New Materials for Teaching Computational Thinking in Early Childhood Education

by

Kimberly Smith

M.F.A. Fine Arts
School of Visual Arts, 2012

B.F.A. Fine Arts
Oregon State University, 2005

Submitted to the Department of Media Arts and Sciences, School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2017

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Abstract

The need for computer science education is greater than ever. There are currently over 500,000 unfilled computer science jobs in the United States and many schools do not teach computer science in their classrooms. Computers are powerful tools, and *computational thinking*—skills of problem-solving, logic, and abstraction that form the foundation of computer science—can be applied across other disciplines.

Many current approaches to computer science education use computer screens. Though computer science education is important and effective from a young age, the American Academy of Pediatrics recommends we limit screen time in children; and research shows that excessive screen time is detrimental for a child's development.

A 2006 research study by Angeline Lillard published in *Science* showed that Montessori students scored higher on academic, cognitive, social, and behavioral tests than students in a traditional elementary school setting. The Montessori Method is characterized by mixed-age classrooms, child-driven learning, and a series of sensorial, physical materials. Developed nearly 100 years ago by Dr. Maria Montessori, the Montessori curriculum does not explicitly include computer science in its curriculum.

This research examines the Montessori Method as a way to teach computer science for early childhood education. Interpreting and extending Dr. Montessori's original pedagogy, I have developed a curriculum with new learning materials for young children that breaks down the fundamentals of computational thinking into a set of discrete concepts that are expressed in tactile, hands-on ways. This research evaluates this approach through direct observation and teacher feedback; and suggests the potential for this Method as an effective approach to teach computational concepts to young children.

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We especially need imagination in science. It is not all mathematics, nor all logic, but it is somewhat beauty and poetry.

- Maria Montessori

Introduction

Computation

> "Ideas from computer science [are] not only instruments of explanation of how learning and thinking in fact do work, but also instruments of change that might alter, and possible improve, the way people learn and think."[1]
>
> - Seymour Papert

The computer is a powerful tool that has changed the ways we create, connect, and see the world. As we adapt and change with technological advances, how do we prepare children for the skills necessary to succeed and thrive in this dynamic landscape? There are currently more than 500,000 unfilled computer science jobs in the United States,[2] and last year, only 42,969 computer science students graduated into the workforce.[3] While the job market is an important indicator of its necessity, some of the larger applications behind this knowledge are more valuable and far-reaching. As Seymour Papert said, "Computer presence could contribute to mental processes not only instrumentally but in more essential, conceptual ways, influencing how people think even when they are far removed from physical contact with a computer."[4] The term *computational thinking* has come to encompass these skills of problem-solving, logic, system design, and abstraction that form the foundation of computer science and can be applied across other disciplines.[5]

Given the relevance, value, and need in the job market, it is surprising to learn that only one out of four K-12 schools teach any computer science,[6] leaving many students without early introduction to these important computational skills. There is also evidence that children really like learning computer science in school, along with the arts.[7] Not only are children interested and enjoy it, 9 out of 10 parents wish that their children were learning computer science in school.[8] Introducing computer science education to children at a young age may decrease gender imbalances, and create opportunity for minority and low-income populations to later thrive in this unbalanced field.[9] But often teachers are not aware of the scope of computer science

1 Papert, Seymour, *Mindstorms: Children, computers, and powerful ideas.* (New York: Basic Books, 1993), 208.
2 "Promote Computer Science." Code.org, accessed November 10, 2016, https://code.org/promote.
3 *Ibid.*
4 Papert, Seymour, *Mindstorms: Children, computers, and powerful ideas.* (New York: Basic Books, 1993), 4.
5 Wing, Jeannette M, "Computational Thinking," *Communications of the ACM* 49, no. 3 (2006): 33.
6 Google (Firm) Gallup (Firm). "Images of computer science: perceptions among students, parents and educators in the US." (2015).
7 "Promote Computer Science." Code.org, accessed November 10, 2016, https://code.org/promote.
8 Google (Firm) Gallup (Firm). "Images of computer science: perceptions among students, parents and educators in the US." (2015).
9 "Computer Science Education Coalition Press Release." CSE Coalition. Accessed November 10, 2016. http://www.csecoalition.org/Computer-Science-Education-Coalition-PressRelease/

education,[10] and often have difficulty integrating it into their classrooms.[11] For younger students, there are limited learning materials available, and many classrooms rely on computers and tablets, which many schools may not have access to or prefer not to use in their classrooms.

Children and Technology

Computers and digital technology are integral in our lives, and we are inundated with screens throughout every day. We are connected digitally through our devices, and we are increasingly more and more connected with our technological objects. We spend significant time experiencing much of our world through a digital window.

Adolescents, young children, and even infants across diverse socio-economic backgrounds are using digital media on a daily basis.[12] Younger generations are increasingly adept at using digital media, and there is no doubt that children understand how to use a computer in a different way than older generations. While computers are a ubiquitous part of our lives, is it best that young minds spend their critical developmental years interacting with digital media and screens?

