Building For Robots: An Alternative Approach of Combining Construction and Robotics

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Abstract

Robots and robotics toolkits are becoming a growing part of the introductory computing landscape. One very common approach for the use of robotics in learning contexts is to have kids construct their own robots. This paper explores the affordances of focusing the activity of construction in robot-related activities on the setting rather than on the robots themselves. Using conventional arts-and-crafts materials (e.g. pipe cleaners, paper cups, cardboard), this paper describes a study in which groups of children (ages 7 to 13) engaged in an experiential learning activity focused on collaborating, designing, building landscapes for robots to explore followed by programming Sphero robots to navigate them. Shifting construction to the setting in which the robot runs rather than on building the robot itself enabled new and productive forms of engagement, participation, and learning. The benefits of the building-for-robots approach includes relying on inexpensive materials, supporting new forms of collaboration and sharing, and opportunities for learners to draw on prior knowledge and experience. Further, the shift towards constructing for the robots introduces productive interplay between the construction and programming components of the activity where constructing for the robot can influence what is programmed, while authoring the programs shapes the way the world is constructed around the robot. This paper provides examples of these new affordances and explores the potential of this shift towards designing for robots. In doing so, it advances our understanding of ways to productively use robotics as a means to support meaningful engagement with powerful ideas of computing.

Keywords

Constructionism, Robotics, Design, Youth

Introduction

Robots and robotics toolkits have an increasing presence in both formal and informal learning contexts. Be it in homes, classrooms, or on television and in the movies, robots are becoming ubiquitous. One common argument made for robots and robotics toolkits either as toys at home or as devices to be integrated into classroom activities is the potential they have to serve as meaningful learning devices (Chambers, Carbonaro, & Rex, 2007). A quick internet search reveals dozens of books, toolkits, videos, and articles all espousing the virtue of robots for kids. This enthusiasm is not unwarranted as much research has been done showing the potential and effectiveness of robots and robotics toolkits to support learning and serve as a means to engage learners in productive learning activities (Blikstein, 2013; Papert, 1980; Resnick & Rosenbaum, 2013; Yu & Roque, 2018). Looking specifically at work that has grown out of the Constructionist tradition, an emphasis has been placed not just on using robots but on constructing them as well (Blikstein, 2013; Resnick et al., 1998; Resnick & Silverman, 2005). Having learners construct robots provides opportunities for deep engagement with foundational concepts of engineering, mathematics, science, and computing. Further, providing learners with the building blocks can impart a powerful sense of belonging and ownership over both the device and the concepts that it demonstrates. While there is much promise in the use of robots and robotics toolkits for authentic learning, challenges remain related to robotics and education, including costs associated with tools and toolkits, opportunities for collaboration and drawing on prior knowledge and experience during construction, and issues around reuse of construction kits and their components.

In this paper, we explore an alternative way to bring Constructionist principles and robotics together that seeks to draw on the strengths of both while addressing some of the aforementioned challenges. To do so, we asked learners to construct a world around the robot, rather than construct the robot itself. We call this approach *Building for Robots* and contrast it with the more conventional approach of building the robots themselves. These setting-based constructions were created using inexpensive art-and-crafts materials most children are familiar with such as construction paper, paper plates, pipe cleaners, and tape. We argue combining low-tech materials with high-tech robots can provide an alternative approach for construction and robotics that retains many of the benefits present in conventional robot construction activities while also introducing new forms of engagement and opportunities for learning. This paper presents the motivation for this strategy and then outlines three affordances of the Building for Robots approach that make it distinct from more conventional robot construction activities. In doing so, we seek to advance our understanding of ways to blend construction and robotics as a means to provide engaging learning experiences for youth. Our approach introduces new design opportunities and opens new pathways into the world of robotics, engineering, and computing.

The paper continues with a description of how constructionist ideas undergird this work, and a discussion of prior research on robot toolkits for constructionist learning. We then introduce the Building for Robots approach relative to existing approaches to learning with robots. The methods for the study conducted follows before we present our findings in the form of three distinct affordances of the Building for Robots approach. The paper concludes with some challenges and limitations of the approach.

