WHITE PAPER

Photo: Scratchfoundation.org

Learning through Digital Play:

The Educational Power of Children Making and Sharing Digital Creations

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The LEGO Foundation

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Executive summary

Background

In order to flourish in a world of rapid change, children need a broad range of holistic skills – skills such as creativity, communication, collaboration, problem-solving and self-regulation – as well as knowledge of academic subject areas and technological literacy. This research paper shows the potential value of learning through digital play to help children build such necessary skills, knowledge and literacy.

For several years now, the LEGO Foundation has been working with research institutions to understand the process of learning through play. The LEGO Foundation aims to build a future in which learning through play enables children to become engaged, lifelong learners, and helps them develop the wide range of skills, knowledge and literacies that will serve them, their communities and society. In this paper, the LEGO Foundation's Bo Stjerne Thomsen has teamed up with James H. Gray from the MIT Media Lab, to look specifically at learning through digital play: the possibilities of digital technologies as a basis for playful learning. Digital play is able to incorporate many different kinds of play, and so it seems to have great potential to provide children with the benefits of playful learning. The subject is timely, since digital play can support children's learning, development and wellbeing during times of crisis or rapid societal change by offering innovative new ways to play, learn and interact.

Three exemplar platforms

This paper takes the form of three case studies, examining technology platforms in three broad categories: creative computer coding, digital games and educational robotics. It looks at the nature of learning through digital play in each of these three different environments. The study is informed by research carried out over recent years by the LEGO Foundation, and is based on literature reviews, as well as interviews with experts on the design and use of the three exemplar platforms and related issues of learning through play.

The platforms examined in this paper are: **Scratch**, **Minecraft**, and **LEGO® MINDSTORMS®**. **Scratch** is a visual programming language and online community, enabling users to create their own animations, games, stories and interactive media.

Minecraft is an open-ended 'sandbox' game that allows users to create, explore and interact in 3D virtual worlds.

LEGO MINDSTORMS is a robotics construction kit that includes motors, sensors and a programmable brick that connects and controls the other parts.

The central theme connecting these platforms is learning through play by making and sharing digital creations.

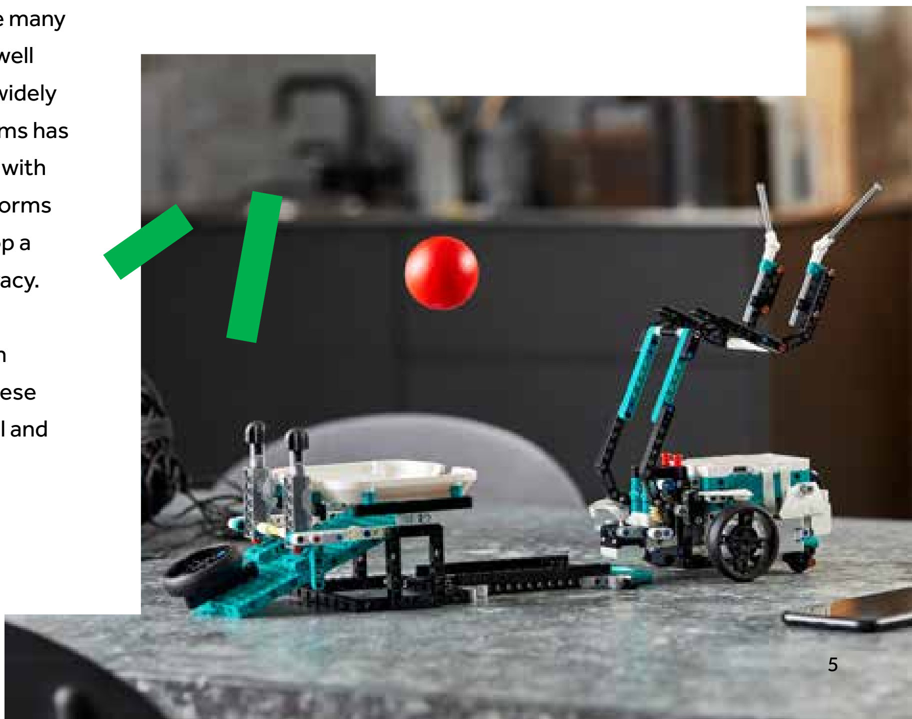
These three platforms have been chosen as the focus of this paper for a number of reasons. Each is an exemplar in its particular area, and has inspired other platforms with similar features. Each makes possible many different kinds of play, and so would seem to be well suited for learning a wide range of skills. Each is widely used in schools. Finally, each of the three platforms has been the focus of a significant body of research, with evidence having been collected on how the platforms are used in learning, and how they help to develop a range of skills, knowledge and technological literacy.

Unlike educational technologies that put users in the passive role of receiving new information, these platforms empower learners with choice, control and agency; tools to create their own content; gentle guidance towards learning opportunities; and the feeling of safety, trust, and freedom that they need to have a playful approach.

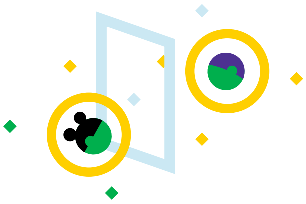
Principles of learning through digital play

It is important to remember that the learning outcomes of using a particular digital environment depend not just on the technology itself, but on how it is used in relation to the '3Cs': the Content that the technology makes available, each individual Child's specific attributes as a learner (for example, their developmental level, pre-existing knowledge and motivation), and the Context that it is used in, including setting (home, community, school), curriculum and teaching approach (Guernsey, 2007).

Based on our analysis of the three technology platforms presented in this paper, review of related research, consultation with other experts, and the utility of frameworks like the 3Cs, the authors have developed a framework (presented in this paper) to guide the design and use of environments that support playful learning through making and sharing digital creations. The framework is a set of design principles that can also be applied to the design and use of any educational environment with similar learning goals.



Agency



Guidance

Creation

Playfulness

Four principles of learning through digital play

Agency: children's ability to make choices, and act for themselves in a self-motivated way – in the digital world this can mean having choices over how to use a technology, where to move within a platform, what to create, and how to communicate with others.

Guidance from other people, or feedback that is incorporated within the digital technology itself.

Creation of artifacts as pieces of self-expression that can be shared. In relation to digital technology, this can mean creating virtual worlds, computer programs, robots, and other digital creations.

Playfulness: the experience of joyful curiosity, experimentation, exploration and creativity.

Learning outcomes and other benefits

This paper shows in detail how technology platforms such as Scratch, Minecraft and LEGO MINDSTORMS are especially well designed to support the wide range of holistic skill development, subject area knowledge and technological literacy that today's children will need.

To evaluate the digital learning environments that it describes, this paper also draws on previous research carried out for the LEGO Foundation, which identifies five characteristics of learning through play that are associated with positive educational outcomes. These characteristics of playful digital learning have been observed across different digital media, and different cultures. The paper shows in detail how the three platforms, in their different ways, give children an experience of play that is: **actively minds-on and engaged**; **socially interactive**; **meaningful**; **iterative** (allowing users to try things out repeatedly in different ways), and **joyful**.

As research evidence shows, users of these three platforms can gain **holistic skills** (creativity, innovation, collaboration, self-regulation and self-expression), **knowledge** in subject areas (with content designed around particular academic disciplines), and **technology skills** such as coding and computational thinking (using approaches from computer science to solve problems across a wide variety of disciplines).

Beyond subject knowledge and technological literacy, the paper describes various broad-based benefits of learning through digital play, especially when it includes making and sharing *digital creations*.

These benefits include:

Student engagement – personally meaningful creative activities are very motivating for students. Guidance from adults and peers supports student agency and sparks engagement with the educational community.

Holistic skills – help students prepare for a dynamic future by developing skills such as creativity, communication, collaboration, problem-solving and self-regulation, as well as becoming good people and productive citizens.

Deeper understanding – children build deeper understanding when they engage through minds-on activity, make meaningful connections, iterate on their ideas, include social interactions, and adopt an attitude of joyful play.

Adaptivity – open-ended digital environments can adjust to suit individual students, specific populations, local communities and academic subjects, and adapt to sudden change such as the need to embrace remote learning during a pandemic.

Bridge school, home and community settings – connections between personally meaningful experiences in different settings help learners draw on their own identities and build on the strengths of their peers, families and cultures.

Authentic assessment – when children make digital creations, the process and product of their efforts can function as authentic assessment by revealing useful information about their knowledge, skills, attitudes and learning.

Recommendations

The paper concludes by considering how adults can facilitate children's learning through digital play. It makes a series of recommendations for educators – teachers and school administrators, but also parents who (by choice or necessity) seek to be actively involved in their children's education. And it makes recommendations for designers on how to apply the four principles – agency, guidance, creation, playfulness – to create digital environments for children's learning. These recommendations are aimed not just at professional product developers, but also at teachers in their role as learning designers, who plan and guide their students' educational activities.

SECTION 1

Introduction

1.1 Introduction

In order to flourish in a world of rapid social, economic and technological change, children today need to develop a broad range of holistic skills, deep knowledge of subject areas and technological literacy. Learning through play can help meet these needs, especially through the development of holistic skills such as creativity, communication, collaboration, problem-solving and self-efficacy (Istance & Paniagua, 2019; Paniagua & Istance, 2018; Parker & Thomsen, 2019; The World Economic Forum, 2020).

The LEGO Foundation aims to build a future in which learning through play empowers children to become creative, engaged, lifelong learners, and to develop the holistic skills that will serve them, their communities and society. Recently, the LEGO Foundation has been working with research institutions to understand the process of learning through play, including the possibilities and limitations of digital learning technologies, and how playful learning in the digital realm can help education systems evolve to meet children's needs, and the needs of rapidly changing societies.

Digital technologies provide an especially promising basis for playful learning. Researchers and practitioners have traditionally recognised many different forms of play, such as physical play, object play and symbolic play, with different kinds of benefits (Whitebread et al., 2012). Digital play can incorporate and extend any of these other types of play, and therefore has the potential to provide a wide range of benefits in terms of children's health, wellbeing, learning and development.

Examples of learning through digital play in elementary classrooms include creative computer coding, playful approaches to using digital games and educational robotics. In this paper, we examine one technology platform in each of these categories; technology platforms which have strong learning design, a solid research base, and evidence of learning, especially in relation to a broad range of skills – specifically, we examine Scratch, Minecraft and LEGO® MINDSTORMS®. The central theme connecting children's learning experiences and outcomes using these platforms is learning through play by making and sharing digital creations.

It is important to remember that the learning outcomes of using a particular digital environment are not the result of the technology in isolation, but rather how it is used in relation to the '3Cs': the Content embedded in the technology, each individual Child's specific attributes as a learner (their developmental level, pre-existing knowledge and motivation, and other characteristics), and the Context of use – including setting (home, community, school), curriculum and pedagogical approach (Guernsey, 2007).

Just as the '3Cs' provides a broad and useful view of children's digital experiences, a holistic perspective can illuminate the various factors that shape children's experience of learning through digital play. Based on our analysis of the three technology platforms presented in this paper, review of related research and consultation with other experts, and recognising the utility of frameworks like the 3Cs (cf., Resnick, 2017; Barab et al., 2010; Gray, 2014), the authors have developed a framework (presented in this paper) to guide the design and use of environments that support playful learning through making and sharing digital creations. The framework constitutes a set of design principles for the platforms that are analysed in this paper, and by extension any educational environment with similar learning goals (eg, those which use digital storytelling tools).

Briefly put, it focuses on

1. **agency as children's capacity to make choices and act with self-efficacy on the basis of their intrinsic motivation,**

2. **how their agency is shaped by the guidance of other people and settings,**

3. **the creation of artifacts as self-expressions that may be shared with others, and**

4. **a playful attitude.**

To evaluate the digital learning environments presented in this paper, we draw on research that identifies five characteristics of learning through play that are associated with positive educational outcomes. Specifically, such learning is :

1. **actively 'minds-on' and engaging,**
2. **socially interactive,**
3. **meaningful,**
4. **iterative, and**
5. **joyful**

(Zosh et al., 2017).

These characteristics of playful digital learning have been observed across many different digital media and cultural settings, for example in both the United Kingdom and South Africa (Marsh et al., 2020).

In summary, technology platforms such as Scratch, Minecraft and LEGO MINDSTORMS are especially well designed to support the wide range of holistic skill development, subject area knowledge and technological literacy that today's children will need – but only if they are used in particular ways, which support agency, provide guidance, enable creation and nurture playfulness. These platforms, and other digital learning environments, can be evaluated in terms of whether children's experience of them is cognitively active, socially interactive, meaningful, iterative and joyful.

1.2 Methodology

As background, this paper has been informed by research carried out over recent years by the LEGO Foundation, bringing together insights from a combination of literature reviews, large-scale surveys, ethnographic in-home studies, and interviews with leading experts on related topics. Specifically, for our analysis of learning through digital play, the authors carried out literature reviews of three digital platforms that were seen to be well-suited for learning a wide range of skills, using keyword searches of academic databases (e.g., ' Minecraft ', ' learning outcomes ', ' educational technology ', ' playful learning ', etc.) and recommendations from colleagues.

Drawing on professional networks, we selected a set of experts in the design and use of the three exemplar platforms, and related issues of learning through digital play. We interviewed these experts about platform design, user experience, learning outcomes, enabling factors, and related topics.

1.3 Design principles: agency, guidance, creation, playfulness

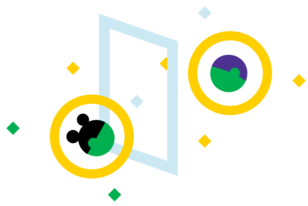
We now discuss in detail a framework of design principles for learning through digital play, focused on agency, guidance, creation and playfulness.

