Constructionism 3.0: The emergence of digital fabrication learning in K-12 educational technology: A four-decade narrative history of objects-to-think-with

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Abstract

Distinctly and in tandem, constructionism (an educational philosophy) and digital fabrication (a process or workflow in which manufacturing machines and tools are controlled by computer) have received amplified consideration in current efforts at K-12 education reform. This article, which reflects on over five decades of documents, transcripts, and interviews with participants, illustrates how constructionism in K-12 educational technology has evolved starting at MIT from the inception of the Logo computer language (Constructionism 1.0) to its second iteration, MIT Media Lab's Lifelong Kindergarten Scratch block-based programming environment (Constructionism 2.0). Fab labs, conceived by MIT's Center for Bits & Atoms, is the third-generation platform for constructionist teaching and learning (Constructionism 3.0). A rich diversity of educational innovations emerged from the historical and growing relationship between constructionism and digital fabrication. This article explores the nature of constructionism as an epistemology, which is concerned with the scope of knowledge building, and how that can be enriched and amplified by the technologies of digital fabrication. A secondary contribution is a historical narrative reflecting on the evolution of constructionist technology driven principles in K-12 education. A final section probes the role of constructionist approaches in teaching and learning with digital fabrication technology.

Keywords

Papert, Logo, Scratch, fab labs, constructionism

1 Introduction

In 1966, Seymour Papert, Wally Feurzeig, Daniel Bowbrow and Cynthia Solomon created the Logo programming language. Logo was designed as an environment where children could explore mathematical ideas and create personal projects, and was the first programming language developed for children (Solomon, et al. 2020). At the time, there were only approximately 200,000 personal computers in the world, and Papert was amongst the first to recognize that education would need enormous, arguably disruptive change, especially in math and science in order to both take advantage of, and accommodate, developing technologies as drivers of the global economy (Sculley, 1993).

The Logo team initially developed the programming language at the firm Bolt, Beranek and Newman (Solomon, et al. 2020) but migrated to MIT primarily for funding purposes. Like most progressive educators of the era, this team shared the view that their efforts were designed to change the nature of schooling. Strauss provided a succinct summary of the sentiment that prevailed during this period:

DOI: 10.5281/zenodo.5169830

> These MIT scientists wanted to dismantle institutional barriers that schools had erected over time—the rules, traditions, and culture—because they retarded student learning. LOGO, then, would be a vehicle for transforming teacher-centered schools into student-centered ones…. (Strauss, 2016, para. 2)

In the late 1960s Papert gained National Science Foundation (NSF) funding for the LOGO Project, which is now “broadly considered the beginning of K−12 Computer Science Education” (Chakraborty, 1999; Google, 2018, p. 4). Logo’s most widely recognized feature was the use of a robotic turtle that sat on the floor, which children could ride and drive around via the programming commands FORWARD, BACK, LEFT and RIGHT. In this personalized learning approach, the “turtle” served as an “object-to-think-with,” as Papert described:

> I begin by describing one example of a constructed computational "object-to-think-with." This is the "Turtle” … The Turtle serves no other purpose than of being good to program and good to think with. Some Turtles are abstract objects that live on computer screens. Others, like the floor Turtles…are physical objects that can be picked up like any mechanical toy. (Papert, 1990, p. 11)

Papert proposed that objects-to-think-with should be able to grow with a child, having a “low floor”—easy access for even very young children—and “no ceiling,” or near-limitless potential for complexity (Papert, 1991). This broadened concept of learning environments creates excitement and engagement for young learners through a combination of a kindergarten-style, spiral approach to learning, including a cycle of "Imagine, Create, Play, Share, Reflect" and again Imagine, and through a communal learning and mentoring approach (Resnick, 2007, p. 1). In his book *Mindstorms*, Papert visualizes both the excitement and communal nature of Logo learning, adopting the metaphor of the samba schools often located in the favelas, the neglected neighborhoods of Rio where extreme poverty prevails and persists.