Theoretical Orientation and Prior Work

Constructionism & Robot Construction Kits

Papert's constructionism builds upon Piagetian Constructivism and identifies the act of constructing public and shareable artifacts as being an especially productive and generative learning activity (Harel & Papert, 1991). Adding to this idea, distributed constructionism focuses on situations in which more than one person is involved in design and construction activities (Resnick, 1996). Distributed constructionism asserts that collaborative activities that involve information exchange, design and construction of meaningful artifacts lead to effective knowledge-building communities (Resnick, 1996). Both building and collaboration are central to the Building for Robots approach discussed in this paper. The Building for Robots approach also draws from Friere's perception of learning as a form of empowerment (Blikstein, 2013). Friere argued learners should go from the "consciousness of the real" to the "consciousness of the possible" as they perceive the viable new alternatives" beyond "limiting-situations" (Freire, 1974). Therefore, learners' projects should reflect their personal and community problems as they design solutions to problems that would become both educational and empowering (Blikstein, 2008). Recent versions of educational robotics activities involve programmable bricks, that enable learners to control the behavior of tangible objects using virtual and physical environments. Such tools make possible new types of experimentation, in which children can investigate everyday phenomena in their lives both in and out of the classroom (Resnick, Bruckman, & Martin, 1996).

Physical computing devices and robot construction kits specifically designed for kids have a long and rich history (Blikstein, 2013; Martin et al., & Berg, 2000; McNerney, 2004). Blikstein (2013) traces the history of these toolkits back to the same research center from which Constructionism grew: MIT's Media Lab and the LEGO group. Early robotics toolkits include LEGO bricks (Sargent et al., 1996), which served as an antecedent to the popular line of Lego Mindstorms construction kits still in use today. As part of this work, designers sought to give learners more direct access to the underlying computational capabilities, moving beyond the "black box", making underlying processes more visible and accessible (Resnick et al., 2000).

As robotics advanced, construction kits became cheaper and more diverse and were designed to meet different goals and audiences. Examples of this diversification includes kits designed for younger learners (Yu & Roque, 2018), open-hardware kits seeking to democratize learning with construction kits (Sipitakiat et al., 2004), new ways to integrate robotics with traditional crafting practices (Eisenberg, 2002; Kafai et al., 2014; Rusk et al., 2008), and new designs seeking to welcome learners who historically have not been a part of the robotics and construction community (Buechley et al., 2008; Holbert, 2016). Central in this thread of work is the emphasis on learners as empowered builders and exploring the ways that robots and physical computing devices can facilitate this form of exploration, expression, and discovery.

Learning with Robots

There have been two pervading approaches that shape existing approaches to the use of robotics in education that have distinct views on the role of the robot. In the first approach, fully functional, prefabricated robots are introduced as tools for learners to explore and program. In this approach, learners investigate ways to take advantage of the robot's existing capabilities, this usually takes the form of programming the robot to carry out a set of instructions. This approach has been called a "black box" approach because instead of allowing learners to "get under the hood" of the robot and explore how it is made and how it carries out commands, it focuses on the actions the robot can take with the existing, already-put-together robot (Alimisis et al., 2007). One concern with this approach is the missed opportunity for construction and creativity with the result being that the robot is a passive tool used by the learner (Mitnik, Nussbaum, & Soto, 2008).

A very different view of the role of robots in learning can be seen in the "white box" approaches which foregrounds the inner workings of robots and how their parts are put together and how, when assembled, the parts can carry out the functions of the robot (Resnick, Berg, & Eisenberg, 2000). There are a large number of robotics construction kits that emphasize the building of robots reflect this perspective. Examples of technologies in this category include Lego Mindstorms, Pico-Crickets kits, and the growing ecosystem of do-it-yourself microcontroller kits like the Arduino and Go-Go Board (Lego Systems Inc, 2008; Sargent et al., 1996; Sipitakiat, Blikstein, & Cavallo, 2004). The white-box metaphor provides opportunities for construction, creative thinking and involving learners of all ages, mainly in informal educational settings (Alimisis et al., 2007). However, there is a limit to the complexity of the kinds of robots children can make and program. As hardware and sensors become smaller and the ways they can be combined becomes more complex and precise, new robots designed for young learners are being introduced whose sophistication is beyond the capabilities of what can be expected of young learners to assemble (e.g. Ozobots and Spheros).