Agency relates to the need for self-directed, lifelong learning in a rapidly changing world, and the widely accepted child development theory and educational practice that emphasises child-centred approaches (Piaget & Inhelder, 1969; Vygotsky, 1978; Forman et al., 1993; Montessori, 1972). Agency reflects the personal motivations of each individual learner, and their ability to make choices and maintain control over their own activities. Notably, it is a concept with a long history across multiple scholarly disciplines, including child development (Bandura, 2008), social sciences (Lippke, 2020), and literary criticism (Burke, 1945). Digital technology can support children's agency by providing choices over how to use the technologies, where to move within a platform, what to create, and how to communicate with others (Blumberg et al., 2013; Johnson & Christie, 2009; Sullivan, 2011).

Furthermore, agency is about being in charge of yourself and shaping the world: about the ability "to influence intentionally one's functioning and life circumstances" (Bandura, 2008). As a developmental goal for children, it means supporting their capacity for *self-efficacy*, *self-regulation*, *forethought* and *planning*, and other aspects of *executive function* – qualities that are associated positively both with academic achievement and life success (Harvard Center on the Developing Child, n.d.). As an educational goal, it is central to pedagogies that are self-paced, self-directed, student-driven, and lifelong – approaches that are increasingly important for success in the future (World Economic Forum, 2020) and for navigating through a complex and uncertain world (Paniagua & Istance, 2018). As a design goal for environments that support learning through digital play, it means providing users with choices, multiple entry points to a topic, and control over their own activities and how they use technologies.

Agency is also at the heart of narrative understanding. It's in the stories that children tell themselves about themselves, which shape their self-image and self-esteem, as well as the grand cultural narratives that determine how individuals and groups are empowered to take more or less effective action in a society. It's also part of the many narrative forms in between, including the stories that children hear from parents and peers, and the ones they tell, otherwise communicate, or enact amongst themselves in their play.

Narrative is one of the primary ways in which human beings make sense of the world and their place in it (Bruner, 1992), and so it makes sense that children are immersed in stories throughout their daily lives. Virtually all stories are about agency in one way or another: a main character or *'agent' acts* in *setting* – real or imaginary – with some *goal* in mind – predetermined or emerging – using the *means* available in that world (Burke, 1945). Each of the digital platforms discussed below lets children experience agency, often in the process of consuming and telling stories of various kinds.[1]



Guidance relates to nurturing, supporting, encouraging, scaffolding, gently directing, offering feedback, or otherwise shaping a child's agency, in a way that leads toward positive outcomes. It can be a kind of wisdom or helpful support offered by adults, peers, or aspects of the learning environment such as access to physical

1 in the conclusion of the paper, we return to this topic by considering tools for digital storytelling.

materials, and technology design (eg, tutorials, sample projects). As with agency, it is a concept with roots in diverse scholarly disciplines, such as developmental science (Weisberg et al., 2016), psychology (Vygotsky, 1978) and anthropology (Rogoff, 1990). Digital technology often incorporates guidance and feedback, which can positively affect learning when students can use it to make iterations in what they create, or otherwise improve the quality of their work (Clark et al., 2016; Gee, 2008; Kearney & Schuck, 2006; Sullivan, 2011).

As a developmental process, guidance builds on our innate sociability, natural use of modelling and imitation, participation in social activity, and other common processes of socialisation and enculturation – "the varied ways that children learn as they participate in and are guided by the values and practices of their cultural communities" (Rogoff, 2003, p. 283). This includes a child being in their "zone of proximal development", where they develop skills by performing at a higher level, with the aid of their guide, than would be possible without it (Vygotsky, 1978).

The concept of 'scaffolding' highlights a similar process whereby a guide's support of a child's performance is gradually withdrawn until it is no longer needed. As a pedagogy, it is exemplified in 'guided play', in which the adult's role is to "create a play context, with or for children, with an embedded learning focus [and then] observe, build on and extend children's thinking and ideas" (Jensen, et al., 2019, p. 15). As technology design, it is also a system of affordances (Gibson, 1966; Norman, 2013) governing the range of possible user activities, *feedback* in the form of potentially useful information to be used for iteration, and *persuasive technology design* (Fogg, 2003) that shapes users' activities (potentially at the expense of agency). In all cases, the guidance that is most useful for promoting holistic skills avoids simply directing students to correct answers or learning particular facts, but rather supports and extends their agency.

Creation is an essential aspect of *playful learning through making and sharing digital creations*, which reflects the widely documented educational value of learners creating content. This theme is present in the practice of portfolios as formative assessment, the educational arm of the maker movement, and various forms of project-based learning. From a child's perspective, creating projects or other content is perhaps the most salient goal in engaging with Scratch, Minecraft, LEGO MINDSTORMS, or related platforms.

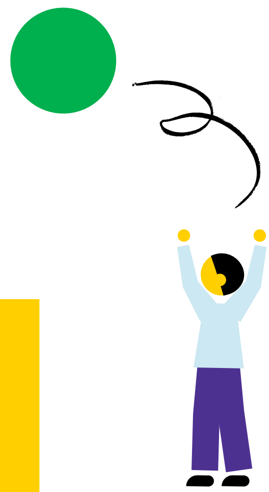
Constructionism is a theoretical perspective that describes the educational value of this approach. Starting with Jean Piaget's observations of how children naturally construct their own knowledge through interaction with the world (as opposed to passively receiving information given by others), Seymour Papert observed the intellectual potential of building this knowledge while constructing sharable artifacts, which then become the basis for social discourse and self-reflection (Papert & Harel, 1991). With an observable product at hand, children can examine its features, discuss it with others, assess its quality, plan improvements, consider their capacity to make desired changes, and attempt iterations. Throughout the process, they can also reflect on what they created, how they did it, what it means to others, and what they learned. In short, constructionism highlights the way that creation of content can express personal meaning, afford self-reflection and social interaction, and provide feedback for the iterative development of the project and the child's deepening knowledge.

In terms of creative substance: what 'content' do children create using these platforms? Certainly they create digital artifacts in the form of virtual worlds, computer programs and multimedia projects, and physical artifacts in the form of robotic devices of various types. As the constructionist perspective makes clear, they also build personal knowledge, interpersonal relationships, and shared meaning through their reflection and conversation. Below we examine some of the specific kinds of content that can be constructed with Scratch, Minecraft and LEGO MINDSTORMS, and in the process, how children can construct knowledge through self-reflection and social discourse – that is, learn.

Finally, ***playfulness*** emphasises the quality of learners' inner experience, emotions, and attitudes as they engage in learning through digital play. By contrast, a student may have a strong sense of agency, the benefit of guidance from others, and create a high-quality, personally meaningful project, but with an unhappy emotional experience (e.g., a resentful attitude towards the assignment), and very little playfulness. While this kind of experience can be productive, it may not provide the benefits of joyful play.

Playfulness is the experience of joyful curiosity, experimentation, exploration and creativity which is most likely to emerge in a context of perceived safety (e.g., the absence of high-stakes consequences). It can include loud, expansive happiness and quiet, focused satisfaction. It may be similar to the psychological state of 'flow' in which individuals are so deeply absorbed in an activity that they lose track of time. Or it may be the kind of 'hard fun' that comes from sustained, passionate work on a personally meaningful project (Papert, 2002; Resnick, 2017).

As a psychological state, playfulness requires a sense of trust in the social and physical environment. To be playful, children need to feel safe (Winnicot, 2005; Vytotsky, 1978; Garvey, 1990). In physical settings this is achieved with tools such as fences dividing playgrounds from highways, or rules limiting hard physical contact in sports. In digital environments designed for educational uses, developers work to establish safe social behaviour with written codes of conduct and adult leaders who model and support these social norms. They also have formal and informal rules determining which adults may actively participate with children.



SECTION 2

Platforms

In this section, we consider how three technology platforms support learning through digital play, by examining user experience and learning outcomes. The three platforms are **Scratch**, a programming language and online community, the open-ended 'sandbox' game/ virtual world of **Minecraft**, and **LEGO® MINDSTORMS®** robotics construction kits. Each of these platforms enables many different kinds of play, helping children to develop a wide range of skills and knowledge. Each one is also an exemplar that has inspired other platforms with similar features.

We focus on these exemplars because they support activities that are actively engaging, socially interactive, meaningful, iterative, and joyful – the five characteristics of playful learning. Also, they have each been the subject of a significant body of research that documents their role in children's learning, and they are used in schools. Unlike educational technologies that put users in the passive role of receiving new information, these platforms empower learners with choice, control, and *agency*, tools to *create* their own content, gentle guidance towards learning opportunities, and sufficient safety, trust, and freedom to adopt a *playful* attitude. As research evidence shows, users of these three platforms can gain holistic skills, domain knowledge and technology literacy.

2.1 Scratch

Scratch is a visual programming language and online community designed for young people from 8 to 16 years old, enabling them to create their own animations, games, stories, and interactive media. Launched in 2007, it now has more than 50 million registered users. The Scratch community is fundamental to fostering engagement and learning by providing open access to millions of peer-created projects, their underlying code, and multiple ways for Scratchers to communicate with each other. This platform also supports new kinds of interactions in the social and physical world using features such as video sensing, text-to-speech, and a language translator, and connections to robot construction kits, inexpensive miniature computers, and novel data input devices.

Scratch is used in schools, homes, and community centres around the world. Children can choose or draw images, and then bring their project to life by snapping together colourful blocks of code, like snapping together LEGO bricks in the physical world. This supports children in going beyond interacting with pre-made games to creating and sharing their own content, in the form of "projects".

Photo: Scratchfoundation.org

Learning design: agency, guidance, creation and playfulness

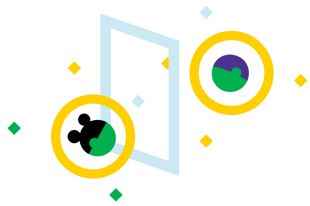
Agency. Scratch supports children's agency by providing the freedom to choose what they create, and the media used in their creations. Children put together coding scripts to control images and sounds that they create themselves, import from external digital sources, or remix from other projects shared in the Scratch community. They can also copy programming code from other projects as part of the remixing process.

While this sort of freedom and control tends to support children's sense of agency, some children may feel unsure about what they want to create or how to do it. To this end, Scratch is designed to provide creative constraints. Like LEGO bricks, there are a number of ways that Scratch programming blocks can be combined, and their shapes suggest how the blocks fit together. Children can experiment with putting blocks together (and taking them apart) in different ways, with none of the 'syntax errors' that are common in other programming languages. In this way, Scratch is designed to provide a kind of happy medium of choice and control that will best support users' agency and capacity for self-direction.

Creative drive: what motivates Scratchers? Agency, as the capacity to influence one's self and surroundings, is intrinsically motivating, and fundamental to the design of Scratch. In all the ways described above, children have a high degree of freedom and control in what they choose to create and the processes they use. These qualities are the basis of agency.

Social connection is another key motivation for Scratchers, and is explicitly supported by the design of the platform's online community. Scratchers can easily share their projects with the community and receive feedback from their peers in the form of comments and remixing. This social environment is the context in which agency is expressed, validated and developed. In this way, both self-expression and social connection drive agency.

The desire for *agency* (eg, self-expression) and social connection are basic human drives that stand in contrast to the artificial systems of rewards and punishments that are often designed into educational software in the form of game mechanics (eg, levels, points) or formal assessments (eg, quizzes, grades). Scratch is designed to support intrinsic motivations of self, identity and social relations, more than the extrinsic motivations of points, badges and levels attained. In the relatively open-ended environment of Scratch, children's natural desire for self-expression and social interaction can emerge and drive the creation of content and a stronger sense of agency.



Guidance. Although Scratch is an open-ended creative tool, it provides several forms of guidance to help children as they learn to create with code. The programming environment does this by providing features such as colour-coded programming blocks that snap together like puzzle pieces to help beginners figure out how to build functioning programs. It also provides relatively sophisticated programming logic for individuals who have become more advanced coders. In this way, Scratch is an educational environment with "a low floor, high ceiling, and wide walls" in terms of programming skills (Resnick, 2017). It also facilitates motivation and engagement for a wide range of children, by providing tools to import multimedia content of a child's choice. Likewise, remixing existing projects is a way to quickly engage with code that works well, and learn from making adaptations.

Just as children learn a spoken language through social interactions within a community, children learn the language of Scratch by exploring and participating in the Scratch online community (Roque et al., 2016). Novices can explore a vast library of existing projects to consider what they might like to build, and how to code it. They can connect with current community interests by consulting lists of 'What the Community is Loving' and 'What the Community is Remixing'. Alternatively, they can choose content curated by the Scratch staff ('Featured Projects' and 'Featured Studios'), or particular peers ('Projects Loved by Scratchers I'm Following').

Like social media generally, the human connections in the Scratch community are driven by user feedback and moderator decisions within the platform affordances. When members click 'heart' or 'star' on a project page, it provides encouragement to the creator of the project. Over time, children take feedback from the community into account when deciding what types of projects to create and how to present them to the community. Written comments can add more detail to the overall valence of the assessments if peers offer specific details of what they like and do not like, or what they suggest changing.

Remixing provides guidance by offering a kind of template that others can read, experience, explore, and then modify as they wish. By examining programming code in detail, with the option of altering the code, Scratchers can explore the structure and function of a set of code, in the context of a particular project experience chosen by them. This is similar to the process of learning a cultural practice (eg, household chores, pickup basketball, babysitting) as a legitimate peripheral participant who is well positioned to grasp the overall shape of the practice, understand the context and purpose of learning particular component skills, and (over time) take on increasing levels of responsibility and core tasks (Lave & Wenger, 1991). Scratchers experience a project – whether through game play, interactive lessons or viewing an animation – and then explore and modify the source code underlying the project, as a way of gaining a deeper understanding.