> Each group prepares separately – and competitively – in its own learning environment, which is called a samba school. These are not schools as we know them; they are social clubs with memberships that may range from a few hundred to many thousands. Each club owns a building, a place for dancing and getting together. Members of a samba school go there most weekend evenings to dance, to drink, to meet their friends. During the year each samba school chooses its theme for the next carnival, the stars are selected, the lyrics are written and re-written, the dance is choreographed and practiced. Members of the school range in age from children to grandparents and in ability from novice to professional. But they dance together and as they dance everyone is learning and teaching as well as dancing. (Papert, 1980, p. 178)

During a 2017 MIT Media Lab symposium entitled *Thinking about Thinking about Seymour*. Resnick reflects further:

> Seymour had a more organic view of teaching and learning—and a more organic view on how ideas spread. The process is not like an engineer building a structure according to specifications; it’s more like a farmer or gardener tending to plants, creating an environment in which the plants will flourish…. As LOGO spread around the world, he worried that the core ideas were becoming diluted; he even coined the term “epistemological dilution” to describe the process. (Evens, 2017, paras. 1-4)

Papert’s fears of dilution became reality. Classrooms used Logo as a tutorial tool, rather than a medium through which students could express themselves and explore ‘powerful ideas.’ Computers were used more as systems for delivering and accessing information, than media for thoughtful discovery, learning through making and creating, or for personal expression (Resnick, 2012). These idealistic experiments in education disappeared during the 1960s and 1970s due to a “back to basic” reform from civic and political leaders (Evens, 2017).

The path from Constructionism 1.0 to Constructionism 2.0 lay with the collaboration between Papert, The LEGO Group, Mitchel Resnick, and the Epistemology and Learning Group at the MIT Media Lab. In the 1980s The LEGO Group began collaborative research with MIT in learning through play (Kristiansen, 2021). The research involved creating a construction kit that would allow children to build things that were personally meaningful, as well as to program and control those things (Resnick, 1994). The highly successful LEGO/Logo kits became a staple of science education as hands-on learning tools. But again, classroom adaptations often tightly prescribed what a student could make, omitting the critical freedom for students to create things that were personally meaningful (Resnick, 1994). Resnick was thinking about, and working on, new versions of programming languages for children, based around decentralized and distributed systems, a concept that was increasingly recognized in computation as well as other fields (Resnick, 1994). The StarLogo revision was an epistemology-technology combination that provided a rich learning environment, accommodating a more decentralized concept of learning, bringing together constructionism with parallel computation and programming languages, and the ability to perform massive parallel processing. (Resnick, 1994). Several features developed in StarLogo, the characters, the communications between characters, the "demons" or simultaneously running programs that interact with one another, the "breeds" or ability to duplicate characters, as well as the use of colors for identity and organization, all influenced the development of the sister program Scratch, first launched in 2007.

Resnick's Lifelong Kindergarten Group led, and continues to lead, the development of Scratch's block-based program, which drew additional inspiration from the hip hop culture and the DJ technique called 'scratching' while 'remixing' or adding new elements to original content (Resnick, 2017a). Resnick ascribed the success of the widely popular Scratch program to the focus on 'Seymour's advice to aim for low floor and high ceiling,' with one important caveat—the dimension of 'wide walls':

> That is, we try to design technologies that support and suggest a wide range of different types of projects. It's not enough to provide a single path from low floor to a high ceiling; it's important to provide multiple pathways. Why? We want all children to work on projects based on their own personal interests and passions—and because different children have different passions, we need technologies that support many different types of projects, so that all children can work on projects that are personally meaningful to them. (Resnick, 2017, p. 64).

Scratch 2.0 developed this idea further by integrating Web 2.0 online code editor features into their social platform, where the entire learning community (instead of just one student) collaboratively constructs artifacts. The incorporation of a distributed context transforms '*objects-to-think-with'* to '*objects-to-think-with-together*.'