Most studies that focus on programming with robots from inside the Constructionist tradition take the white box approaches - engaging learners in the design and implementation of the robots themselves. We hypothesize that black box approaches to robotics could also engage learners in authentic and productive constructionist learning experiences. Learning experiences with black box robots rarely utilize constructionist learning approaches, instead focusing on more didactic activities (e.g., programming a robot to navigate a predefined maze). We view this as a missed opportunity. Prefabricated robots have an exciting set of capabilities while constructionist design approaches can lead to personally meaningful learning experiences. The Building for Robots approach seeks to leverage creative design and construction with black box robots. In doing so, we endeavor to blend affordances of the two. In investigating this approach, we seek to understand ways that contemporary robots can support the underlying values and philosophies of constructionism - i.e., design, making, personal and epistemological connections (Harel & Papert, 1991; Papert, 1980).

The Building for Robotics Approach

The main focus of the Building for Robots activity was for learners to use common building materials to construct worlds for their robots to explore. In this way, rather than focusing on designing robots or programming existing robots to complete predetermined tasks, the children were tasked with designing and constructing environments and then deciding how they want their robots to move through the world they built. Over the course of the activity, the children iterated on their environmental designs, building increasingly complicated environments and longer, more sophisticated programs to explore them.

The Building for Robots approach presents the learner with common arts-and-crafts construction materials (e.g. cardboard, popsicle sticks, pipe cleaners) and then asks them to construct a world for a programmable robot to explore. Three features are central to this approach. First is the familiarity of the construction materials. This means materials that are readily available to learners and items the learners already know how to use. Second, the building challenge encourages learners to draw on their own lived experiences and daily lives. This is reflected in both the aforementioned materials as well as the types of environments built. This aspect of the activity is both a result of how learners are introduced to the activity as well as a result of the materials used (as will be shown below). Finally, learners are given complete control over the materials, the robot, and how the two are going to interact. In this way, learners are empowered to build what they want, how they want, and they can have their robots navigate their world as they see fit.

Methods

Participants and Context

This research focuses on a series of robot design activities that were included as part of a summer camp at a local church. The camp was created to engage children in the community with educational experiences during the summer break from school and was led by the church's assistant pastor and youth coordinator. There was a nominal fee to participate in the camp designed to ensure full-time attendance. The camp was held Monday through Friday from 9 am – 5 pm for 4 weeks during the summer. The Building for Robots activity was comprised of 2 2.5-hour sessions each week for the 4 weeks. Two researchers led all 8 design sessions. One led the design, building and programming activities while the other researcher took field notes and captured video and audio data.

The camp included 58 kids ranging in age from 7-13, 49 of which participated in the study (2 second graders, 7 third graders, 9 fourth graders, 7 fifth graders, 9 sixth graders, 8 seventh graders, and 7 eighth graders). Child participants were drawn from the local community, characteristics of which can be seen by looking at the neighbouring public school, which is racially diverse (57% Black or African American, 34% Hispanic/Latino, 4% White, 3% Asian) with 61% of its attendees receiving free or reduced-priced meals and 20% English language learners. Along with the young participants, 16 high school student volunteers from the wider region supported facilitators during the program. The 58 camp attendees were split into 10 groups, with 9 of these groups presenting their environments and programs during the final Building for Robots session.

During Building for Robots activities youth constructed worlds to be explored using the Sphero SPRK+ robot (Figure 1). The Sphero is a spherical robot that can be programmed via tablets using either a block-based or a text-based programming interface. The robot includes motors, accelerometers, LED lights, and communicates with the tablet via Bluetooth. The Sphero programming language includes primitives to move the Sphero, respond to external inputs (such as collisions), change colors, make the tablet produce noise, along with containing conventional programming constructs such as iterative logic, conditional logic, variables, and functions.

Figure 1: The Sphero SPRK+ robot.