Scratchers have created a variety of collaborative activities that are both enjoyable to experience and educational. These include contests, communities of interest (eg, Anime), and role-playing games. In developing 'multi-animator projects', or MAPs, Scratchers have devised a way to work collaboratively on the same project, by taking turns doing the coding. Like other examples of learning through participation, this interaction pattern is well suited to learning a set of skills, knowledge and dispositions oriented around a valued product (Rogoff et al., 2003).

Finally, Scratchers can receive guidance from knowledgeable adults. In the Scratch community, they can view tutorials when they want to learn a particular approach, and can see inside others' projects to get ideas. When Scratch is used as a part of classroom learning, of course, students receive guidance in whatever ways their classroom culture affords, including through teacher feedback, group work or observing peers.

Creation. Scratchers primarily create on-screen animations, games, stories and interactive media (and sometimes off-screen interactions using various extensions and input/ output devices). To illuminate how creating this content can support learning, we imagine the role of reflection and conversation in making a game.

Games are inherently interactive, and making a successful one requires imagining an engaging environment and the role of the player. A Scratch game designer might start by reflecting on their own previous game-playing experience, playing new games with their design goal in mind, and examining the underlying programming code to assess the complexity of the task and their capacity to complete it. Whether coding their game from scratch or remixing an existing game, the designer is likely to pause at many points to test game play, assess the experience, and make changes. This iterative process involves reflection on the quality of the game play, the structure of the code, and the designer's strategies and ideas. With clearly visible code and what it produces on screen, they could discuss any of these issues with others nearby or online. When the designer decides the game is ready, they can 'share' it in the Scratch community, and receive a host of feedback. Additional, in-depth conversation and reflection may be pursued by the designer, or guided by a teacher or parent. Experimental software exists to facilitate this sort of reflective process by auto-generating a video summary of Scratchers' projects, and how they have participated in the online community over months or years (Dhariwal, 2018).

Playfulness. The Scratch community provides the necessary safety, trust and freedom to support playful attitudes among participants. Informal social norms and formalised Community Guidelines encourage values such as being "respectful, constructive and honest" (Scratch, n.d.). Moderators model and enforce these kinds of pro-social norms to help provide the psychological safety needed to experiment and explore (Lombana-Bermudez et al., 2020). Over time individuals build trust among each other and the community overall. By providing freedom from harm, a welcoming community and a wide array of multimedia content and tools, Scratch offers children the opportunity to openly play with materials, ideas and one another.

Learning environment evaluation: five characteristics of learning through play

How does using Scratch support children's experience of the five characteristics of learning through play? By design and in practice, the user experience is actively engaging, most fundamentally through the creation of projects. While it is possible to join the Scratch community simply as a 'consumer' – observing and playing with others' projects – the essence of Scratch is to engage as a creator by combining, recombining, and making one's own projects using the tools of coding and multimedia that Scratch provides. The stated goal is to "nurture a new generation of creative, systematic thinkers comfortable using programming to express their ideas" (Resnick et al., 2009, p. 60).

Likewise, *social interaction* is at the heart of Scratch, because it is both a programming language and online community. Scratchers can share their projects with the click of a button, making them available for viewing and interaction. Members can also examine the underlying code, and remix a project to create their own adaptation, with attribution automatically documented. Community members comment on each other's projects, and apply stars or hearts. From the start, Scratch was designed to support creative collaboration, "coming together to design, build, and invent shared artefacts", which has resulted in formats such as remixing projects and ideas, creating supportive spaces for communities of interest, and coordinating 'Multi-Animator Projects (MAPs)' (Roque et al., 2016, p. 241).

Like sociability, *meaningfulness* is a core design principle of Scratch (Resnick et al., 2009). This is expressed in terms of diversity and personalisation. Scratch supports a wide range of project categories (eg, stories, games, animations and simulations) to engage children with a wide range of interests. Personalisation is supported with tools for users to import and edit content across various audio-visual media, as well as to create their own drawings and animations. With these tools, Scratchers can easily represent personally relevant content and themes from their everyday lives, and connect with others who share their interests.

Iteration is also a core design principle of Scratch. As mentioned above, Scratch programming blocks are easy to put together and (importantly) easy to take apart, just like LEGO bricks, so that children can start quickly and easily make changes. Children learn how well their code operates by running it and observing the results, which facilitates the process of testing and trying out what works. The capacity to remix projects, and the cultural norms valuing it, combine to make tinkering with code a fundamental feature of the Scratch community. While the materials afford iteration, many users need the social support of the Scratch community as well.

Likewise, *joy* is fundamental to the Scratch user experience, defined broadly as a positive emotion such as the pleasure or satisfaction that accompanies the process of using Scratch, or when reflecting on the experience (Zosh et al., 2017). It may also be stimulated by curiosity, or emerge from the balance of fun and challenge, akin to the state of 'flow' (Csikszentmihalyi, 2014). Joy is the quality that helps transform work into play. While it may not be present in every moment, it is inherent in the sort of intrinsic motivation and self-directed learning that is supported by Scratch.

Learning outcomes

The benefits of using Scratch encompass three elements: 1) *holistic* skills and development in domains such as creativity, innovation, collaboration and self-expression, 2) *technology* skills such as coding and computational thinking, and 3) *knowledge* and understanding in subject areas that are the focus of Scratch projects.

Holistic skills are fundamental to Scratch. For example, in a study of kindergarten-to-9th-grade programming classes, teachers reported creativity as being one of the general, '21st-century skills' that their students gained in addition to computational skills (Nouri et al., 2020). A study of Scratchers who emerged as leaders over 1–7 years of participation revealed how the Scratch community supported "well-rounded development" such as "gaining skills to express themselves, connecting with others and eventually seeing ways that they could apply these skills to help others and pursue their goals" (Roque & Rusk, 2019).

Gaining technology skills in computer programming and the more general practice of computational thinking (CT) is the most widely studied learning outcome of using Scratch (Zhang & Nouri, 2019). There are many definitions of CT among scholars, but essentially it is about using approaches from computer science to solve problems across a wide variety of disciplines (Wing, 2006), or "thinking like a computer scientist when confronted with a problem" (Grover & Pea, 2013, p. 39). A commonly cited framework for understanding CT includes three components: concepts (eg, sequences and loops), practices (eg, debugging and iterating) and perspectives (eg, questioning and self-expression) (Brennan & Resnick, 2012). A recent review of 55 studies investigating what and how children learn with Scratch (Zhang & Nouri, 2019) found evidence of CT learning across all three components and several related categories (eg, predictive thinking).

Other knowledge gained by using Scratch is as varied as the subjects of Scratchers' projects, whether for school assignments or for Scratchers themselves. For example, a middle-school student who used Scratch to produce a guided tour of the layers of the Earth learned important geological concepts while also developing computational skills (Resnick & Rusk, 2020). In a two-year study of 107 elementary school students who created Scratch projects in various subject areas, learning outcomes were reported in art and history as well as computational concepts and practices (Sáez-López et al., 2016).

Photo: Scratchfoundation.org

Related platforms

As a pioneering, educational programming environment, Scratch has inspired both non-profit and commercial organisations to develop other educational block-based coding languages. The children's media review site Common Sense Media currently lists 41 options for learners aged 4–15 years in its list of Cool Coding Apps and Websites for Kids and 33 platforms for school use in its list of Best Coding Tools for Elementary (cf. Rich et al., 2019 for a related review of platforms that support learning through coding). These products represent many different approaches to children's motivation, activity structure and sharing of creations.

ScratchJr is an *introductory programming language* designed around the developmental needs of younger children, aged 5–7 years (Bers, 2018), developed jointly by the DevTech research group at Tufts University and the Scratch team at MIT. It is inspired by Scratch, which is aimed at children aged 8 and upwards, and children can use it to create their own personalised projects by assembling colour-coded programming blocks to manipulate multimedia content including drawings, graphics and sounds. They can make their own art, take photographs and record audio. To meet the needs of young children, ScratchJr offers a simplified set of blocks, slower pacing to facilitate the noticing of cause-and-effect relationships, and left-to-right connections between blocks to match the syntactic patterns already familiar to children who are learning to read in English and many other languages (Bers, 2018).

Projects can be shared with a parent or teacher, for example via email, but (aligned with the developmental needs of young children) there is no online community. A supporting website provides free learning resources for parents and educators.

ScratchJr is designed to provide children with an experience of play and literacy. As a kind of *playground*, it is intended to support holistic learning across cognitive, social, motor and linguistic domains. As *literacy*, it engages children in the use of a symbolic system for self-expression and communication (Bers, 2018). How each child's experience is shaped by the content and context has been explored in several ways. For example, a special PBS (Public Broadcasting Service) version of the ScratchJr app provides a library of characters and settings from popular children's television programming, which children adapt for their own purposes.

In schools, ScratchJr is used to support 'coding as another language', with benefits in relation to traditional language learning, computer coding as a 21st-century literacy, and computational thinking as a broader cognitive skill, with the potential for applications beyond computer programming (eg, sequencing, repeat loops). Several studies have shown that elementary school students can learn foundational coding concepts with ScratchJr in a classroom context (Strawhacker & Bers, 2019), and have improved outcomes with the help of flexible and responsive teachers (Strawhacker et al., 2018).

2.2 Minecraft

Minecraft is an open-ended 'sandbox' game that allows users to create, explore, and interact in 3D virtual worlds composed of landscapes, buildings, machines, creatures, characters, other players and sound. A Minecraft world is built from colourful cube-shaped blocks that can be combined in nearly infinite ways. Like a first-person virtual reality videogame, users participate by controlling their own character, who can move around the world and take various actions, such as 'mining' stone to make a house, building simple electronic circuits to move pistons or turn on lights, and trading materials with computer-controlled 'non-player characters' (NPCs), and expressing themselves with various gestural 'emotes' such as waving, pointing or clapping. There are two primary modes. In survival mode, users work to gradually build resources to survive and thrive in worlds populated with dangerous creatures. In *creative* mode, users exist in peaceful worlds with unlimited access to all resources with which to express their creativity.

The underlying software allows users to create new worlds that are accessible to a few local friends or the entire global Minecraft community, design a private world for themselves, and modify the functionality of worlds to meet particular goals. For example, there are modifications to the software, or 'mods', tailored to exploring topics such as dinosaurs, forestry and sustainability, animals, geology, outer space, mechanics, electronic circuitry, computer programming and even quantum physics.

Minecraft: Education Edition adds school-related features to support teaching, learning and assessment.[2]

2 For clarity, we discuss Minecraft: Education Edition in terms of its unique educational features compared to 'creative' and 'survival' mode in the consumer versions of Minecraft. In fact, Minecraft: Education Edition can be played in 'creative' and 'survival' mode, which opens up an even wider range of options for educators and learners.

It accommodates whole-class and small-group collaborative learning by allowing up to 30 simultaneous players in a world. Students can document their projects and reflect on learning using *camera* and *portfolio* features, which also provide efficient sharing with their teachers who might read a PDF document or view a 60-second narrated video walk-through instead of attempting to navigate a complex 3D world for the sake of assessment. Teachers can communicate assignments and guide student activities using chalkboards with written text, and non-player characters (NPCs) who interact with students using pre-programmed dialogue. They can also decide on what parts of a world students can access, and some of their abilities (eg, flying). Academic subject matter may include any topic the teacher chooses, using pre-built worlds or making their own. Computational thinking is supported with built-in programming languages that control a robot-like companion *Agent* who performs the tasks described by programming commands. Administrative support includes secure sign-in, teacher tutorials, community, mentors and tech support.

Learning design: agency, guidance, creation and playfulness

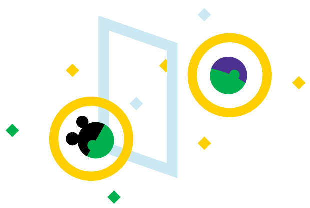
Agency. Minecraft agency takes on different characteristics in each of the three modes: survival, creative, and educational (Education Edition). In *survival* mode, players are free to act in any way that the world affords, but they quickly discover the need to protect themselves against predators with a shelter, and other strategies. This fact reminds us that agency is both an internal perception of self-efficacy and also the capacity to shape one's world. In this case, players' agency is constrained by the need to survive, and to craft most possessions from raw materials. As its name implies, this mode affords a kind of agency akin to real-world human experience in historical periods and current cultures where people's choices, opportunities and control orient largely around basic survival needs.

In *creative* mode, agency is potentially much more expansive than in survival mode. Players can attempt virtually any action using a full supply of tools and materials provided in Minecraft, and if they fail, adjust their approach as frequently as they wish. This opportunity for iteration allows for a playful approach and the development of relatively sophisticated skills as a result of repetition. With a broad palette to work with and safe boundaries, players are especially free to engage in self-expression, exploration of new topics, development of complex worlds over long periods of time, and interactions with peers in many different settings. Likewise, creative mode affords a wide range of peer interactions and forms of collaboration as individuals develop shared goals and build worlds that they can cohabit.

Agency in Minecraft: Education Edition depends on how educators adapt worlds for particular pedagogical and curricular goals. This could range from a highly constrained world in which students' actions are limited to a narrow topic, in order to be assessed on progress towards learning goals, to an expansive world open to any activity, with additional educational opportunities afforded by the unique features of the Education Edition. These features include educator-created non-player-characters that can inhabit roles such as guides or information sources; cameras and portfolios that allow students to document their activities, project development and learning, and chalkboards for communicating in-world. Using Code Builder (a complementary programming language in the Education Edition), students can control their virtual robot using a visual programming language similar to Scratch. The associated agency ranges from being virtually non-existent to vast possibilities akin to what is afforded in the creative mode, further enhanced with educational features. For example, students could use the camera and portfolio features to tell stories of their accomplishments in ways that communicate their strengths to parents, teachers and potential future collaborators, and empower themselves with concrete evidence of their skills.