Constructionism 3.0 originated at the Center for Bits & Atoms (CBA) at MIT. Fab labs emerged in 2001 from early CBA and Media Lab research into personal fabrication. The first fab labs, established in inner city Boston, rural India, and rural Norway formed the beginnings of a global network of digital fabrication labs that today number more than 2000 fab labs in over 125 countries. Fab labs comprised a curated set of low-cost, high precision manufacturing and prototyping tools and processes that allowed anyone to make almost anything they could imagine. Neil Gershenfeld, Director of CBA, synopsizes Papert's legacy as 'a historical blurring of the distinction between toys and tools for invention, culminating in the integration of play and work in the technology for personal fabrication' (Gershenfeld, 2005, p. 133). Recollecting a conversation with Papert, circa 2005, Gershenfeld observed:

> As fab labs started doubling and began to grow, Seymour came by to see me to talk about them. I had considered the whole fab-lab thing to be a historical accident, but he made a gesture of poking his side. He said that it had been a thorn in his side that kids could program the motion of the turtle but could not make the turtle itself. This had been his goal all along. Viewed that way, learning in fab labs follows directly from the work he started decades ago. It's not an accident; there's a natural progression from going to MIT to play with a central computer, to going to a store to purchase and play with a toy containing a computer, to going to a fab lab to play with creating a computer. (Gershenfeld, *et al*. 2017, pp. 29-30)

In that conversation, Papert expressed clearly that fab labs were the fulfilment of a learning lineage, from mini-computers to turtles to Logo to Scratch to fab labs. Students could not only program the turtle, but make the turtle, using the tools of digital fabrication. Fab labs ushered in a transformation by extending constructionism beyond computers and coding, turning the computational bits of programs into the physical atoms of the world, embodying abstract concepts in physical reality. The fab lab itself became a powerful embodiment of Constructionism 3.0, a place where it was possible to make and share globally *objects-to-make-and-think-with-together*.

Many innovations have come from faculty and researchers at the MIT Media Lab over time, such as Bakhtiar Mikhak, Cynthia Breazeal, Leah Buechley and Amon Millner to name a few amongst many. They are innovators who think deeply about digital fabrication and constructionism, and about how both the technologies and the pedagogy can be used in educational environments to enhance learning and engage learners. We acknowledge the substantial contributions of these pioneers; however, here we focus our reflection solely on the three constructionist platforms identified above for learning: Logo, Scratch and fab labs.

2 Digital Fabrication In Classrooms

Traditional neoliberal education reforms, in pushing for standardized testing for example, represent a top-down attempt to implement the industrial techniques of Taylorism into classrooms (Taylor, 1911). A primary feature is the single-mindedness and unyielding separation of thinking from doing. In this widespread behaviorist-positivist practice, knowledge is viewed as a commodity to be transmitted to students. Freire designated this "banking concept" as an oppressive classroom dynamic. In an unparalleled appraisal of Taylorism, he writes:

> Teacher teaches and the students are taught; teachers know everything and the students know nothing; teacher thinks and the students are thought about; teacher talks and students listen; teacher disciplines and the students are disciplined; teacher acts and the students have the illusion of acting through the action of the teacher…the teacher is the Subject of the learning process, while the pupils are mere objects. (Freire, 1970, p. 73)

Paulo Blikstein is a lead scholar advocating for the incorporating of digital fabrication in K-12 spaces. Providing historical context, he writes:

> The analogy with the development of Logo is clear: simultaneously, digital fabrication technology became better and more accessible, and the intellectual activities enabled by the new technology became more valued and important. What Logo did for geometry and programming – bringing complex mathematics within the reach of schoolchildren – fabrication labs can do for design and engineering. Digital fabrication is Logo for atoms. (Blikstein, 2013, p. 204)

As the word spread and the price of machines decreased, schools started creating their own digital fabrication laboratories and classroom makerspaces. Blikstein warned educators to "shy away" from "the seductions of the 'keychain syndrome:"

> For the first digital fabrication workshops we held in 2009, I designed introductory activities to get students acquainted with the machines: semi-structured short projects such as creating a keychain, a nametag, or an acrylic sign for a sports team… The plan worked too well – it backfired. Students found an activity that was personally meaningful, produced professional looking products that were admired and envied, and used a high-tech device. However, as much as it was a very effective solution to engage them in digital fabrication, it offered a too big reward for a relatively small effort, to produce an object that did not include any computation or complex constructive challenges. (Blikstein, 2013, pp. 210-11)