Data Collection and Analysis

Distributed constructionism serves as the framework we use to both structure and understand the learning space (Resnick, 1996). Video, audio, researcher notes, and learner constructions (both the physical worlds and virtual programs) were collected and analysed. The focus of the analysis was on looking for various ways learners engaged with the Building for Robot task to identify affordances of the construction activity and knowledge and resources learners drew upon as they engaged in the activity. Data analysis was performed based on emerging themes observed and discussed by the research team.

Affordances of Building for Robots

In this section, we present three affordances of the Building for Robots approach that were identified in our analysis of the data collected. These three affordances are: (1) a low barrier entry to building with robots, (2) engagement with robots grounded on existing knowledge and experiences with the immediate environment, and (3) mutually-informing practices of building and programming.

Low-barrier to Entry

A primary affordance of the Building for Robots approach is that it provides a low barrier to entry in two specific but distinct ways. First, as the primary construction activity uses conventional arts-and-crafts materials, it is possible for very young learners to authentically participate in the activity in a way that might not be possible when construction takes the form of soldering or precisely assembling smaller gears. The low barrier can also be seen in the programming phase of the activity. Since running the program involves the robot navigating the physical space being constructed, younger participants can be involved by interacting directly with the robot (e.g., picking it up and returning it to the start position), or by refining and reconstructing the environment after a run (Figure 2). Both of these activities serve as ways for those too young to traditionally be involved in robotics activities to engage in legitimate peripheral participation (Lave & Wenger, 1991). This low-barrier to entry aspect of Building for Robots can be seen in the composition of the groups who participated in the activity and in the designs of specific groups enabled the youngest member to be fully participating members of the group.

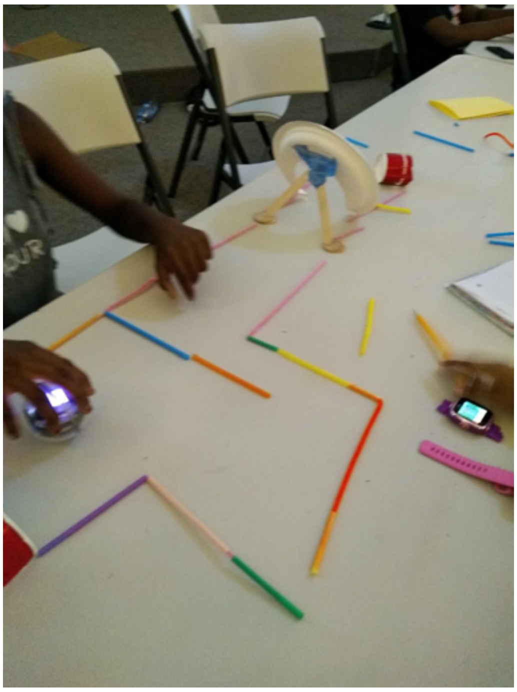
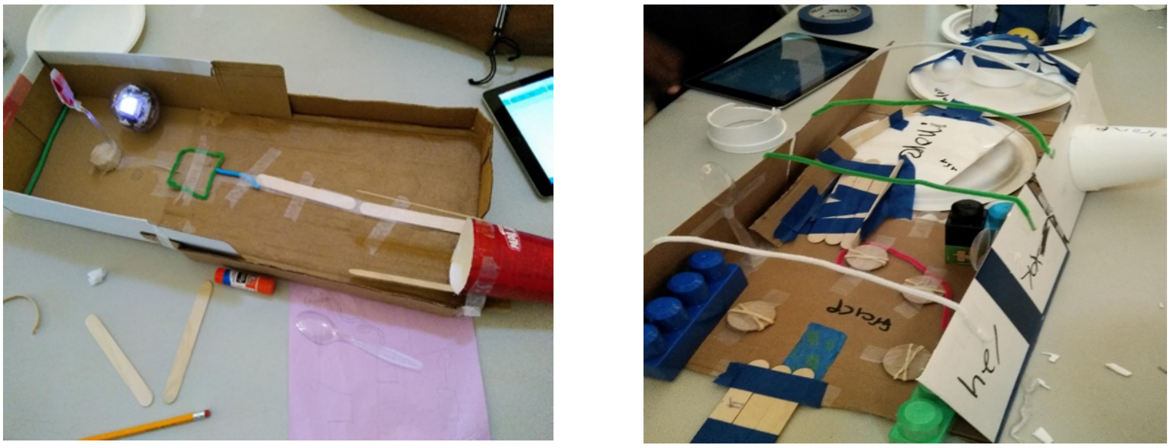


Figure 2: After a run of the Sphero, a young participant moves the robot back to the start position and adjusts the environment, resetting it to its initial starting state.