Creative drive: what motivates Minecraft players? As an intrinsic form of motivation, agency varies in form across the different modes of Minecraft, as discussed above. Like Scratch, Minecraft supports the motivating quality of social connection, but in a somewhat different way. Whereas most work in Scratch is pursued by individuals working alone – with some creative exceptions (Roque et al., 2016) – who then share their projects with a community, in Minecraft, players can easily collaborate on projects in a world, and fluidly adjust how they work together or apart as projects progress. This opportunity for working directly together makes *collaboration* stand out as another kind of social motivation, in the same way that peers seek out ways to participate in activities with each other.

Education Edition worlds situated in a classroom or other formal learning setting are also likely to provide academic motivations, ranging from the fun of group projects and (virtual) field trips, to competitive grading, to pride of accomplishment (eg, through a portfolio of projects). Teachers who use a learn-by-teaching model could promote agency among students who share their knowledge by teaching peers. In a similar way, teachers and students have reported a kind of para-social motivation as students interact with the *Agent* robot sidekick included with Code Builder. As Sara Cornish from Minecraft at Microsoft observed, "[it] gives the students a sense of agency and confidence… they empathise with this little golem and like having the support character, so they're not feeling like they're doing this all by themselves" (personal communication, 21 February 2020). Minecraft-based programs such as *Block by Block* extend in-game agency to local communities who use the platform to address their desire for real-world improvements.



Guidance. In Minecraft, guidance takes the form of in-world participation with peers, external materials such as video tutorials and walk-throughs, and written resources such as websites and books. In all these ways, guidance in Minecraft is closely aligned with user agency – actively sought, or naturally occurring during in-world activity. The platform itself provides little explicit guidance, but rather guides user activity by virtue of how each element functions as opportunities for trial-and-error learning – for example, the properties of 'slime blocks', 'redstone' and 'pistons'. Just as significantly, users learn from peers, either in-world or in other settings.

Overall, then, guidance occurs naturally, as it does during real-world activities that are not intentionally designed to function as formal or informal educational processes. Users learn skills from peers as they are needed in the course of joint activity, through imitation, perhaps with text-based chat providing additional explanation (voice chat is also possible with additional mods, but is not built into Minecraft). By contrast, educationally oriented worlds built using the Education Edition are often specifically designed with a focus on curricular goals, and are used in the context of related classroom instruction. Forms of guidance in these worlds vary as widely as pedagogical approaches.

Creation. In an immersive virtual world like Minecraft, every new construction is immediately available for the player to experience, and supports related reflection and conversation. Primarily, players break or build block-by-block directly in front of their avatar, and can see the effects of their actions. Other actions, such as building an electrical circuit of lights, switches and pistons, might involve a delayed experience until the system is functioning. In either case, the builder and peers can reflect on the newly created content, assess its effects, and choose their next steps. They can also discuss these topics via text chat, voice chat if enabled, or in channels external to Minecraft. If they are building in Education Edition, the players have additional tools to facilitate reflection and critical dialogue, namely through cameras and portfolios, and perhaps educator-created resources such as tutorials, mentors and classroom activities. In either case, the educational value of reflection and discussion can be further enhanced with external resources in print and online.

Playfulness. Like Scratch, Minecraft has a set of rules "to keep our community a positive, safe, and enjoyable place for everyone" (Minecraft, n.d.), which likewise helps provide the necessary conditions for *playful* attitudes to thrive. Minecraft also supports a wide range of activities and content creation, which gives users the opportunity to explore, experiment and play freely. However, the breadth of freedom varies across modes, from the vast freedom to build and iterate in creative mode compared to the necessity of dealing with dangers in survival mode. Freedom and playfulness may also be constrained in academic uses of the Education Edition that include high-stakes grading.

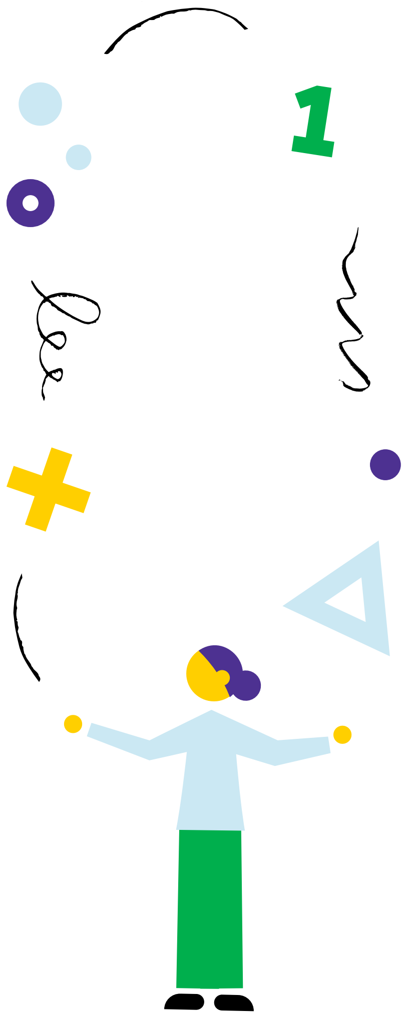
Learning environment evaluation: five characteristics of learning through play

How does using Minecraft support the five characteristics of learning through play? First, the experience of building, exploring and interacting in a virtual environment is fundamentally about *active engagement*. Multiple modes and versions of Minecraft result in at least three varieties.

In *survival* mode, players must quickly find and use resources to meet basic needs (eg, shelter, food) before embarking on additional projects that may involve imagining, planning, systematically acquiring resources, building, and interacting with NPCs and other players. In this mode, players need to be intensely engaged – hands-on/ minds-on – in order to survive and thrive in a complex and often hostile environment.

In *creative* mode, acquiring resources involves a visual or text-based search of inventory menus rather than mining and crafting in the virtual world itself (eg, searching for 'iron block' vs. digging iron ore and transforming it into a block). In the absence of (virtual) life-and-death decisions, players are free to engage with the Minecraft world, based on their own intrinsic motivation or factors external to the game (eg, peer collaboration or competition, teachers' assessments). Nonetheless, engagement may be extremely active – eg, in the process of imagining and creating a virtual project – but it may also be relatively passive, as when a player wanders through a pre-existing world created by others.

In the Education Edition of Minecraft, students often engage with academically oriented content in worlds designed to support only activities that are related to a particular lesson. In other settings, such as in a 'build challenge', they may have the freedom to engage in more open-ended exploration and creation, with minimal facilitation by a teacher (Cornish, personal communication, 21 February 2020).



Social interaction is another key aspect of the Minecraft experience. Players can use text to chat in real time, and make written signs that persist in their worlds. Using their avatars (virtual bodies), players can also take advantage of non-verbal communication including gesturing, physical proximity, and acting on the environment in visible ways (eg, making or breaking objects). Coordinating joint attention and activity in this way affords a wide range of communication and collaboration inside virtual worlds. In addition, players in the same location (whether the classroom, home or elsewhere) can interact face-to-face during their Minecraft activities. Beyond the immediate setting, players, peers, teachers and others interact in relation to game activity for various reasons, including academic assessment of assignments, informal socialising with peers and learning new techniques. These interactions are often facilitated by recordings of in-game activity, walk-throughs and commentaries, which are available on YouTube or in the Education Edition (Niemeyer & Gerber, 2015).

The *meaningfulness* of Minecraft activity is likely to vary widely, depending on the context. Individuals driven by their own intrinsic motivation or relationships with friends and family to play Minecraft are likely to find meaning inherent in their activity. The ability to create and develop one's own world, design an avatar, and interact with others in that context are key to meaning-making for young players. Students who are required to engage with the Education Edition may experience more or less meaning, depending on the pedagogical context.

Iteration is possible in Minecraft, but more cumbersome than in coding environments such as Scratch. Using the core set of available tools, players build one block at a time even in creative mode, and in survival mode may need to expend significant effort acquiring building materials.

One exception is in the Education Edition, where the Code Builder tool allows players to write computer programs that automate activities through an *Agent* that appears next to the player as a small robot-like character. Using user-friendly block programming languages (Tynker and Microsoft MakeCode) players can, for example, instruct their *Agent* to plant a row of seeds for a garden, build a wall, or perform other repetitive tasks.

Another exception is the use of programming tools to edit the Java code in Minecraft Java. For individuals with even modest coding skills, creating mods results in new versions of Minecraft with features customised for a specific purpose such as research, learning subject matter (eg, chemistry), or exploring what is possible in the design of virtual worlds. While programming languages can support the iterative process in Minecraft, players are always free to make incremental improvements to a project, given the necessary motivation and awareness of how to make changes.

Joy in Minecraft can emerge from the spark of curiosity, open-ended exploration, and pride of creation common in the Minecraft experience. Creative mode is especially well suited to afford the joy associated with intrinsically motivated, self-directed, playful experience. In survival mode, the fundamental act of staying alive and active in the world can be cause for pride in accomplishment, and joy. In the Education Edition, students' experience of joy or its absence is the result of pedagogical goals, processes, assessments, and social relations with peers and teachers.

Learning outcomes

Next, we examine the benefits of using Minecraft in terms of: *1. holistic skills* and development in domains such as creativity and collaboration, *2. technological literacy*, and *3. knowledge* and understanding in subject areas that are the focus of Minecraft worlds.

The theory of 'transformational play' (Barab et al., 2010) is especially relevant to learning through playing Minecraft. As mentioned above, educational outcomes of digital play are not determined by technologies in isolation, but in relation to the 3Cs – attributes of the particular *child*, *content* and *context* (Guernsey, 2007). The theory of transformational play takes a similar approach to understanding how videogames such as virtual worlds shape learning in terms of person, content and context. Specifically, based on ten years of research, researchers predict positive learning outcomes from a type of *role play* in which users have agency in making purposeful choices in the world ('intentionality'), have access to learning content that is useful for problem-solving ('legitimacy'), and have a context in which user actions have real impact (ie, actions have consequences in environments such as Minecraft) (Barab et al., 2010). This work reminds us that the factors of *child*, *content* and *context* are relevant both around and inside immersive digital worlds such as Minecraft, where players can inhabit social roles as themselves or as fictional characters.

The opportunity to develop *holistic skills* is a key aspect of playing Minecraft. A review of related literature (Nebel et al., 2016) reveals a wide range of benefits including self-regulation, cooperation, collaboration and problem-solving in Minecraft. In a study of 118 elementary school students using Minecraft over the course of one academic year, researchers found evidence of collaboration, cooperation (eg, helping to troubleshoot game issues), and increased creativity. As one student put it, "in Minecraft, we're more together, we're tighter, and we work much better in teams than on other projects" (Karsenti et al., 2017, p. 21).

In the context of six high school classes on Animation and Video Game Design, with an assignment to design and build one Minecraft world of students' choosing per class, researchers found evidence of 21st-century skills (ie, creativity, communication, collaboration, critical thinking) and a pattern of students self-organising and student leaders emerging (Hewett et al., 2020).

The potential for Minecraft to help children develop holistic skills is further illuminated in a study of 60 secondary school students, who were given a build challenge in Minecraft under one of two conditions (an open structure in which collaboration was voluntary, or a 'jigsaw' structure in which students were assigned interdependent roles). Researchers found that collaboration increased with the assigned roles (Nebel et al., 2017). Again, we see that context matters, and Minecraft can be shaped to meet a wide variety of needs.

Technological literacy can also be learned in Minecraft. At a basic level, players must learn to navigate, break and place blocks, store and use resources, interact with human and NPC characters, and otherwise function in a technology-based virtual world. Playing in this way entails a variety of technology skills such as keyboarding, navigating a hierarchical menu structure, and understanding the logic of different modes, which individuals need to grasp in order to play. Code Builder in the Education Edition adds opportunities to learn computer coding and computational thinking skills. It has additional features such as 'redstone', which mimics the functionality of electrical currents, allows players to build circuits ranging in complexity from a light switch to the logic circuits of a 32-bit calculator, and more (Nebel et al., 2016).

Building *knowledge* in academic subject areas is another potential benefit of Minecraft, especially when participating in Education Edition lessons, or customised worlds (mods) designed around particular academic disciplines such as literature, art, mathematics, chemistry and ecology (Nebel et al., 2016). In one study, fifth-grade students learned geometry using one of three conditions: traditional instruction, play-based Minecraft, or lesson-based Minecraft. Both Minecraft conditions resulted in better outcomes for students, regardless of ability level (Stanton, 2017). In another study, elementary school students have been shown to improve their reading and writing skills based on their Minecraft activities (Karsenti et al., 2017).