A team of Denmark scholars documented teachers adopting Fab tools in their classrooms as part of the Danish FabLab@School project. Smith, et al. present evidence that the "modest keychain experiment" was not the only challenge:

> The teachers experienced the tension between the traditional educational system and their own ambitions to engage students in explorative new ways of learning with technology as a fundamental challenge. As several teachers stated, the challenge was not merely the teachers' lack of ability to develop and navigate open-ended learning processes, but also the structural dilemmas in the overall school system…The overarching impediment hence, is not operating the 3D printer in the classroom, but to thoroughly investigate the question: "What should the 3D printer actually print? (Smith, et al. 2016, pp. 43-45)

Building from the Danish project, the FabLab EU partnership, consisting of five organizations from four EU countries, was created to develop common methodological principles for digital fabrication education starting in primary and secondary schools across Europe, with the following objectives:

- To increase teachers' competences and pedagogical skills in educational digital fabrication;
- To provide pupils with innovative skills and digital competences required in the 21st century;
- To develop methodological principles for educational digital fabrication; and
- To develop EU recommendations and policy formulation adaption of educational digital fabrication in EU (FabLab Schools EU, 2016, p. 4)

As outlined in a 2016 publication, *Manual on Teaching and Learning with Digital Fabrication*, the EU project primary focus is on "six main skills needed in 21st century life, work and education:" critical thinking; communication and collaboration; creativity and innovation; complex problem solving; technological mastering; and digital citizenship (FabLab Schools EU, 2016). While fabrication technologies such as 3D printers and laser cutters become more common in classrooms, the "talk and chalk" behaviorist-positivist tradition remains the dominant teaching method. Promising exemptions to this rule seek to offer robust constructionist fab lab learning opportunities.

3 Fab Lab Classroom Best Practices

Marina Umaschi Bers, a leading expert in the design of Early Childhood Makerspaces and co-developer of Scratch Jr. with Resnick, wrote:

> Back in the late '90s, when I was a doctoral student working with Seymour Papert at the MIT Media Lab, the joke was that Seymour did not come in the LOGO box. What we meant was that, although we were bringing LOGO and its full expressive potential to schools, many teachers tended to use LOGO in traditional instructionist ways. Creativity and personal expression were left out. (Bers, 2017, p. 20)

Social and emotional learning (SEL) skills, such as creativity and collaboration, are integral parts of early childhood development (CASEL, 2021). Rooted in constructionist principles, Bers's research confirms the positive impact of fab lab tools on enhancing SEL in pre-K-settings. The intersection of digital fabrication and SEL is reflected in Ber's Positive Technological Development framework (PTD). The SEL-aligned framework consists of six Cs (Communication, Collaboration, Community-Building, Content Creation, Creativity, and Choices of Conduct). These behaviors are associated with a second set of six Cs related to personal assets (Caring, Connection, Contribution, Competence, Confidence, and Character). Extending constructionist best practices, her international body of empirical research reminds us that students learn by:

1. Designing a personally meaningful project to share in the community
2. Using concrete objects to build and explore the world
3. Identifying powerful ideas from the domain of study
4. Engaging in self-reflection as part of the digital fabrication learning process (Bers, et. al. 2018, p. 21)

Finland is one of the first EU countries to introduce "twenty-first century skills" and "computational thinking" as a mandatory element of its National Core Curriculum for Basic Education. A team of constructionist scholars at Fab Lab Oulu, located at the Teacher Training School at University of Oulu, conducted numerous studies on teaching and learning with fab lab tools (Pitkänen, et al. 2019; Iwata, et al. 2020; Milara, et al. 2020; and Baykal ,et al. 2021). Iwata et al. pursued the following research questions:

- To what extent are twenty-first century skills recognized in digital fabrication activities?
- To what extent are Computational Thinking practices recognized in digital fabrication activities?