A second way Building for Robots presents a low-barrier to entry is in the fact that the construction materials used in the activity are inexpensive and readily available. Unlike robot construction kits that can cost significant amounts of money (e.g. Lego Mindstorms EV3 currently retails for $349.99 USD), the materials used when constructing for robots are inexpensive and at times free (e.g., recycled pizza boxes). While a potentially expensive robot is still required for the activity, it is possible to share a single robot among a large group. This also makes it more possible to run robotics activities by relying on temporary access to the robot through programs like library technology checkouts. Since the construction is happening around the robot, the user need not own the robot, this relieves the steep monetary barrier to entry that exists for some robotics tools kits.

This second form of low-barrier to entry was on full display throughout this study. First, an inexpensive church-run summer camp with a very limited budget was able to actively engage 58 children in four weeks of robotics programming activity. The constructions produced relied heavily on inexpensive crafts materials or other materials available, such as leftover pizza boxes and empty packing containers found around the church. Looking across learner constructions, we can see how the low-cost materials were utilized, sometimes in literal ways, like when a cup from a local pizza place was used to represent a pizza restaurant that the robot would visit (Figure 3A) or in more imaginative ways, such as how one group used little wooden tokens taped to a piece of cardboard to serve as hazardous materials for their robot to avoid (Figure 3B).



(A) (B)

Figure 3: (A) Learners use a cup from a pizza restaurant to represent the final destination for the robot and (B) Learners tape wooden tokens on cardboard to represent hazardous obstacles for the robot.

Grounding Engagement with Robotics in Existing Experience

A second affordance of the Building for Robots approach is in how shifting focus to building the environment allows the learners to draw on prior knowledge and experiences as part of engaging in the robotics activity. By this we mean, the vast design space presented by asking them to build something for the robot (rather than the robot themselves) provides an opportunity for them to draw upon a wide array of prior experiences and ideas. This is best demonstrated by looking at the types of environments and challenges that were built by the learners over the course of the workshop. For example, one group built a course for their robot to navigate that mirrored the drive that their parent makes going to and from work, including the introduction of stop signs and stops for errands along the way (Figure 4). There were also projects where the robot played the role of mailman delivering mail, a shopper that needed to scan barcodes as it shopped, and a pizza delivery man out making deliveries (Figure 5). Other constructions included features like car washes in the forms of tunnels and gas stations for the robot to stop at along its journey. Looking across these activities, we see inspiration drawn from daily life while also aspects of creativity and imagination.