Related platforms

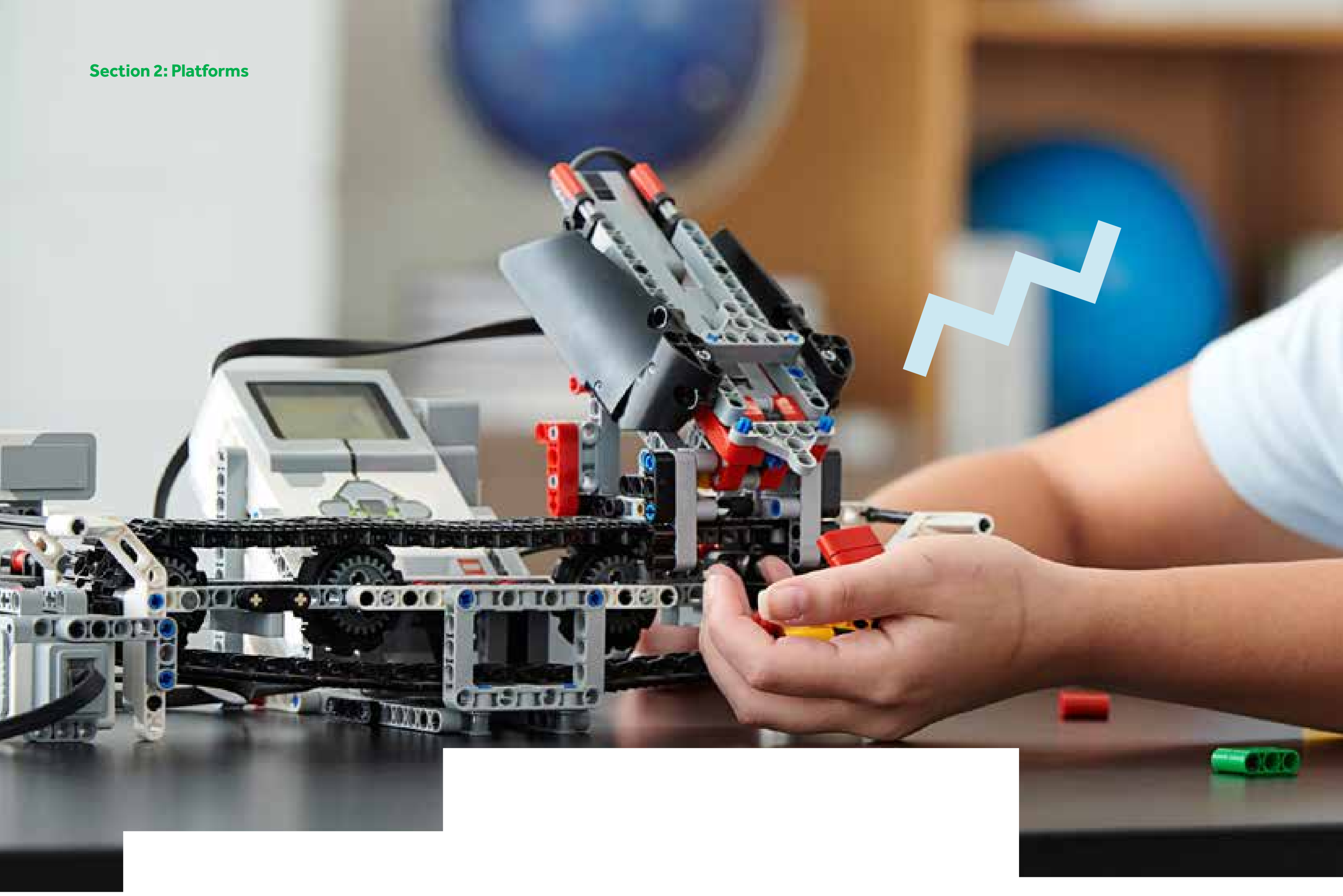
Community learning
An extension of Minecraft worth noting is the Block by Block programme that helps community residents learn about and actively participate in public space projects; especially people whose voices may not otherwise be heard, including women, children, elderly and disabled people and refugees. In workshop settings, participants use Minecraft to model their surroundings, play with possibilities, express ideas, and ultimately design improvements that become reality. Results from projects in over 30 countries suggest that participants experience all the elements of high-quality learning through play: active engagement, social interaction, meaning, iteration and joy. Learning can occur both among the individuals actively involved, and in communities as a whole, when they see that residents' engagement and creative imagination have meaningful local impact.

Other sandboxes
Other platforms use some of the open-ended, creative features found in Minecraft, usually with specific themes and more traditional game mechanics. For example, Roblox is a popular game development platform and community, with a programming environment (Lua) for building 3D immersive games. While most games are free-to-play, developers may charge Robux (a virtual currency) for certain in-game features, and ultimately convert the currency into real-world money, a portion of which goes to Roblox as a revenue stream. Various formal and informal educational organisations (eg, after-school programmes) use Roblox to teach "coding, design thinking, entrepreneurship and interdisciplinary learning" (Roblox, n.d.), and 'digital civility' is a stated goal (G. Johnson and B. Jaquet, personal communication, 21 February 2020).

Gamestar Mechanic is another successful game development platform and community, originally created more than a decade ago by researchers at the University of Wisconsin and the New York City non-profit Institute of Play. Subsequently acquired by E-Line Media, GSM has a "late elementary and middle school" user base and, starting in 2019, a companion platform, Endless Mission, designed for users over 13 years of age (Brian Alspach, Executive Vice President of E-Line, personal communication, 18 February 2020). The academic lineage of these platforms provides insights into the three design principles required for their success: 1) a quest mode: a play experience in which it is possible to learn the basics, including game-making concepts and use of tools in a safe and supportive environment, 2) an embedded creation tool which enables users to make games, and 3) a community in which users play each other's games, and offer feedback. As summarised by Brian Alspach: "all three of those components, the quest, the creation tool and the community, were integral to the designs of both products" (personal communication, 18 February 2020).

Creative, sandbox modes are often included in other games. For instance Fortnite, the online multiplayer war game, has three modes: small-group survival ('Save the World'), a large-scale 'last-man-standing' battle game ('Battle Royale'), and a sandbox ('Creative'). Currently, Creative mode is marketed as a personalised version of the other battle modes ("Imagine a place where you make the rules, filled with your favourite things and your favourite people. Claim your own personal island and start creating!" (Fortnite Creative, n.d.). However, there is also a nascent movement to use the Fortnite game engine to create worlds with more traditional educational themes (Fortnite Students, n.d.), for example by incorporating a museum (Fortnite Innovating in the Classroom, n.d.). Compared to Minecraft, the development tools are much more complex, and the worlds are more photo-realistic.

LEGO Worlds is a child-friendly sandbox world. As with Minecraft, players can create and develop their own 3D virtual worlds, but with building materials that resemble physical LEGO bricks and characters such as LEGO Minifigures. There are two modes: story mode which functions like an extended tutorial for learning about the various features of the platform while visiting different worlds and completing tasks for the characters who live there, and earning gold bricks. In the second mode, sandbox mode, players have access to all of the tools, and freedom to do what they choose. Players have access to many powerful tools for crafting the landscape, vehicles and creatures. Two-player multiplayer and world-sharing options are available.



2.3 LEGO® MINDSTORMS®

LEGO® MINDSTORMS®[3] is a robot construction kit that includes a specialised set of LEGO building bricks, motors, sensors of various types (eg, detecting touch, colour) and a programmable 'intelligent' brick that connects and controls the other parts. Code for the control brick is written on a separate computer or tablet using a visual block-based programming language, similar to Scratch. With these tools, a builder can create a functioning vehicle, animal, home or other creation that combines sensing, moving and information-processing capabilities.

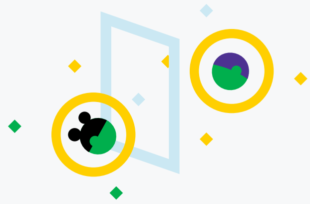
As a 'robot invention kit', LEGO MINDSTORMS extends the kind of creative coding supported by Scratch into the physical world where children's creations may function autonomously, interact with objects and people, and allow builders to collaborate, interact and reflect. In this way, the physical and social environment is a fundamental aspect of the user experience, whether at home, in a robotics club, or in a school classroom. Indeed, all three 'Cs' are central to understanding the educational experience of MINDSTORMS, and other robotics kits, in terms of their *content* and features, the physical and social *context* of use, and the attributes of the particular *children* involved.

3 This product was named after Professor Seymour Papert's book, *Mindstorms: Children, Computers, And Powerful Ideas*. Papert and his research group at the MIT Media Lab carried out the seminal research on using a 'programmable brick' as the basis of a robotics construction kit.

Learning design: agency, guidance, creation and playfulness

Agency with robot invention kits such as LEGO MINDSTORMS involves the complex interplay of physical, computational and social elements, and the resulting systemic perspective on multi-directional cause-and-effect (M. Sharples, personal communication, 28 February 2020). As with other platforms, agency is expressed in the process of coding and related social interactions, but also in building a physical artefact and its resulting autonomous functioning. In this way, the experience and expression of agency is fluid across these different aspects of robotics, as builders shift between different modes, including engineering a physical artefact, programming its behaviour, collaborating and/or competing with other builders, observing the robot interacting with a real-world environment, and perhaps reflecting on the process and assessing their contributions (eg, after a robotics competition).

Creative drive: what motivates LEGO MINDSTORMS builders? The motivational aspects of agency follow a similarly complex pattern. Other motivations, unique to robotics invention, centre on the creation of the physical and behavioural qualities of a potentially autonomous agent. Perhaps akin to a human parent's relationship to their child, agency for a roboticist is expressed in their attempts to influence the form and function of a separate entity, which may conform to the creator's expectations, or take unexpected directions as a result of physical, computational or contextual factors (eg, how well a mobile robot navigates a physical terrain). In this way the builder's agency is both direct in the design of the robot, and indirect in the robot's independent activities.



Guidance with LEGO MINDSTORMS is a complex interplay of physical, social and computational elements. Initial guidance for building is often the written instructions for a complex creation, or a simple one that can be easily built and then extended or combined with other projects. The physical attributes of the materials and setting have a direct effect on children's activities with this platform. As mentioned above, LEGO bricks are designed with creative constraints – to connect only in specific ways, which guides how builders assemble them and the kinds of projects that are possible. For example, while engineering a bridge, builders may discover that a long, thin road surface falls easily, and with no long curved blocks available, an arch structure must be approximated by assembling a large number of rectangular blocks. While a ready-made long bridge arch would make this challenge easier, the constraints of the small rectangular blocks stimulate thinking in detail about how to create different types of curves, exploring their relative strength, and ultimately learning important engineering lessons.

The physical properties of LEGO MINDSTORMS materials support social interaction, collaboration and observation. Continuing the bridge example, imagine that the builder has a partner nearby, who can easily observe progress on the challenge, discuss options and join in to help. Whether the partner is a peer, teacher or professional engineer volunteering at a robotics event, the physical materials and setting can be arranged for joint engagement. Guidance can take the form of peer collaboration, guided participation and play, instruction, or another pattern of social activity.

The computational dimension of LEGO MINDSTORMS involves the design of control systems that work with the properties of the blocks, motors, wheels, sensors, speakers and other materials. Returning to the bridge example, imagine that the builder and partner(s) have the goal of designing a rolling or walking robot to traverse the bridge autonomously. Programming the robot's behaviour involves the relationship between the physical properties of the robot components (eg, wheels or legs) and the bridge, input sensors (vision, distance, sound), and the motor and other output components. If the challenge includes designing for social interactions with the robot (eg, following voice commands to 'stop' and 'go'), the build team must also consider robot–human interaction design. The source of guidance in the computer control system is the behaviour of the socio-technical system as a whole, and the capacity to notice problems in particular parts of the system (eg, physical movement, environmental sensing, social interaction), fix them, and test the design again.

While, as we have seen, guidance can come in the form of feedback from the functioning robot, it can also come from external resources and social contexts. Given the level of complexity of a functioning robot, direct instruction and related materials are common sources of guidance. Builders use written instructions or exemplars to guide the assembly of a particular robot, at least for the first time. The pre-structured quality of this kind of instruction sometimes comes into conflict with the more flexible, adaptive feedback that emerges from the iterative process of building.

For example, when adults provide models or step-by-step instructions for a build, it can be difficult for children to then shift over to a more open-ended iterative approach. As a LEGO interaction designer put it:

> **When they've been doing next, next, next for a while, the whole idea about thinking openly is a bit of a transition for them… we have to ease them into the openness to avoid the 'blank page syndrome', and that's where we use those prompts or those questions to get the kids to think like… 'Okay, now you've done this thing. How could you make it even more something, or how could you think differently about something?'**
>
> ***(K. Andersen, personal communication, 24 February 2020)***

In this way, a progression of written materials can guide builders' activity from initially following explicit step-by-step directions to open-ended prompts for more creative, self-expressive building.

Social sources of guidance encompass the structures of non-educational (eg, home), formal and informal educational settings in terms of skills, knowledge, attitudes and values expressed in particular cultural contexts. As with other platforms, the kinds of guidance that are available in the classroom depend on the particular teacher and classroom culture. Among informal educational settings, *FIRST* LEGO League[4] stands out as a model for intentionally designing a social context that supports collaborative robotics projects, with a clearly articulated set of values. Indeed, the small-group meetings that accompany robotics building sessions focus on 'core values activities' to teach values such as 'Gracious Professionalism®' and 'Coopertition®'.

Beyond the small groups, across all activities, *FIRST* LEGO League organisers intentionally support particular cultural values, and observe them in action. As the Director put it: "when you see unsportsmanlike behavior… people will talk about you're not being a gracious professional or you're not showing gracious professionalism. So it's really an awareness that we don't behave that way… And it's about how do you accept your teammates' ideas when they don't really agree with your own" (K. Wierman, personal communication, 26 February 2020).

4 "FIRST (For Inspiration and Recognition of Science and Technology) is a global nonprofit organisation that operates after-school robotics programmes for young people aged 6–18 in the United States and internationally. The mission of FIRST is to inspire young people to be science and technology leaders by engaging them in exciting mentor-based programmes that build science, engineering and technology skills, inspire innovation, and foster well-rounded capacities including self-confidence, communication and leadership" (Melchior et al., 2019).

The Director of Evaluation and Impact added: "you see teams helping out other teams, and mentors helping other mentors, but you also see the kids talking to the other kids about their project, about their ideas and about how their robot works, including giving each other programming help" (N. Boyer, personal communication, 26 February 2020).

As we have seen, guidance in the context of *FIRST* LEGO League is not limited to issues of robotics engineering, but also includes a host of social-emotional skills and pro-social values. Looking to the future, *FIRST* LEGO League is committed to extending their approach to teaching positive values, along with STEM skills using robotics, to all children in the US and internationally:

FIRST has hired a Director of Equity, Diversity & Inclusion. A lot of strategies and intentional efforts are focused on being more diverse and inclusive. One of the reasons why we went into the school day, was to remove those barriers... and to really give access to more kids... When we are intentional, we are including more children who are eligible for free or reduced lunch, and much closer to 50/ 50 girls and boys. The youth of colour percentages are more reflective of the school system's breakdowns.

