catalyst. It should support behaviour that questions consumption and favours construction.

6 FUTURE RESEARCH

This thesis reflects on a creative process which generates more questions than answers. The aim is to define a design practice which strengthens the potential of maker-driven design activity in schools. It also examines the aesthetic qualities of a secondary school design experience beyond the established norms of STEM, STEAM, design and technology, or design thinking. This thesis raises critical considerations for designers and teachers involved in this field or who are interested in or requested to work in Fab Labs. This work should be refined and expanded to raise awareness of the essential qualities of contemporary design education geared toward secondary students. A design education that straddles perspectives between communities of practice and encourages design literacy and pluralistic views on meaningful learning in creative-technical spaces like Fab Labs.

The outcomes of this work point to design constraints as a key ingredient in fostering critical making, sustainable action, and creative uses of technology. However, to validate the learning experiences described beyond conjecture, more focused questions should be asked about specific areas of interest and concern surrounding the learning experience. Throughout the integration of maker-driven design activity, there has been a need to measure the rigour, clarity, and amount of work being asked of students. What is described in this paper as the *hard fun principle* is meant to balance these elements. It also puts into question a tool to help validate thresholds between complex and trivial activity and measure student willingness to apply thinking and iterative energy into maker-driven design activities. Here are some questions relating to these boundaries.

- How is rigour measured in maker-driven design activity?
- What are student and teacher impressions of the IB’s Middle Years Programme design cycle, and does it support meaningful design experiences?
- Are evidence journals necessary, and how do we make them more enjoyable and meaningful for students?
- How might different school cultures interpret design as a subject area of interest, and does this impact student willingness to iterate or think critically about design?
- How do students feel about the computational activity required to make almost anything in a Fab Lab?

Understanding what thresholds exist for rigour in a particular school culture is necessary for generating an effective design curriculum. One of the significant challenges with this work has been convincing students and teachers that they can be imaginative and technically profound despite a lack of experience or familiarity. Understanding how creativity leads to complexity is a constructionist perspective and a critical approach in maker-driven design activity. The following questions are raised concerning thinking about the experiences that improve or weaken student and teacher confidence.

- How many people need to know how to use the technology in a Fab Lab to make them a compelling domain for learning in schools?
- Does process avoidance exist in Fab Labs? How is it expressed? What can be done?
- Does app culture influence student expectations in learning? Does this have an impact on how students approach making?

Despite the apparent gap in awareness of each other, this work has been highly influenced by constructionist principles and design research. Throughout this work, constructionist principles are effectively another set of design principles geared toward learning experiences. As the nature of design shifts in higher education, more clarity is needed to guide design education in secondary school contexts. Constructionism offers a way to make meaningful connections between the two. The following questions reflect on the nature and relationships between design education and the art of learning.

- What is the art of learning, and is it instrumental in innovation?
- What has changed in design education, and are we teaching the best version?
- What is design literacy? Should it be taught in schools?
- Constructionism: A model for learning or a model for design?
- Should teacher training in maker-driven design activities qualify makers to teach design in schools in Québec? How does this compare to other provinces or other countries?
- Because of design's impact on innovation and 21st-century learning, what role might a national framework for design education play in secondary education?

Throughout the literature, data collection and research methods that are used in maker environments or design-like secondary education have been questioned. There is a consensus across communities of practice that better research methods must be devised to collect more quantitative data if there is hope that this will improve the adoption of design education in school systems. The following questions have emerged from this research-creation concerning developing effective research methods for maker-driven design activity in schools.

- How might we measure flow in maker-driven design activity?
- What are some strategies for measuring waste from maker activities in schools?
- How do we assess students' ability to synthesize research with creation in maker-driven design activity?
- How might we quantify student impressions of maker-driven design activity based on photographic evidence of behaviour surrounding technology and materials?
- What are some strategies for using AI to enhance human action in maker-driven design activity?
- Does interdisciplinary learning in maker-driven design activity improve student test results in core curriculum subjects?

7 CONCLUSION

This paper describes a creative process used to generate ideas for maker-driven design activity. After defining maker-driven design activity, several terms have been proposed to help unpack the unique experiences and considerations that define design for the art of learning, including *didactic experimentation*, a *hard fun principle*, *patterns of concern*, and *process avoidance*. Concept maps and illustrations are used to help communicate these observations and propose questions to guide future research (Figure 48).