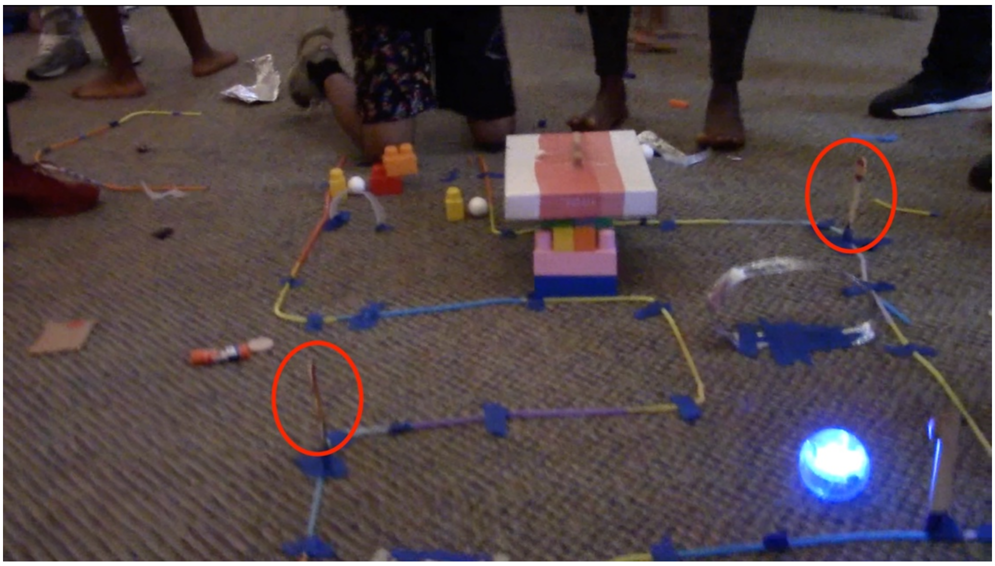


Figure 4: A robot navigates a road including stop signs (circled in red). The robot briefly stops at stop signs and changes colors from blue to red before proceeding.

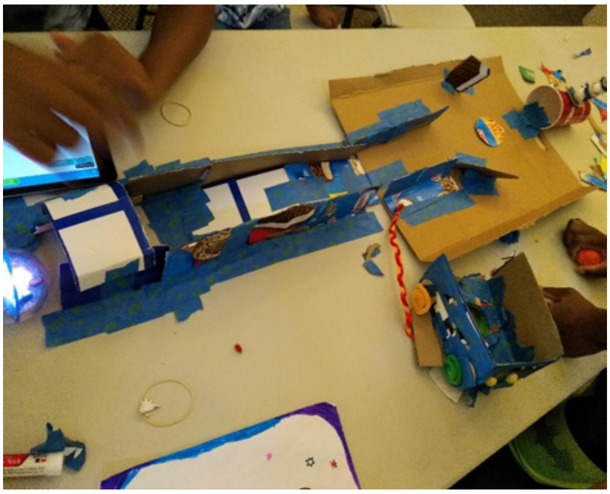


Figure 5: Camp participants design a drive-through track for a robot to navigate to go get a pizza

Mutually-informing practices of building and programming

A third notable affordance of the Building for Robot approach is the unique way that the construction and programming practices become mutually informing. By this we mean, the act of programming informs the construction that is being built while the construction being built informs the program that is being authored. Designing spaces for a programmable robot to navigate provided opportunities for learners to simultaneously work on the designs and program. This is quite distinct from conventional robot construction activities that focus on building the robot because in robot-construction activities programs cannot be run until the robot construction is complete. In contrast, when the construction is happening around an already functioning robot, there is more opportunity to move back-and-forth between programming and constructing. These mutually-informing practices allow for learners to be actively engaged in the process at the same time while also providing generative challenges and solutions throughout the activity. The participants in this activity regularly switched between the physical and the virtual as they refined their designs.

In our analysis, we found instances where constraints encountered while programming the robot shaped the physical construction. For example, one group introduced a traffic light to their environment in the form of wooden discs that were painted red, green and orange. In discussing how the traffic lights would change to allow the robot to stop or move, the learner raised the issue of there being no interactivity between the discs with the robot. As the learners were working through the initial idea, one participant said: "*How are we making the traffic lights? We can color one side of the disc red and color one side green and put them here.*" A discussion on how long to make the robot pause ensued, leading to one learner proposing using a stop sign instead, saying "*When it gets here (pointing to the floor), it has to stop then wait for like 3 seconds just like when you are driving you have a stop sign and [Learner 3] was saying something about traffic light, but we don't really know how to make it work*". Here we can see the issue of not knowing how to program the stoplight behavior shaping the physical construction.

At the same time, there were many instances of the physical construction itself shaping the programs being authored. In fact, the constructions served as the driving motivation for the programming. This interaction could be seen in how learners went about building their environments. Several groups took the approach of incrementally authoring their programs and building their constructions in parallel, meaning they'd build a bit in the physical world, then spent time expanding their programs to account for what was just built, before returning to build the next chunk of their construction. Other cases saw groups complete their physical constructions and then author working programs only to go back and add new obstacles to the course. This type of interactivity and mutually-informing practice produced a generative pattern in which teams kept building more elaborate courses and more sophisticated programs.