(K. Wierman, personal communication, 26 February 2020)

FIRST LEGO League is pursuing similar goals in other countries, and discovering the need to take different, culturally specific approaches:

As we are global, we have different issues in some countries related to their education systems and their laws around competitions. We are actively addressing those barriers, but again getting into the school helps address a lot of that. We are especially working with countries to create more equity and not have these kinds of programmes to be just for kids whose parents can afford it.

(K. Wierman, personal communication, 26 February 2020)

To be effective, guidance needs to be attuned to the norms and values of the immediate setting (classroom, family), but also the wider culture.

Creation. Robot invention kits such as LEGO MINDSTORMS support reflection and social dialogue in ways similar to Minecraft, but in the real world. As in virtual worlds, *construction* is immediately accessible to inspection and conversation, and also perhaps interaction if it is a functioning unit (eg, wheels and axle). Unlike Minecraft, players have a rich multi-sensory connection to materials that they can touch and physically manipulate. They also have the potential for face-to-face interactions with peers via rich channels of communication – linguistic, paralinguistic or gestural – that can convey social information that is useful for coordination and collaboration. This fluid natural communication may be important given the complexity of robotic projects that integrate physical, computational and social systems. Peers working to manage this complexity may divide tasks according to interest or skills. Programmes like *FIRST* LEGO League facilitate this sort of social group coordination, with mentors and clearly articulated values for mutual respect, communication and collaboration. With this kind of adult support, builders are better able to communicate productively and reflect on their project as they progress.

Playfulness. Inspiring and maintaining a *playful* attitude while creating with LEGO MINDSTORMS appears to be the result of personal, interpersonal and cultural features of particular settings. Assembling the materials is a complex task, often guided by step-by-step directions that do not necessarily encourage playfulness. However, children are free to play with their creations after they are completed. Likewise, when children experience the freedom to experiment with various ways of assembling their robots, playfulness can emerge. In addition, programmes such as *FIRST* LEGO League demonstrate how the intentional design of group activities can foster playfulness even in the context of a competitive challenge.

Learning environment evaluation: five characteristics of learning through play

How does using LEGO MINDSTORMS support the five characteristics of learning through play? LEGO MINDSTORMS supports a wide range of hands-on/ minds-on active engagement through physical creation with digital programming and interactions between the robotic creation and its environment via sensors, sounds and movements. It can include projects that express clearly formed ideas from a child's imagination; bricoleur designs that emerge from an iterative trial-and-error process of experimenting with forms of both code and bricks; patterns provided in a licensed-content kit (eg, Star Wars), which may be adapted according to the builder's personal preferences, or completion of a teacher's assignment with little engagement beyond the physical-spatial pattern-matching task. A key feature of this engagement is the relatively complex interplay of the physical, computational and social elements, and the resulting systemic perspective on multi-directional cause-and-effect (M. Sharples, personal communication, 28 February 2020).

Building with a robot kit inherently affords social interactions, given the visible nature of the medium which, compared to a computer screen, allows multiple people to more easily see the component parts and emerging project (Mitch Resnick, personal communication, 18 February, 2020). This allows two or more individuals to collaborate in a variety of ways, closely or loosely aligned, organised around different materials or functions, equally or unequally active, with complementary or conflicting processes and goals. Of course, the kit designers, parents, educators and other adult stakeholders hope for social interactions that are productive for the project and participants' learning and development – indeed kits may be designed specifically to support two collaborators in particular roles, such as those of programmer and builder, but allow other variations (K. Andersen, personal communication, 24 February 2020).

Physical factors such as the working surface and computer hardware can also support or inhibit productive social interactions. As one designer observed:

A tablet is usually more shared than a laptop, because unlike a clam-shell laptop where the screen almost becomes this wall, it's a flat piece of technology that you can switch back and forth... Kids will just put the device on the floor and slide it around, and then [the interaction] becomes way more fluid and shared, because it's at the same level as the bricks.

(K. Andersen, personal communication, 24 February 2020)

In classroom settings, some teachers are comfortable supporting this sort of interaction pattern on the floor, while others prefer a more traditional workspace on desks which may better fit their classroom culture, but may involve students spending more time “crawling around under the table” looking for dropped bricks (K. Andersen, personal communication, 24 February 2020).

Outside of school, LEGO MINDSTORMS and other robot construction kits are used in many informal educational settings such as after-school and museum programmes, and dedicated clubs where organisers can pursue educational outcomes using a wider range of formats than a traditional classroom might allow. A prime example is *FIRST* LEGO League, which encourages adult coaches to model ‘Gracious Professionalism®’ and guide young people to balance competitive and collaborative motivations with a system of values including the concept of ‘Coopertition®’ (K. Wierman, personal communication, 26 February 2020).

Like other platforms, LEGO MINDSTORMS affords meaningful experiences to the extent that it supports children in making connections between their creations and other aspects of their lives. This happens when a design provided by others, such as LEGO or their teacher, makes specific connections to what they care about, or when they customise the design, as when a child makes an interactive device to turn on a light when they enter their bedroom, or recreates their favourite fictional character.

The flexibility with which building materials are introduced and used largely determines the meaningfulness of the process and product. As Mitch Resnick put it: “if it's going to be meaningful to me, there better be variety in what I can create, because it's not going to be as meaningful to me if I'm just following a set of instructions to do the same thing that everybody else is doing” (personal communication, 18 February 2020).

This flexibility is especially important in structured educational settings such as schools and clubs. For example, the *FIRST* programme strives to provide children with challenges that are “authentic and relevant”, both in small-group “core values activities” and in the building challenges themselves, in which young people collaborate on projects. In some cases personal and community meaning is built into the challenge directly, as the Director of Education explained: “they're going out into their community and doing research and exploring problems to solve, and then that is reflected back in some of their final solutions” (L. Simpson, personal communication, 26 February 2020). Projects that are personally meaningful, and have a direct contribution to a child's community, are likely to be doubly meaningful.

Product design can also have a significant effect on appeal and usability for different children. For example, many versions of LEGO MINDSTORMS have a dark colour palette of grey and black, with sample projects that emphasise vehicles and shooting machines, which in many societies tend to appeal more to boys than girls. LEGO Education's new SPIKE Prime kit was intentionally designed to appeal equally to everyone, as the lead designer noted:

A lot of decisions around SPIKE Prime were made to open up who technology is for and change the expression of technology. We chose Scratch, a programming language and community that reaches millions of kids across the world. We made the LED matrix which allows kids to turn their drawings and animations into physical pixels. For the

physical elements, we used a lot less grey and more vibrant colours like yellow, violet and azure blue. We didn't want it to be a boys-only product, but to reach boys, girls or whatever your gender identity.

(K. Andersen, personal communication, 24 February 2020)

Likewise, he noted that the default image on the LED matrix screen shows a heart: "I think that changes the whole expression of the technology to be a lot more friendly and a lot more emotionally connecting to the kids" (K. Andersen, personal communication, 24 February 2020). With similar goals, the *FIRST* programme has been able to achieve almost equal participation by boys and girls in programmes where they intentionally focus on strategies for equity, diversity and inclusion: "we evaluate what works and then we also look at the demographics of who we're serving and reaching" (K. Wierman, personal communication, 26 February 2020). Iteration is a fundamental feature of LEGO MINDSTORMS. By design, LEGO bricks are as easy to take apart as they are to put together. This fundamental principle of "the LEGO idea" was the inspiration for Scratch's block-based design, which makes it "easy to try something, make adjustments, keep revising it. The materials themselves [support this]: it's different than if you're using wood and nails" (M. Resnick, personal communication, 18 Febryuary 2020). As a result, LEGO robotic kits that use a block-based programming language support iteration across both the physical and digital elements.

Physical and digital material can allow for iteration, but often users need social support as well. As Mitch Resnick put it, "you need to be in an environment where others around you are encouraging it. When things go wrong, to encourage you: 'why don't you try this?'... It can't come just from the materials" (personal communication, 18 February 2020). While support for iteration is valuable in the creative process, it is sometimes in conflict with other forms of guidance. For example, as discussed above, when adults provide models or step-by-step instructions for a build, it can be difficult for children to then shift over to a more open-ended iterative approach, but guidance can be designed to facilitate this shift towards greater iteration.

One factor in this may be historical trends. Compared to previous generations "a lot of kids today don't want to take LEGO apart", according to Kevin Andersen, an interaction lead at LEGO Group, "and it kind of goes against our DNA: we want kids to rethink and rebuild". As a result, SPIKE Prime is specifically designed to avoid focusing on the one correct way to complete a build, by designing models that will work with multiple configurations. In this way, the designers hope to help children remain flexible in their thinking through the process, and iterate more. *FIRST* encourages iteration through the structure of the challenges and the support they offer:

You give them some instruction and then you just let them do it... They build, rebuild and rebuild again. And there's definitely iterating on designs... almost like a natural part of their play.

(K. Wierman, personal communication, 26 February 2020)

Like other platforms, LEGO MINDSTORMS affords *joy*, primarily in that it supports curiosity with intrinsically motivated, self-directed creative activity. Joy may be present in the process of building, and upon reflection after the build has been completed. One unique opportunity for joy comes when builders create an interactive robot that functions autonomously, and the builder can observe its activities with a sense of pride and accomplishment.

Some elements of robotic kits are designed to evoke joy, in other smaller ways. For example, SPIKE Prime has been designed to evoke moments of joy:

You build a little character. It's a little weather robot, and it looks very cute, and it has that umbrella and sunglasses and tells you about the weather. So, there's some joy in that, and it has a functionality that hopefully appeals to kids. It just comes down to the small details like the way that the hub starts up. It doesn't say 'Starting up'. It has all these shimmering pixels appearing from behind the white plastic, out of nowhere, and the heart emoji, that represents the default program, slides in. So, the whole expression is also meant to give joy to the kids.

(K. Andersen, personal communication, 24 February 2020)

So, we see that joy can take many forms as an experience of pleasure or satisfaction that emerges in the process of playing, or when reflecting on the experience.

Learning outcomes

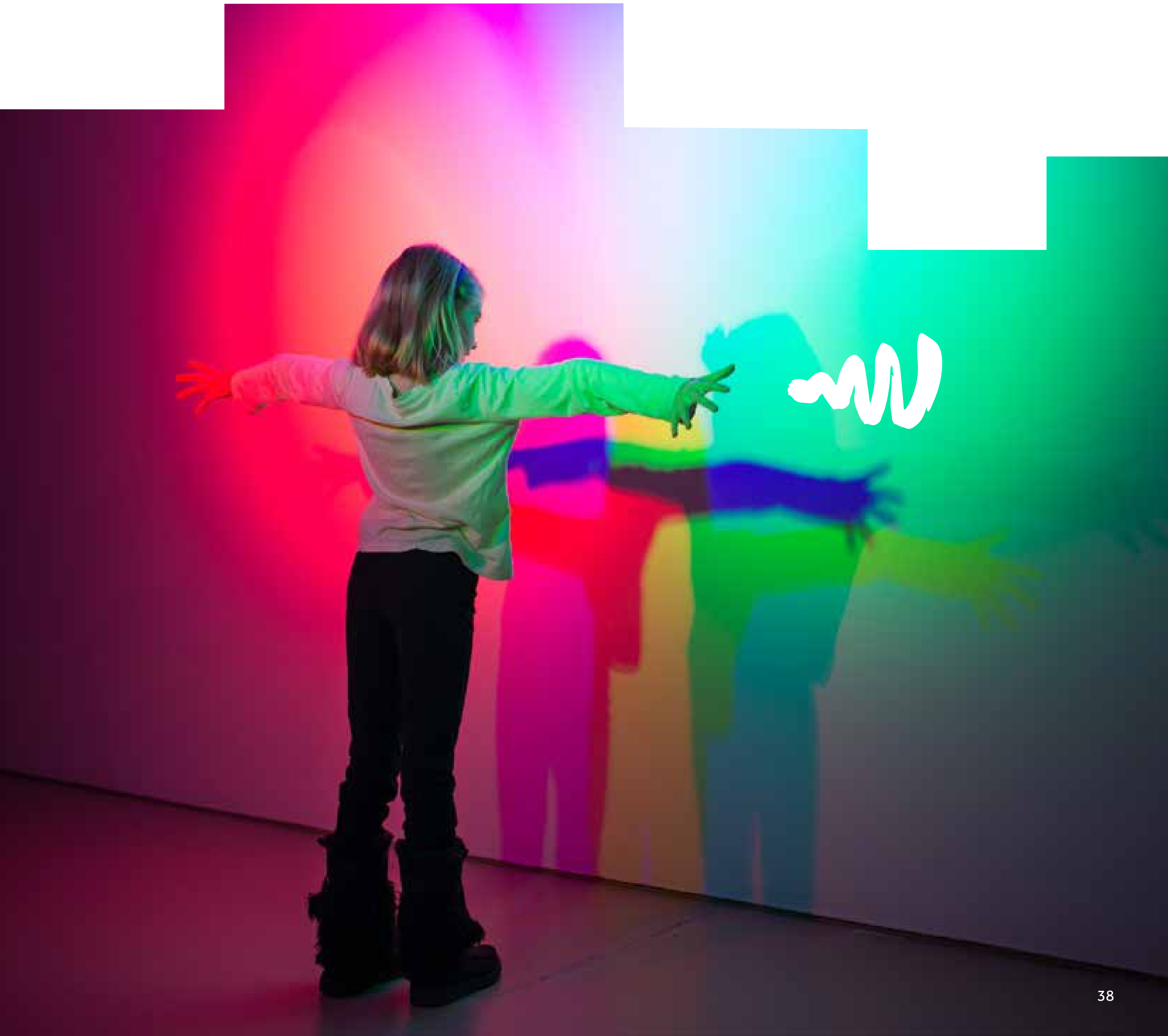
Next, we examine the benefits of using LEGO MINDSTORMS in terms of 1) *holistic skills* and development, 2) *technological* literacy, and 3) *knowledge* and understanding in academic subject areas.