There is growing research that suggests that digital screens are affecting the cognitive development of young children.[13] The Policy Statement from the American Academy of Pediatrics (*Media and Young Minds*) outlines the developmental concerns for children ages 0-5 due to excessive screen time, and presents recommendations for digital media use and young children in order to mitigate these negative effects.[14]

The American Academy of Pediatrics outlines three health and developmental concerns in young children, specifically ages 0-5. These concerns are child development, sleep, and obesity.[15] Excessive screen time, particularly television viewing in early childhood has been linked to cognitive, language, and social and emotional delays.[16] The statement recommends that children under two need social interaction and hands-on exploration in order to develop their cognitive, language, motor, and social-emotional skills.[17] In children older than two years, the APA recommends to limit media to one hour or less per day of high-quality programming. For

10 Google (Firm) Gallup (Firm). "Images of computer science: perceptions among students, parents and educators in the US." (2015).

11 "Promote Computer Science." Code.org, accessed November 10, 2016, https://code.org/promote.

12 Kabali, Hilda K. et al. "Exposure and use of mobile media devices by young children." *Pediatrics* 136 (6) (2015): 1044-1050.

13 Duch, Helena et al, "Screen time use in children under 3 years old: a systematic review of correlates," *International Journal of Behavioral Nutrition and Physical Activity* 10, no. 1 (2013): 102.

14 American Academy of Pediatrics Council on Communications and Media, "Media and Young Minds," *Pediatrics* 138 (5) e20162591 (2016): doi: 10.1542.

15 *Ibid.*

16 *Ibid.*

17 American Academy of Pediatrics Council on Communications and Media, "Media and Young Minds," *Pediatrics* 138 (5) e20162591 (2016): doi: 10.1542.

children under the age of two, the APA recommends no screen time at all.[18]

The APA recommendations also emphasize the quality and the content of digital media. And while this is important, the form itself may also be detrimental for children.[19] Children at this age have difficulty transferring information from digital media into their real environment.[20] During this critical developmental period, children are developing spatial understanding and how to relate in a three-dimensional world with its sensorial experiences.[21] With all of this growing evidence, many have returned to physical approaches for children's learning, using materials that allow a child to develop spatial awareness, dexterity, and sensory-motor control. Notable physicians and educators such as Jean-Marc Itard, Eduard Sequin, and Maria Montessori incorporated sensorial stimuli in the learning process.[22] The Montessori Method is characterized by what are called Sensorial Materials, materials that utilize all of the child's senses.

Computer science is important and relevant for our children, and evidence shows that young children can learn computational concepts[23] and doing so at young ages has its benefits.[24] Given that the ideas and skills necessary to think computationally are not necessarily dependent on the need for a computer, we can introduce these ideas to young children in a developmentally appropriate manner, without digital media.

The Montessori Method

> "For man, who has formed a new world through scientific progress, must himself be prepared and developed through a new pedagogy."[25]
>
> \- Maria Montessori

In the Social Computing Group, we developed a model for innovative shopfront Montessori schools. We were inspired by the Montessori Method and its timeless relevance in education.

The Montessori Method was developed by Dr. Maria Montessori in Italy at the beginning of the 20th century. This pedagogy focuses on the idea that children are developing as young

18 *Ibid.*

19 Lin, Ling-Yi et al, "Effect of Touch Screen Tablet Use on Fine Motor Development of Young Children," *Physical & Occupational Therapy In Pediatrics* (2017): 1-11

20 Barr, Rachel, "Memory constraints on infant learning from picture books, television, and touchscreens," *Child Development Perspectives* 7, no. 4 (2013): 205-210.

21 Anderson, Daniel R., and Tiffany A. Pempek, "Television and very young children," American Behavioral *Scientist* 48, no. 5 (2005): 505-522.

22 Lillard, Angeline Stoll, *Montessori: The Science behind the Genius,* New York: Oxford University Press, Inc., 2007, 16.

23 Bers, Marina Umaschi et al, "Computational thinking and tinkering: Exploration of an early childhood robotics curriculum," *Computers & Education* 72 (2014): 145-157.

24 "Computer Science Education Coalition Press Release." CSE Coalition. Accessed November 10, 2016. http://www.csecoalition.org/Computer-Science-Education-Coalition-PressRelease/.

25 Montessori, Maria, *The Montessori Method,* 25.

people, eager for knowledge, and naturally peaceful and capable. The Montessori classroom is a carefully prepared learning environment with special furniture appropriately sized for children, with an adult who serves as a guide more than a traditional teacher. Montessori teachers are observers in the classroom, responding to the needs of children and supporting their learning.

The Montessori classroom is characterized by mixed-age groups, intrinsic motivation, peer learning, and uninterrupted blocks of time in which children have freedom to choose their *work*. The environment is neatly ordered and arranged according to subject matter, with special consideration for what is appropriate for the children at a given time.