- What are teachers' and facilitators' conceptions of the factors which influence pupils' learning of twenty-first century skills and Computational Thinking practices in digital fabrication activities? (Iwata, et al. 2020)

The scholars identified six factors to consider when incorporating fab lab technologies:

> **Factor 1: Complex and multidisciplinary tasks:** Fab Lab projects were complex and required knowledge and skills of multiple subjects, such as mathematics, physics and art. The projects were difficult for students to complete without dividing and sharing the tasks.
>
> **Factor 2: Designing and making with computers:** Students needed to design on the computers and create the design files with a certain format to use Fab Lab machines. The teachers and the facilitators found using the computers to fabricate artifacts enhanced Information and Communications Technology (ICT) skills.
>
> **Factor 3: Self-directed learning:** The facilitators reflected they tried not to interfere too much in the student's work and fabrication processes. They described themselves as "*older colleagues, with expertise"* and let the pupils work without controlling. The facilitators emphasized the students can be creative because they have autonomy in designing and making processes.
>
> **Factor 4: Reflection during the Fab Lab activities:** The teachers and the facilitators found that presentations enhanced student's metacognitive skills through reflecting on their learning. In addition, the teachers found the reflective practice enhanced the skills of managing goal, time and project which are critical skills of life and career.
>
> **Factor 5: Digital Fabrication activities where trials and errors are encouraged:** The teachers explained Fab Lab activities as the environment where trials and errors are encouraged.
>
> **Factor 6: Fluent and flexible time frame:** Both the teachers and the facilitators found the positive effects of fluent and flexible time frame on pupils' continuous thinking and working process. The pupils focused on one project during the activities, thus their thinking was not interrupted by time, as it often happens at schools. (Iwata, et al. 2020, pp. 9-11)

Milara, et. al reviewed the Fab Lab Oluo creation of their Community of Practice (CoP) (Milara, et al. 2020). Their inquiry provides three recommendations. First, school principals are fundamental for creating school environments where teachers are receptive to new instructional strategies. Next, teacher training was one of the most important events organized during the year. The training serves at least four different purposes: educate teachers, prepare teachers to discuss with other teachers (ensuring continuity in the community), define common goals (joint enterprise) and engage teachers in the community (mutual engagement). Finally, it is important to provide the teachers with the feeling of complexity, trials and errors, and experiencing hands-on activities, which are part of the digital fabrication processes. However, a primary objective was aimed at teachers building some tangible object, both to provide the teachers with the feeling of first-time success and to have something to present and discuss with the colleagues (Milara, et al. 2020).

In the United States, a repeated criticism of the K-12 science curricula is that the curriculum tends to be 'a mile wide and an inch deep' (Schmidt, McKnight, & Raizen, 1997). The Next Generation Science Standards (NGSS) brought major changes, particularly in the areas of curriculum construction, content, pedagogy and assessment (NGSS Lead States, 2013). NGSS left open queries about which practices, crosscutting concepts, and core ideas to feature in lessons and units. Blikstein's Teachers College's Transformative Learning Technologies Lab (TLT Lab), recently gained NSF support to develop a constructionist inspired "technological ecosystem;" that is, a unified curricular activity system (i.e., a system that includes constructionist curricular materials, fab lab technology, and teacher professional development). This promising effort will include NGSS aligned, co-designed with classroom science teachers, constructionist learning units that will enable students to create, test and compare their own ideas about science (Teachers College, 2020). New learning opportunities include posing questions that uncover students' understandings and methods of reasoning, providing adequate time for in-depth dialogue, and the application of open-ended problems. Such an approach can narrow the gap between K-12 science classroom practitioners, the maker education community, and ivory tower scholars through the co-design of scalable NGSS aligned - fab enhanced curricula. However, such an approach can easily go awry, too much of a focus on learning standards can result in pedagogical practices that favor high-stake-testing skills; decontextualized, and fragmented curriculum (Giroux, 2010). The caution is that these often myopic, technical and generic practices repress creativity, silence voice, and strip individuality, hindering the *joie de vivre* of Fab learning.