Engaging in LEGO MINDSTORMS activities can build *holistic skills* such as creativity, collaboration, communication, problem-solving and self-efficacy, according to multiple reviews of research on educational robotics (Pedersen et al., 2020; Anwar et al., 2019; Toh et al., 2016). The reviews examine a wide range of educational robotics platforms, but overall, LEGO MINDSTORMS is the most frequently studied. Collaborative problem-solving was a particularly common outcome. As one student put it: "we were faced with various problems while designing and programming the robots to complete the task. As a group, we had to develop new solutions to these problems" (Sibel, 2015, p. 32).

The *FIRST* programme provides important insights into how LEGO MINDSTORMS and related robotics kits can be used in an informal educational programme to address the holistic development of young people. Results from ongoing longitudinal evaluation studies show positive outcomes, especially in terms of children's attitudes towards and interest in STEM careers (Melchior et al., 2019). The central role of holistic learning is also evident in the 'core values' integrated into the competitive team model for robotic construction, including 'Gracious Professionalism®', teamwork and inspiration as categories in the assessment rubric.

Spending many hours planning, building and programming robots inevitably leads to learning outcomes related to *engineering and computer coding*. However, in the area of STEM, most research studies document gains in students' attitudes and interests more than their specific skills (Anwar et al., 2019; Melchior et al., 2019), along with the more holistic skills described above. One interesting exception to this pattern of research is a study showing that Pre-K to 2nd-grade children learned to program LEGO WeDo robots using a specially designed tangible-visual programming language (icons on wooden blocks and computer screens), and generalised their sequencing knowledge to other tasks (Kazakoff et al., 2013).

Compared to holistic skills and STEM attitudes and interest, learning domain *knowledge* through robotic construction is a relatively rare topic of research. Indeed, one systematic review study reported not finding any such research (Pedersen et al., 2020). However, there is some published evidence that LEGO MINDSTORMS is well suited for learning STEM topics, especially in authentic contexts. For example, in one study, a student noted that "I learned how to calculate the circumference of a circle better while calculating the path the robot should take on the mat" (Sibel, 2015, p. 33). In another study, high school students explored principles of evolution by building robotic vehicles to be more or less well adapted to navigating particular environments. Pre-post tests revealed large learning gains in their knowledge of concepts such as natural selection, adaptation and niche specialisation (Whittier and Robinson, 2007).



Related platforms

The above discussion of LEGO MINDSTORMS includes related platforms such as LEGO SPIKE Prime and a host of related activities provided by *FIRST* LEGO League. The LEGO company also has other platforms in this category, such as LEGO WeDo, designed for elementary school students. While there are meaningful differences among the platforms, the key concepts in our analysis of learning through digital play apply across them all.

Other organisations have developed robotic kits with different scope, functionality, or educational emphasis. A notable example is KIBO, which enables children aged 4–7 to program a robot without screens or keyboard, using wooden blocks to program the robot's behaviours. Children can customise a (wooden and clear plastic) robot base by connecting wheels, sensors, a rotating 'art platform' to display craft materials, and other modules. The sensors are shaped like equivalent human body parts or tools (eg, an ear-shaped sound sensor, eye-shaped light sensor, telescope-shaped distance sensor). Children use a 'screen-free' method to program the robot by arranging wooden blocks with commands (eg, turn right, move forward) into a sequence to control the robot, which receives the program via a built-in barcode scanner. Created by the Tuft University developers of ScratchJr, this robot kit is designed to meet the needs of young children, primarily in classroom settings.

A variety of commercial robot kits provide control of a robot via a block-based programming language on a tablet or computer. Sphero offers a programmable ball-shaped robot, a customisable 'all terrain' robot, a snap-together electronic circuit kit, and various educational materials. Wonderworkshop sells a three-wheeled robot in two varieties, and several accessories such as xylophones and catapults that the robot can operate, based on programming input from a tablet computer. There are dozens of other relatively small specialised robotics kits, as well as open systems such as Arduino and Raspberry Pi that can be used by more advanced programmers and electronics tinkerers to create robots, and perhaps learn in the process.

SECTION 3

Applying the design principles: digital storytelling

Our discussion so far has illustrated examples of learning through digital play in environments as varied as creative coding (Scratch), open-ended 'sandbox' gaming (Minecraft) and robot construction (LEGO MINDSTORMS). We have described how these environments can provide an experience of play that is actively minds-on, socially interactive, meaningful, iterative and joyful – characteristics known to foster significant learning. Research on Scratch, Minecraft and LEGO MINDSTORMS has revealed that children engaged in these environments can learn holistic skills, subject area knowledge and technological literacy. And we identified agency, guidance, creation and playfulness as fundamental features of children's experiences in these environments, which can function as learning design principles that may be applied more generally.

We now look at one example of how our design principles may be applied in other ways. Rather than looking at a specific platform, we examine the activity of digital storytelling.

There is no especially salient exemplar technology in this case; rather, we describe a continuum of digital tools or apps that are used to support storytelling, in order to illuminate the nature of our design principles, and to offer concrete models of how they can be applied in other relevant educational settings.

Digital storytelling

As a multifaceted activity, storytelling is well suited to learning through digital play. For instance, it supports agency through a wide range of products and processes. Stories may be short or long, with a traditional narrative arc, creative variations or novel structures; they may be fictional or reality-based; conveyed orally, in written text or multimedia; they may be composed in a collaborative group or by a solo writer, using a pen, simple word processor or myriad multimedia tools to record and manipulate the content. This great variety of choice facilitates *agency* for any child who engages in the writing process. The persistence of recorded media supports *guidance* from adults and peers during the writing process or afterwards. *Playfulness* can emerge from humorous topics, rhyming structures, or creative processes of exploring, creating or experimenting with language.

More fundamentally, the stories that children consume and create are at the heart of their social-emotional wellbeing, since narrative is one of the primary ways that human beings make sense of the world and their place in it. As mentioned previously, the stories that children tell themselves about themselves shape their self-image and self-esteem. The stories that they consume from parents, peers and the media provide a map of the social-cultural world which they must navigate.

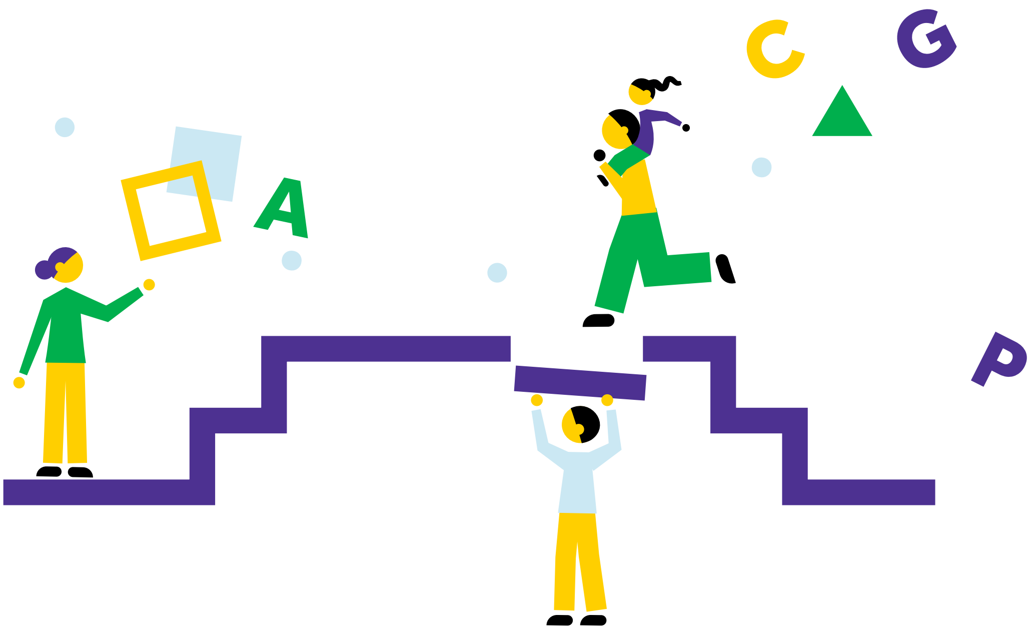
There are many different tools that children might use for digital storytelling, including ones with built-in narrative scaffolds (eg, the three-part story arc of beginning, middle and end), and ones with more generic capabilities. We can place these tools on a continuum from heavily scaffolded, to light, to none. Heavy scaffolding may help support young writers or those with learning challenges, while little or no scaffolding designed into the digital environment may work well for skilled students, or they may require teachers to provide support in other ways. Virtually all novice writers need some kinds of scaffolding to create stories; what differs across digital tools is the degree to which that support is built into the digital environment itself, rather than provided by a teacher.

ComicBook!, Toontastic 3D and StoryBlocks are all digital environments with built-in narrative scaffolding. ComicBook! is an iOS app that lets children create their own graphic story by providing templates for arranging images into comic book layouts, with filters that can make a child's photo look like an ink drawing, and text tools for putting dialogue into speech bubbles. This kind of scaffolding provides *agency* for children who cannot independently create content following these conventions, but want to express themselves in the graphic story genre. *Guidance* may come from the palette of available choices, friends using the same or similar apps, and published examples of comics and graphic novels. *Playfulness* can be encouraged in myriad ways, from the wide range of image control (eg, making your friend's face look like a purple ink drawing), easy-to-input dialogue, the tradition of comic strip humour, and fantastical characters to imitate.

Toontastic 3D is a kind of virtual puppet theatre app that lets users create, select or customise characters, backgrounds, spoken dialogue and soundtracks, with multiple scenes organised around one of three story arcs. The flexible quality of these features provides young authors with a personalised level of scaffolding to support their agency. The features themselves, tutorials, and examples provided by peers can offer guidance, with the result being a story of their own creation. Playfulness may come from juxtaposing different kinds of characters and backgrounds, creating funny new characters, and the spoken dialogue's content and tone.

StoryBlocks[5] is the content creation app within the Learning Loops system for connecting children (age 6–10), their parents, and literacy coaches, with the goal of empowering children as authors and facilitating their narrative development. It is an experimental project developed at the MIT Media Lab, which illustrates the potential for creatively combining social relationships and technical tools to support children's storytelling. StoryBlocks lets children make comic-style stories, and fosters their *agency* with tools for selecting and customising puppet-like characters, choosing or creating background scenes, typing dialogue, adding props and recording narration. Using companion digital tools, coaches provide direct support and guidance to the children, and communicate with their parents regarding the children's activities and accomplishments. Parents can communicate back to the coaches, and use any new-found insights in their parent–child interactions at home. The resulting coach–family network is a unique source of *guidance* for children's story-making. As with Toontastic, *playfulness* may be expressed through various story elements, and also in the emotional tone set by coaches and parents (cf. related dissertations: Nazare, 2021; Sysoev, 2020; Woolf, 2020).

5 StoryBlocks builds on SpeechBlocks and PictureBlocks, two apps that facilitate open-ended early literacy learning through play (Sysoev, 2020; Makini, 2018).



A wide range of more generic digital software can be used for children's storytelling, including still cameras, video and audio recorders, music creation and composition software, multimedia productivity tools such as presentation software, and word processors. As a final example of how our design principles can be applied to students' use of generic tools, we consider the use of digital cameras and video recorders together with Google Slides and Docs as a widely available set of content creation tools. As noted above, student use of these kinds of tools may require external scaffolding, arranged by the teacher. They also have the benefit of being used for formative assessment of student skills and knowledge, in forms that are easy to share widely.

Imagine a pair of elementary-grade students investigating a local event and *creating* a multimedia presentation to share with classmates, friends and family. *Agency* and *playfulness* may be expressed in their choice of topic, sources of information, use of still or moving images, and the way that they assemble the story in a particular order and craft written text to accompany the images. *Guidance* may come from the teacher's directions for this assignment, her project-based learning rubric, occasional advice, peer collaboration within the group, and models from other groups. The process of *guidance* might be supported by the collaborative features of Google Slides and Docs, as students express their ideas, critique each other, and solicit input from others all at a distance, and share their project with other students who leave comments and suggestions, or edit directly.

SECTION 4

Conclusions

In this paper, we have seen the potential value of learning through digital play. Children today are growing up in a rapidly changing, technologically interconnected world that increasingly requires strong subject area knowledge, technological literacy and a broad range of holistic skills. Research demonstrates that learning through play can support these outcomes, and is especially well suited to fostering the development of holistic skills. Five characteristics of playful learning can be used to evaluate the quality of learning environments by examining how well they provide children with experiences that are: minds-on/ actively engaging, socially interactive, meaningful, iterative and joyful.

We have seen how children can experience learning through digital play, and that their experience is shaped by the affordances of the digital technology itself (*content*), how and where the technology is used (*context*), and each child's unique qualities (*child*) – ie, the '3Cs'. We presented case studies of Scratch, Minecraft and LEGO® MINDSTORMS® – exemplary platforms that support playful learning in terms of their design and opportunities for diverse patterns of use. Finally, we offered a framework of agency, guidance, creation and playfulness to guide the design and use of environments for learning through digital play.