Figure 48

Design For the Art of Learning – Exhibition

MDes22 – Graduate Exhibition

4th Space – Concordia University – 2023

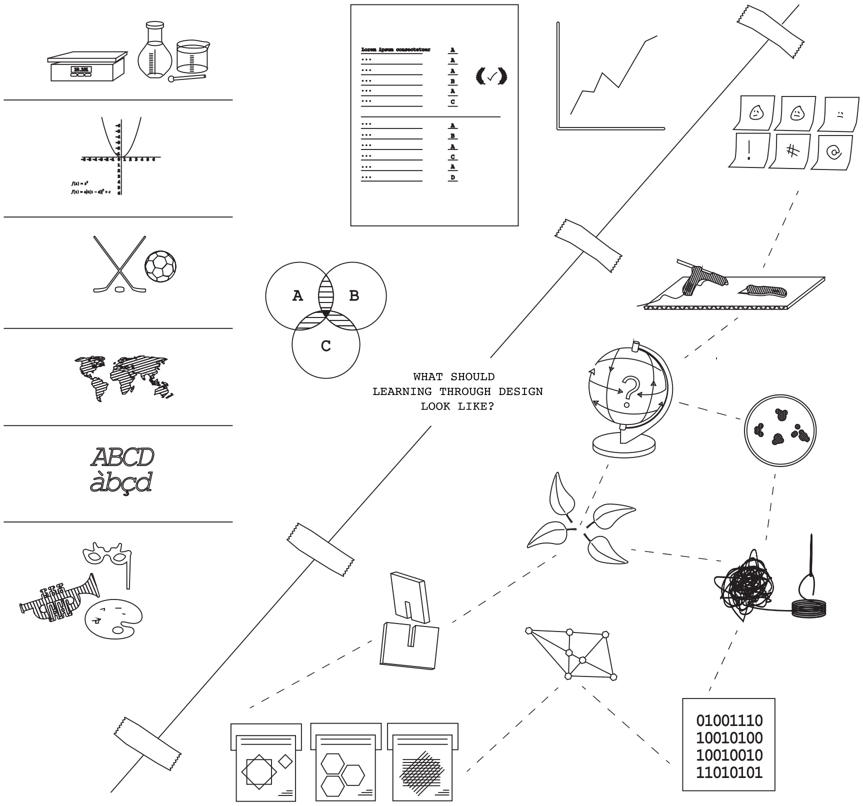
It is clear from the literature reviewed that design education is hard to define concisely and is influenced by different contexts.

> Anybody who has been confronted with design education would readily admit that proposing a satisfactory definition of design is a rather risky, if not impossible, enterprise. Its definition indeed depends on whether design is considered to be an idea, a knowledge, a project, a process, a product, or even a way-of-being. Its fundamental characteristics may also vary according to the historical and geographical, that is, cultural context. (Findeli, 1990, p. 4)

This paper is not an attempt to define design education in its totality. Still, it aims to generate interest and a direction for future research and to put into question the aesthetic qualities of learning through design and maker experiences in secondary school (Figure 49). What has been proposed here is a kind of learning centred on critical making, sustainable action, and creative uses of technology.

Figure 49

Aesthetics of a Design Education – Poster



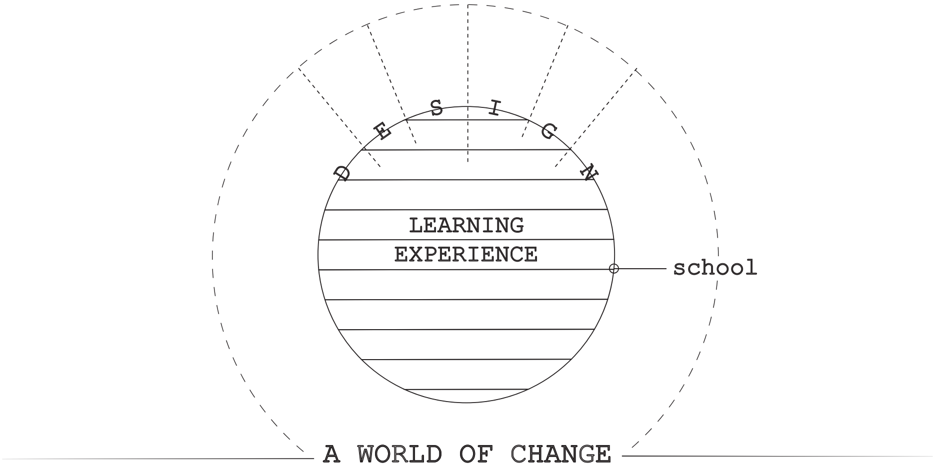
The spread of creative and technical spaces in schools, like Fab Labs and makerspaces, indicates an interest in learning through design or its derivatives in STEM/STEAM education. Such initiatives look progressive and future-facing and can be prominently displayed in school redesigns and marketing campaigns. They represent exciting changes to a school setting but do not speak to the systemic changes required to broaden the support of this type of learning. Fab Labs and makerspaces, initiatives installed through initial capital investment and then outlay to purchase materials and machinery, need to adequately expose students to essential principles of a design process that takes more time to cultivate. While there are educational benefits to tinkering with materials and technology, learning through design does not require significant capital. It is an operational expense and involves synthesizing ideas and interests with available technology by individuals willing to generate meaningful learning experiences. It requires individuals comfortable with creative, technical, and polymathic thinking. In this vein of thought, research, and support for essential literacies among students, teachers, and administrators are needed to make this learning more salient. As they do in the UK, national or provincial organizations should assess the value of secondary design education and generate interest, quantitative research, and collective support to train teachers and provide resources for schools interested in this approach. For this to work, more designers need to explore education as a vibrant space for interaction design, and more educators need to see the value of design education for interdisciplinary learning. Beyond the various journals on design, STEAM, technology, maker, and STEM education, universities and not-for-profit organizations with an interest in the nature of design or design research need to consolidate what has already been done and agree on what constitutes contemporary design education, design literacy, and what value this has on innovation or student and teacher experiences across disciplines. We need to work together to address the issue of what cultural, economic, and, more specifically, educational value design studies have in Canadian culture. The emphasis here is first on raising the importance of design as a subject of study, defining its value in education, and then devising communication strategies and resources to integrate this knowledge into educational systems.