4 Fab Lab Pedagogy Values

Axiology is the study of, or reflection on, the nature of values and valuation. Axiological principles are expressed in pedagogy and are considered to be a part of the humanization of education. Jarvis Givens' *Fugitive Pedagogy* traces the origins of the term pedagogy:

> Our modern word *pedagogy* derives from an ancient term for a slave who was tasked with teaching. The Greek *paidagogos*, later Latinized as *paedagogus*, refers to a slave of relatively "high status" (if you will) who escorted children to and from a site of learning (Givens, 2021, p. 229)

During his acceptance speech in 1969, upon receiving the AMC Turing Award, referred to as the 'Nobel Prize of Computing,' MIT's Marvin Minsky outlined the cornerstones values for what would become known as constructionist pedagogy:

> In the discussion below, I sketch briefly the viewpoint (developed with Seymour Papert) from which this belief stems. The following statements are typical of our view:
>
> - to help people learn is to help them build, in their heads, various kinds of computational models.
> - This can best be done by a teacher who has, in his head, a reasonable model of what is in the pupil's head.
> - For the same reason the student, when debugging his own models and procedures, should have a model of what he is doing, and must know good debugging techniques, such as how to formulate simple but critical test cases.
> - It will help the student to know something about computational models and programming. The idea of debugging itself, for example, is a very powerful concept-in contrast to the helplessness promoted by our cultural heritage about gifts, talents, and aptitudes. The latter encourages "I'm not good at this" instead of "How can I make myself better at it?" (Minsky 1970, p. 205)

Over a half-century later, rooted in the values of Papert's Constructionism and Freire's Critical Pedagogy, the FabLearn Fellows program, housed at Columbia University's Teachers College, brings together an international community of educators committed to constructionist learning with fab lab tools. Brazilian educational philosopher Paulo Freire's "critical pedagogy" suggests that "teaching that does not emerge from the experience of learning cannot be learned by anyone" (Freire, 1970, p. 30). Freire reasons that too many classrooms at all levels of schooling resemble a 'dead zone' where any vestige of critical thinking, self-reflection, and imagination are quickly extinguished (Freire, 1970, 1976, 1995). The FabLearn Principles include:

- Student-led projects is the type of learning that is personal, engaging and motivating: "*I can learn in my own way"*
- Learning is effective when it is meaningful and relevant: *"I understand why I'm learning this"*
- Learning should be interdisciplinary, just like the world: "*I need to apply multiple types of knowledge to this"*
- Learning should not be focused singularly on curricular content or technical knowledge: *"I can learn how to think, learn, work and create"*
- Learning should be assessed on the final product, but also on the process that led to it: "*My project path is just as important as the final product"* (FabLearn, 2021).

Educators incorporating fab lab learning must attempt to connect the Axiological principles to concrete practices -- to make sense of constructionist values and ideologies in as many evidence-based contexts as possible, identifying which principles can be incorporated into which types of instructional practices. As example, one issue in need of empirical research is what content knowledge students should demonstrate in order to be considered fab lab competent. The question of "what content" cannot be divorced from questions of "who determines that content," pointing toward students' self-guiding and curating their own educational experience and a more interdisciplinary and guiding approach to instruction. Another challenge that needs more exploration and connection is the role and types of student assessment to use with constructionist fab lab learning. Learning assessments are often designed around incremental knowledge building, based on disciplinary content, whereas fab lab learning points toward different kinds of assessment around the "how" and "why" of knowledge building, or the continuous and coherent growth from novice to expert over time (Heritage, 2008). While for some, this article may serve as a starting point in their understanding of constructionism, for others who are already familiar with constructionist principles (in the spirit of Papert) this article may serve as an *object-to-think with*, to reflect upon, while envisaging experiences implementing fab lab technologies into K-12 formal and informal educational spaces.