4.1 What are the benefits of learning through digital play?

Beyond subject knowledge and technological literacy, the paper describes various broad-based benefits of learning through digital play, especially when it includes *making and sharing digital creations*. These benefits include:

Holistic skills

The educational approaches described in this paper can help students prepare for a dynamic future by developing a wide range of holistic skills, such as creativity, communication, collaboration, problem-solving and self-regulation, as well as academic subject area knowledge and technological literacy. Beyond being fundamental to the ways that children become good people and productive citizens, holistic skills of many types have been identified as increasingly essential to success in our world of rapid technological, economic and social change.

Deeper understanding

Findings from the science of learning (Hirsh-Pasek et al., 2015) and research on playful learning (Zosh et al., 2017) support the conclusion that children build a deeper understanding when they engage with topics through minds-on activity, make meaningful connections to other knowledge, iterate on their ideas, include social interactions around a topic, and adopt an attitude of joyful play – that is, when they experience the five characteristics of playful learning.

Adaptivity

All the digital environments discussed in this paper provide powerful tools for producing a wide range of digital creations in open-ended environments. This means that activities can be adjusted to suit individual students, specific populations, local communities and academic subjects, or to adapt to a sudden change in educational environment, such as the need to embrace remote learning during a pandemic.

Student engagement

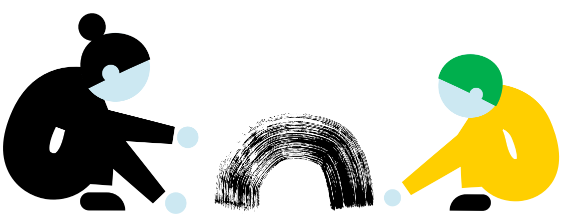
The opportunity to initiate and drive a personally meaningful creative activity is very motivating for students. Guidance from adults and peers supports their underlying sense of agency, and helps students create projects that spark engagement with their educational community.

Bridge school, home and community settings

Connections between personally meaningful experiences in different settings help learners draw on their own identities and build on the strengths of their peers, families and cultures. Such bridging allows them to stay engaged in a project started in one place, and to continue working on it in another. The continuity of this activity supports sustained motivation and agency. It also makes possible collaborative work or conversation about a project with people in different settings, which might mean inviting guidance and encouragement from family, friends and local community members, as well as teachers and other educators.

Authentic assessment

When children make digital creations, the process and product of their efforts can function as authentic assessment by revealing useful information about their knowledge, skills, attitudes and learning. As with projects, portfolios, exhibitions and intentionally crafted authentic tasks, digital content created through students' playful learning activities can provide the basis for both formative and summative assessment. It can help students to reflect on their own capabilities, and to guide future self-directed learning, as well as informing iterations on a specific project. Likewise, digital creations can help educators assess students' abilities, and guide their differentiated or individualised teaching practices.



4.2 How can adults facilitate children's learning through digital play?

Adults play various roles in shaping children's opportunities for playful learning with digital technologies. Our recommendations for **educators** are focused on the needs of teachers and school administrators, but also parents who seek – by choice or necessity – to be actively involved in their children's education. Likewise, our recommendations for **designers** are intended for professionals and product developers who craft digital environments for children's learning, but also teachers in their role as learning designers who plan and guide their students' educational activities across digital and non-digital settings. Indeed, both lists may include useful insights for anyone aiming to facilitate learning through digital play – including children, young people and adults who embrace the goals of self-directed learning.

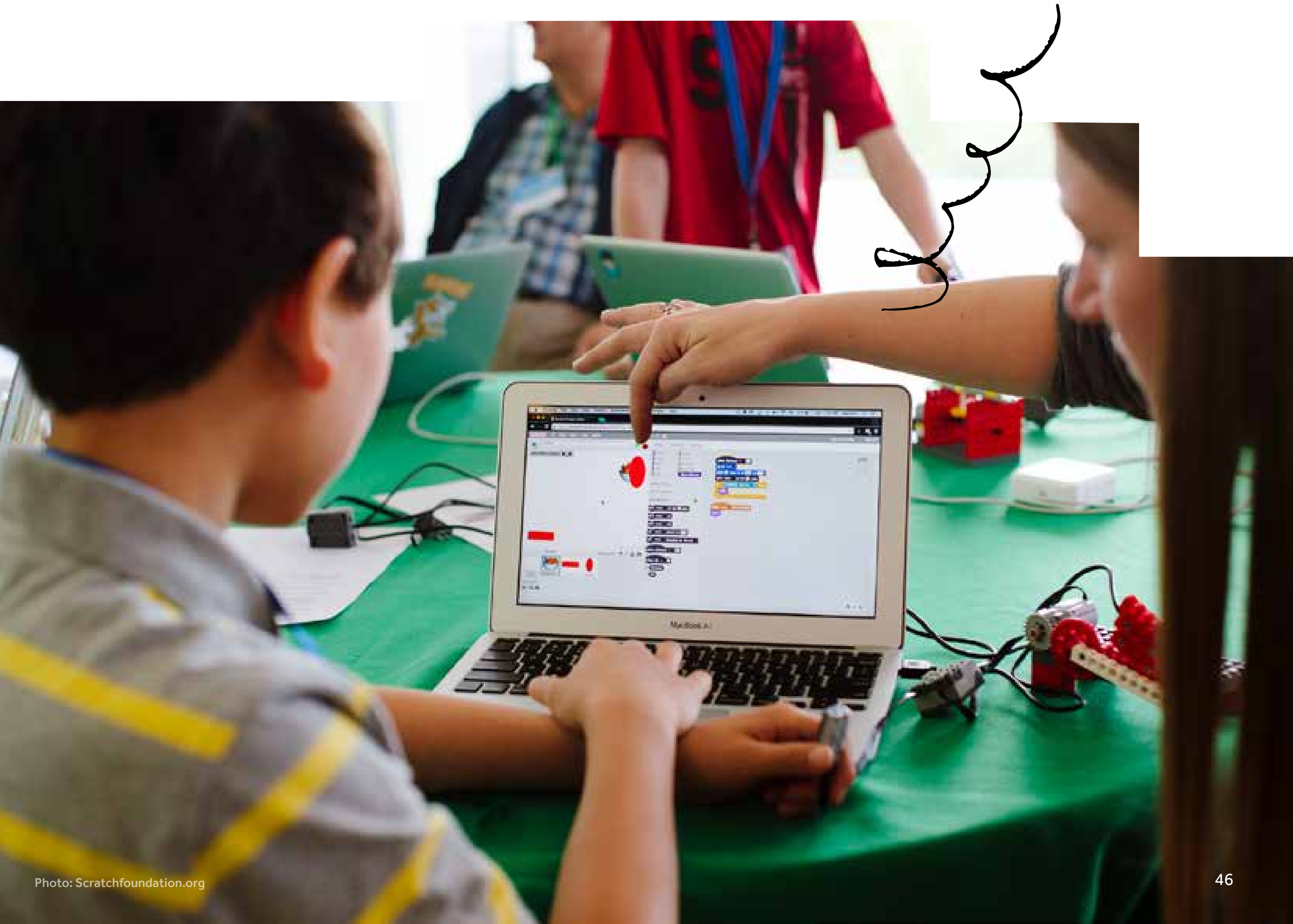


Photo: Scratchfoundation.org

4.3 Recommendations for educators

- Use platforms such as Scratch, Minecraft and LEGO® MINDSTORMS®, which can **scaffold playful learning**, to **help integrate a broad range of skills** into the curriculum.

- **Consider the '3Cs'** in your planning and use of platforms: the **content** of platforms (tools, media, curriculum materials), the **context** (when, how, and where the platforms are used), and the **child** (the unique needs and qualities of individual learners).

- Design and support platform activities that give children opportunities for **agency, guidance, creation and playfulness.**

- Use the **five characteristics** of playful learning to evaluate children's educational environments and activities, and assess the quality of their resulting learning experiences.

- Connect children's digital play experiences in their **home, school and community** to extend and deepen their learning experiences.

- Use **actively engaging pedagogies** such as project-based learning, collaborative learning and inquiry-based learning to structure learning through digital play.

- Use student-created content as the basis for **authentic assessments** such as projects, portfolios, exhibitions and intentionally crafted authentic tasks.

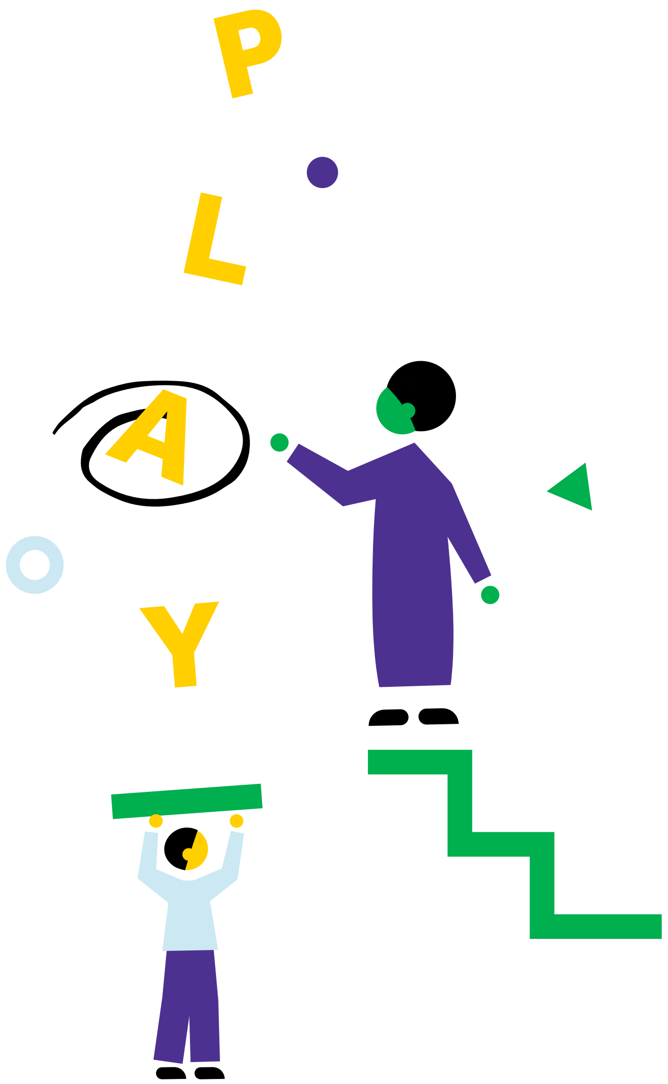
4.4 Recommendations for designers

- **Design for creation:** provide the content and tools that children can use to make meaningful and sharable creations. Allow users to import their own content, as appropriate. Provide multiple ways to share and discuss content.

- **Design for user agency:** give users a wide range of choices in available content and tools to create with. Scaffold their self-efficacy, self-regulation, and self-directed learning.

- **Design for guidance:** support users with tools attuned to their abilities. As with Scratch, design for easy entry points ('low floor'), advanced capabilities ('high ceiling'), and a wide diversity of content and approaches ('wide walls'). Support communication and collaboration among peers, and with knowledgeable others (eg, adult experts, as appropriate).

- **Design for playfulness:** design for safety, trust and the freedom to explore, experiment and create. Ensure that users are safe from physical and psychological harm – eg, protect personal information, and establish and actively support a community of social-emotional health. Make content easily available to children so that they are free to follow their ideas, iterate, and explore new topics.



4.5 Future directions

The current global pandemic has reduced the availability of safe and effective environments for children's play, learning and socialising. Trends such as the expanded use of remote learning and high levels of family stress can present significant challenges for children's well-being. As we have demonstrated in this paper, learning through digital play can help meet these challenges by offering innovative new ways to play, learn and interact with others, such as *learning through making and sharing digital creations.*

As educators continue to reflect on the successes and failures of their pandemic-related adaptations, there will be a growing need for research on associated topics, including learning through digital play. We will need to better understand factors that contribute to positive educational outcomes and features of high-quality learning environments.

We will also need implementation research and professional learning opportunities to help educators integrate learning through digital play into their practice, and help parents understand its value.

For societies to move digital learning practices away from outdated industrial models, and toward methods better suited to helping children flourish in a rapidly changing world, they will need to integrate play into educational environments and guide students to be active agents in their own learning. We hope the frameworks presented in this paper – the five characteristics of learning through play, and the principles of *agency, guidance, creation* and *playfulness* – will help guide the design, use and evolution of digital learning environments that foster a broad range of holistic skills, as well as technological literacy and subject area knowledge.

Appendix

Expert interview participants

Brian Alspach, Executive Vice President, E-Line Learning at E-Line Media

Kevin Andersen, Senior Interaction Design Manager, LEGO Group

Marina Umaschi Bers, Professor, Tufts University

Nancy Boyer, Director of Evaluation and Impact at *FIRST* (For Inspiration and Recognition of Science and Technology)

Karen Brennan, Associate Professor of Education, Harvard Graduate School of Education

Sara Cornish, Senior Marketing Manager, Minecraft at Microsoft

Ben Courtney, Creative Manager, LEGO Group

Brian Jaquet, Senior Director, Public Relations, Roblox

Genevieve Johnson, Senior Instructional Designer, Roblox

Allisyn Levy, Vice President, GameUp at BrainPOP

Srinivas Mandyam, Founder and Chief Technology Officer, Tynker

Aarin Morris, Initiatives Manager, LEGO Foundation

Mitch Resnick, LEGO Papert Professor of Learning Research, MIT Media Lab

Natalie Rusk, Research Scientist, MIT Media Lab

Andy Russel, Product Manager - Chromebooks for Families, Google (and Co-founder of Launchpad Toys)

Mike Sharples, Professor Emeritus of Educational Technology, The Open University

Libby Simpson, Director of Education at *FIRST* (For Inspiration and Recognition of Science and Technology)

Kim Wierman, Director, *FIRST* LEGO League (For Inspiration and Recognition of Science and Technology)

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