We must also emphasize design’s role in the development of technology, our understanding of it, its influence on young minds through education and our ability to train future citizens with the creative-technical confidence needed to be critical and resilient to change. The generation of students entering middle school has grown up with a relationship to technology unlike any other. Their understanding of the world is highly influenced by a complex web of interactions between devices and algorithms, curbing interests and splitting their attention. Not to mention two years of a pandemic that have substituted in-person experiences through digital filters. What will their interest in design be, and how is technology changing what they deem important and worth learning? How do schools perpetuate dependencies on devices without offering a clear understanding of how they operate? It is helpful again to consider Ursula Franklin's (1999) exploration of technology which she describes as both ambiguous and misunderstood. Much like with the subject of design, we find a paradox. We need it, we embrace it, we consume it, and it shapes us. Still, the question of whether we allow everyone the ability to comprehend it, create it, or shape it remains unanswered.

As a revolution in artificial intelligence progresses, more reasons emerge to ensure future generations can think critically and creatively about technology. As economic systems struggle to pivot toward a more circular economy, it makes sense to ensure schools can effectively encourage ideation and alternative solutions. Critical making, sustainable action, and creative uses of technology might seem easy to cast aside in curriculum planning. However, there are more reasons now to imbue learning with a sense of criticality. We need to link learning in schools to the changing world, and few disciplines are positioned to do this as well as design (Figure 50). This work is fostered by an interest in how the design process activates critical thinking, creativity, and resilience when initial habits with technology and essential literacies are formed.

Figure 50

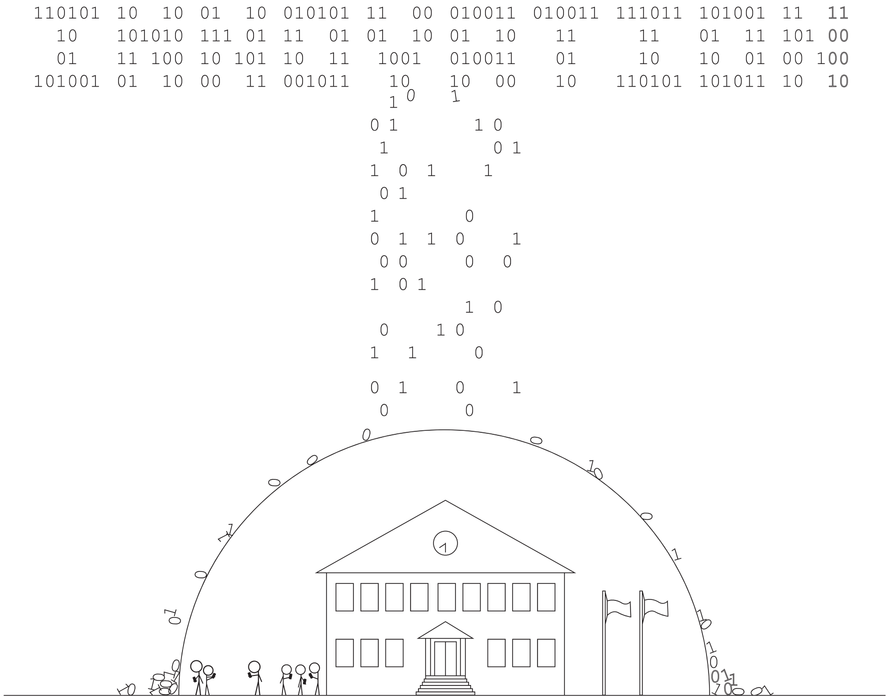
"A World of Change" – Defining Design Education Poster