To conclude, *Mens et manus*, the motto on the MIT official seal, 'mind and hand' was embraced by Papert's Logo team and set out in his seminal text *Mindstorms* which established the foundational underpinnings of the constructionist pedagogy of 'hands-on/minds-on learning' (Constructionism 1.0). As a continuation of the Logo team's pioneering labors, the MIT Media Lab expanded constructionist learning, allowing the user to create, co-create and share online in rich, communal environments for personal expression, creativity, and invention (Constructionism 2.0). Building on these groundbreaking efforts and expanding constructionism beyond coding by turning bits into atoms, fab lab tools offer a robust platform for knowledge construction as students together design, create, and iterate meaningful, digital fabrication-mediated, publicly shareable artifacts. A new paradigm emerged (Constructionism 3.0) in which knowledge construction relies on interdisciplinary collaboration between networks of Fab experts, K-12 educators, practitioners, and students across the globe; this is today's third-generation constructionist platform.

5 An Opportunity for Future Research and Equitable Application

Fab tools offer a robust instrument for knowledge construction as students together design, create, and iterate meaningful digital fabrication-mediated publicly shareable artifacts. An unrelenting issue is digital fabrication implementation with fidelity and equity. The ubiquity of fab tools, in the words of Gershenfeld et al., offer a "unique opportunity to be proactive rather than reactive" toward the adoption of advanced manufacturing tools (Gershenfeld, et al. 2018)." Including "machines that cut precisely with lasers; larger rotating cutting tools to carve things like furniture; automated knives to plot out graphics; molds for casting parts, electronics tools to produce, assemble and program circuits; and scanning tools to digitize objects so that they can be transmitted and replicated" (Gershenfeld, et al. 2018, p. 2). To date, providing high-quality constructionist environments for all children, regardless of their thinking and learning styles, zip code location, race or ethnic backgrounds, has proven elusive:

> The same access gulf seen in the current "digital divide" is being replicated and deepened. Instead of a ubiquitous transformation, with equal access and distribution, what in fact is emerging is a "fabrication divided" (Cooperation Jackson, 2018, paras. 1-4).

Communities of color, without an emergent strategy to move beyond existing models of fab lab-driven K-12 education, risk falling even further behind. Woefully, COVID-19 has wreaked havoc on the lives of millions across the globe—many have died, others are suffering the trauma of economic hardship and food insecurity. The impact of the pandemic is agonizing. By numerous indicators, employment loss, school closures, and disparities in transitioning to remote learning, the pandemic has had disastrous bearings on students in Black, Latinx, and Indigenous communities. McKinsey & Company reports that COVID-19 has positioned "the most vulnerable students into the least desirable learning situations," where "students of color could be six to 12 months behind" resulting in a situation in which "those who came into the pandemic with the fewest academic opportunities are on track to exit with the greatest learning loss" (Dorn, et al. 2020, p. 2). In the intervening time, a collective trauma amplified with the murder of George Floyd, handcuffed, on the ground, with a police officer knee on his neck for over nine minutes and the subsequent wave of Black Live Matters protest has heightened calls for radical solutions to combat systemic racism in K-12 education.

The Center for Universal Education (CUE) at Brookings advanced the concept of "leapfrogging" as a potential answer. An example of "technology leapfrogging" is the smartphone revolution, which put the power of digital technology into the hands of millions of people while allowing countries to skip directly to smartphones without the need to invest in landline infrastructure. CUE concluded:

> We ultimately argue that two of the most important transformations needed are in what children learn—namely, that schooling must focus on a breadth of skills, including but going beyond academics—and how children learn, specifically that schooling must put students' curiosity at the center of the teaching and learning process and make room for hands-on, playful, and experiential learning (CUE, 2018, p. 9).

In such spaces, cognitive, non-cognitive and fab-specific skills can be cultivated and nurtured in alignment with the Fab Foundation mission "to provide access to the tools, knowledge, and financial means to educate, innovate, and invent using technology and digital fabrication to allow anyone to make (almost) anything (Fab Foundation, 2021)." Today, we have a "window of opportunity" to reimagine fab lab learning with fidelity and equity. Creating such spaces for students in communities of color will require a constructionist fab lab "leapfrogging" reorientation of the P-16 education systems, the training and retraining of teachers, as well as redesigning curricula. The small, but growing literature will inform our research efforts.

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