Challenges and Limitations of Building for Robots

While there are advantages to the Building for Robots approach compared to the conventional robot construction kit design, there are also drawbacks. First and foremost, among them is that the machine itself remains a black box and learners are not given insight or access to the bits and pieces that make the robot work. Likewise, as the robots are not the focus of the construction, it makes it difficult or impossible to allow learners to personalize the robots themselves. This is quite different from robot construction kits where this type of personalization is an essential part.

A second potential limitation of the Building for Robots approach is that the activity becomes spatially bound. Whereas it is possible (albeit at times inconvenient) to pack up a robot mid-construction, many of the constructions from this project could not be easily moved, especially the larger constructions. Many groups ended up taping things to the floor or having individual components of their machine that couldn't be moved together. This issue was felt acutely by groups who had programs that were close to working on their constructions in one session, only to find out they had to recalibrate all their commands the next session when they reassemble the construction causing distances to be slightly different than what they had been before.

A third drawback to this approach that emerged during this workshop was learners building things that the robot could not navigate or complete, either because the programming required was beyond the learners' abilities or because the physical demands of the course were beyond the capability of the robot itself. We saw this in the form of ramps that were too steep or courses requiring very high levels of precision to complete. This problem was exacerbated by the lack of precision in the running of programs due to external factors, such as the room having carpeting rather than a flooring with a high friction coefficient that is better for the Sphero.

A final drawback of this approach, at least based on this workshop we ran, was that learners explored relatively little of the capabilities of the robots themselves. This can be seen most notably in the contents of the programs written. Most programs used a small subset of the available set of blocks to complete their programs. This mostly consisted of long sequences of consecutive move commands. Few programs included commands associated with logic operators (e.g. conditional logic), robot events (e.g. on collision), variables, or other robot capabilities such as changing colors, producing audio, or reading in values from sensors. This limitation could probably be partially addressed by having more scaffolded construction activities were learners were encouraged to incorporate one feature or another, but those were largely absent from the programs produced as part of the open-ended approach used in this workshop.

Conclusion

This paper introduces the Constructionist learning approach called Building for Robots. This approach retains many aspects common to robot-based learning experiences but introduces some slight tweaks that bring to life a unique set of affordances that can lead to productive engagement. The Building for Robots approach has learners use conventional arts-and-crafts materials to build environments for robots that the learners are programming. Shifting the construction to the surrounding environment rather than the robot itself results in a low barrier to entry and opportunities to draw on learners' prior knowledge and lived experiences. Further, this design opens up new forms of engagement with construction and programming including making programming and construction mutually-informing practices. Collectively, these features provide an alternative way for learners to engage in meaningful constructionist learning with robots.

As new tools, technologies, and forms of engaging with computing emerge, it is important that we continually revisit the types of learning experiences we create around them. Technology on its own does not produce effective learning, it is in the ways that learners take up, use, explore, tinker, and toy with the technologies that meaningful learning occurs. Considering new forms of engagement and alternative ways to support learners in exploring and expressing ideas with technology is as important as designing new technologies themselves. With this work, we explore an alternative way to bring constructionist ideals to robotics and robotics construction kits and hope to encourage others to explore new ways to use robots and robotics toolkits to engage learners. In doing so, we seek to create yet another way for learners to meaningfully engage with the powerful ideas of computing, thus helping them in their path towards fully participating in our increasingly technological world.

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References

Alimisis, D., Moro, M., Alfredo Pina, J. A., Frangou, S., & Papanikolaou, K. (2007). *Robotics & Constructivism in Education: The TERECoP project*. 11. Bratislava.

Blikstein, P. (2008). Travels in Troy with Freire: Technology as an agent for emancipation. *Paulo Freire: The Possible Dream. Rotterdam, Netherlands: Sense*.

Blikstein, P. (2013). Gears of our childhood: Constructionist toolkits, robotics, and physical computing, past and future. *Proceedings of the 12th International Conference on Interaction Design and Children*, 173–182.