In his book *Imagine If... Creating a Future for Us All*, Sir Ken Robinson (2022) emphasized that interdisciplinary learning and eight core competencies are critical to a healthy 21st-century education. They include curiosity, creativity, criticism, communication, collaboration, compassion, composure, and citizenship (p. 45). These competencies are all facets of creative-technical and problem-based learning in design education. What is needed is a broader cultural awareness of the study of design in secondary education, moving beyond the limited perception of it as an applied art. Missing is a collective voice representing various communities of practice that share similar interests in this type of education. While it is true that schools teach students about technology and design in various ways, and there are impressive examples of this, my personal experiences and observations supported by the literature suggest that the traditional structure of education makes it harder to integrate designerly ways of knowing outside of a sprinkling of optional courses and activities. The average student tends to remain shielded from opportunities to fully embrace the interdisciplinary, iterative, and exploratory activities highlighted in learning through design (Figure 51).

Figure 51

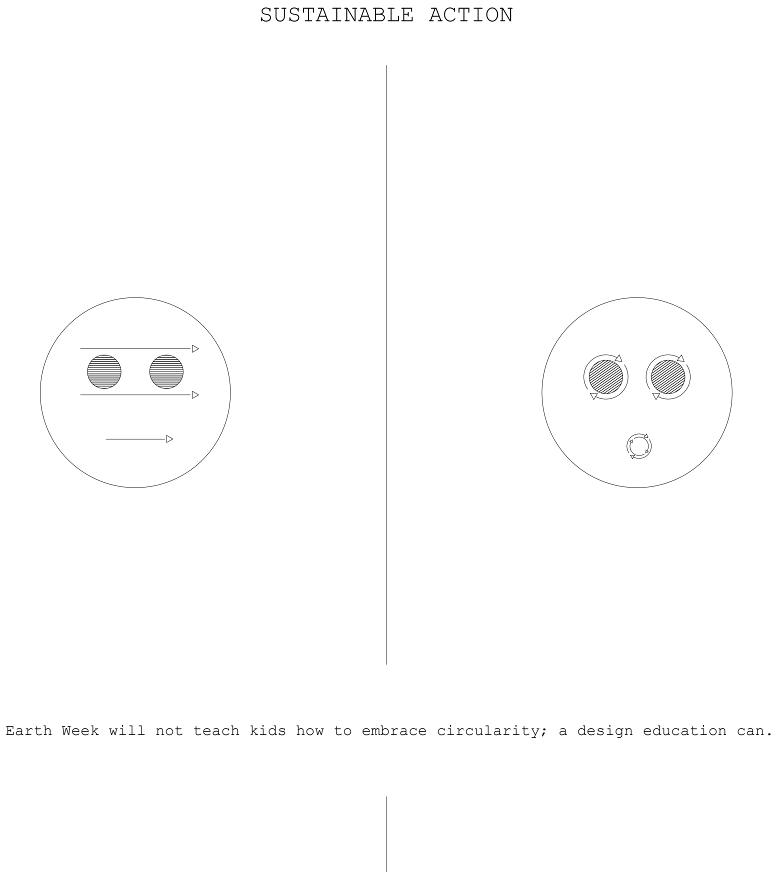
"Innovation" - Defining Design Education Poster



Is it possible that school systems inadvertently support a general blindness to how systems and interactions work and a lack of understanding of the consequences of bad design? When introducing students to complex problems, we tend to stress the challenges without providing the tools to recognize them as complex, wicked, or integrated (Buchanan, 1992). Issues like climate change, inequality, well-being, and diversity emerge through school awareness campaigns, often dealt with through token gestures like Earth Week (Figure 52). Design education helps make room to follow through on these concerns with action while offering meaningful interactions between multiple subjects. The research-creation project described in this thesis is limited in its scope yet proposes a first step in seeing if maker-driven design activity can help offer an "in-sight" and "in-mind" relationship with design in a secondary school learning environment.

Figure 52

“Sustainable Action” - Defining Design Education Poster



SUSTAINABLE ACTION

Earth Week will not teach kids how to embrace circularity; a design education can.

For the ideas posited in this paper to stick, we need to know what questions to ask and how to research them effectively. Access to student impressions and examples of work is a necessary first step. Once we have permission to collect evidence for ongoing risk-free analysis, we can measure the outcomes of didactic experimentation. We can study students as they progress through school and learn whether maker-driven design activity has helped to equip them to “engage in the personal, cultural, economic, and social challenges they will inevitably face in their lives” (Robinson, 2022, p. 45). I don’t believe student success in the 21st century will be related to an ability to make a laser-cut LED night light, a birdhouse, or a self-watering planter. If design for the art of learning is to matter it is because it supports mindsets that stick with the inherent challenges of an iterative process while working toward something personally meaningful. The challenge in a design program like the one described in this thesis is how to turn personally meaningful things into meaningful things for others.

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