Buechley, L., Eisenberg, M., Catchen, J., & Crockett, A. (2008). The LilyPad Arduino: Using computational textiles to investigate engagement, aesthetics, and diversity in computer science education. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 423–432. ACM.

Chambers, J. M., Carbonaro, M., & Rex, M. (2007). Scaffolding Knowledge Construction through Robotic Technology: A Middle School Case Study. *Electronic Journal for the Integration of Technology in Education*, *6*, 16.

Eisenberg, M. (2002). Output devices, computation, and the future of mathematical crafts. *International Journal of Computers for Mathematical Learning*, *7*(1), 1–44.

Freire, P. (1974). *Pedagogy of the Oppressed*. Basic Books.

Harel, I., & Papert, S. (Eds.). (1991). *Constructionism*. Norwood N.J.: Ablex Publishing.

Holbert, N. (2016). Leveraging cultural values and “ways of knowing” to increase diversity in maker activities. *International Journal of Child-Computer Interaction*, *9–10*, 33–39. https://doi.org/10.1016/j.ijcci.2016.10.002

Kafai, Y. B., Lee, E., Searle, K., Fields, D., Kaplan, E., & Lui, D. (2014). A Crafts-Oriented Approach to Computing in High School: Introducing Computational Concepts, Practices, and Perspectives with Electronic Textiles. *Trans. Comput. Educ.*, *14*(1), 1:1–1:20. https://doi.org/10.1145/2576874

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge Univ Pr.

Lego Systems Inc. (2008). *Lego Mindstorms NXT-G Invention System*. Retrieved from http://mindstorms.lego.com

Martin, F., Mikhak, B., Resnick, M., Silverman, B., & Berg, R. (2000). To Mindstorms and Beyond. *Robots for Kids: Exploring New Technologies for Learning*, 9.

McNerney, T. S. (2004). From turtles to Tangible Programming Bricks: Explorations in physical language design. *Personal and Ubiquitous Computing*, *8*(5), 326–337.

Mitnik, R., Nussbaum, M., & Soto, A. (2008). An autonomous educational mobile robot mediator. *Autonomous Robots*, *25*(4), 367–382. https://doi.org/10.1007/s10514-008-9101-z

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic books.

Resnick, M. (1996). Distributed Constructionism. *Proceedings of the 1996 International Conference on Learning Sciences*, 280–284.

Resnick, M, Berg, R., & Eisenberg, M. (2000). Beyond black boxes: Bringing transparency and aesthetics back to scientific investigation. *The Journal of the Learning Sciences*, *9*(1), 7–30.

Resnick, M, Bruckman, A., & Martin, F. (1996). Pianos not stereos: Creating computational construction kits. *Interactions*, *3*(5), 40–50. https://doi.org/10.1145/234757.234762

Resnick, M, Martin, F., Berg, R., Borovoy, R., Colella, V., Kramer, K., & Silverman, B. (1998). Digital manipulatives: New toys to think with. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 281–287.

Resnick, M., & Rosenbaum, E. (2013). Designing for Tinkerability. In M. Honey & D. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 163–181).

Resnick, M., & Silverman, B. (2005). Some reflections on designing construction kits for kids. *Proceedings of the 2005 Conference on Interaction Design and Children*, 117–122.

Rusk, N., Resnick, M., Berg, R., & Pezalla-Granlund, M. (2008). New Pathways into Robotics: Strategies for Broadening Participation. *Journal of Science Education and Technology*, *17*(1), 59–69. https://doi.org/10.1007/s10956-007-9082-2

Sargent, R., Resnick, M., Martin, F., & Silverman, B. (1996). Building and Learning with Programmable Bricks. In *Constructionism in practice* (pp. 161–173).

Sipitakiat, A., Blikstein, P., & Cavallo, D. P. (2004). GoGo board: Augmenting programmable bricks for economically challenged audiences. *Proceedings of the 6th International Conference on Learning Sciences*, 481–488.

Yu, J., & Roque, R. (2018). A survey of computational kits for young children. *Proceedings of the 17th ACM Conference on Interaction Design and Children - IDC '18*, 289–299. https://doi.org/10.1145/3202185.3202738