Montessori believed that the formation of children's fundamental capacities is hugely important during the first years of life. During this time, children are not only engaged in academic learning, but also the ability to concentrate, persevere, develop independence, and socially interact with others. This time lays an important and strong foundation for their future development.

A revolutionary for her time, Maria Montessori was educated as an engineer, in a field dominated by men. She then attended medical school and became the first female doctor in Italy. During her studies in Italy as an assistant doctor at the Psychiatric Clinic of the University of Rome she would frequent the insane asylums to observe the sick and developmentally challenged children. She became interested in the pedagogical effects, rather than medical problems, that contributed to the mental delays in these children.[26] She began to research this idea and present her work to teachers in Italy, which led to the founding of a Medical Pedagogic Institute where children of public schools and the insane asylums would go. In working with these children, she "became convinced that similar methods applied to normal children would develop or set free their personality in a marvelous and surprising way."[27] After working with these developmentally challenged children to read and write, these children passed the examination at the public school, validating the effectiveness of her methods.[28] She believed that the developmentally challenged had been helped through unlocking their abilities and true selves through being taught in a different way, and that the normal children were delayed by their current educational environment.[29]

Based on the observations and successes from this work, she opened the first Montessori School, the Casa dei Bambini, in Rome in January 1907. Interest spread and several other schools opened in the next few years, all adopting this new Method. Today there are approximately 22,000 worldwide, and nearly 5000 in the United States.

Montessori took into careful consideration the physical and the cognitive development of the child, and how the two are interrelated. She understood that the young child is developing

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26 Montessori, Maria, *The Montessori Method,* 44.
27 *Ibid.,* 45.
28 *Ibid.,* 48.
29 *Ibid.,* 49.

coordination, muscle movement, and sensory perception.[30] She developed her Method that allowed for freedom of movement and ability to develop in a prepared classroom that allowed the child to explore and engage with sensorial learning experiences that would equip him or her for the world. She defined 6 Sensitive Periods that are stages of development for young children, in which she adjusted her pedagogy accordingly. She connected these Sensitive Periods with appropriate methods and materials for the child during that time.

The Sensitive Periods[31]

Sensitivity to order
Sensitivity to language
Sensitivity to walking
Sensitivity to the social aspects of life
Sensitivity to small objects
Sensitivity to learn through the senses

Montessori believed in a scientific approach to understanding education; She felt that the teacher is a scientist and that, "The practical progress of the school demands a genuine fusion of these modern tendencies, in practice and thought; such a fusion shall bring scientists directly into the important field of the school and at the same time raise teachers from the inferior intellectual level to which they are limited today."[32]

The Montessori Method is very popular today, increasing in numbers every year. While its success and effectiveness is sometimes considered subjective or anecdotal, research from Angeline Lillard presents quantitative analysis of the effectiveness of the Montessori Method.

In a study from 2006, Lillard evaluated the social and academic impact of the Montessori education.[33] Lillard selected children in the primary (3-6) and elementary (6-12) age group, and through a lottery from a pool of interested parents, Lillard set up a control group and an experimental (Montessori) group at a Montessori school in Wisconsin, that was predominantly urban minority students. Using a lottery system addressed the concern that parents who seek to enroll their child in a Montessori school are different from parents who do not.[34] At the end of the study, the children in the Montessori group outperformed the traditional school group on tests for cognitive, academic, social, and behavioral skills.[35]

Much has changed since this Maria Montessori developed her Method. Today, her

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30 Montessori, Maria, *The Montessori Method,* 53.
31 Montessori, Maria, *The Absorbent Mind,*
32 Montessori, Maria, *The Montessori Method,* 25.
33 Lillard, Angeline, and Nicole Else-Quest, "Evaluating Montessori Education," *Science* Vol. 313, Issue 5795 (2006): 1893-1894.
34 *Ibid.*
35 Lillard, Angeline, and Nicole Else-Quest, "Evaluating Montessori Education," *Science* Vol. 313, Issue 5795 (2006): 1893-1894.

approach is proven-effective and timeless. Given the importance of new fluencies today, we could extend this her approach to include additional subject areas, particularly computational thinking.

Approach

The powerful ideas behind computer science are essential knowledge for children today. Based on the proven effective methods of the Montessori Method,[1] I use this approach in order to develop a new curriculum of learning materials that are specifically designed to demonstrate ideas in computational thinking to young children beginning at age 3.

This work includes:

1) Defining computational thinking in this context
2) Developing a scope and sequence for this curriculum
3) Designing materials that demonstrate computational concepts
4) Writing lesson plans to assist teachers in using the materials
5) Evaluation through observation in classrooms

1 Lillard, Angeline, and Nicole Else-Quest, "Evaluating Montessori Education," *Science* Vol. 313, Issue 5795 (2006): 1893-1894.

Related Work

Computational Thinking for Children

Children today are *digital natives.*[1] They have grown up and live in a world where digital technologies are integrated in their lives. From a very young age, they develop a natural fluency with digital technologies by default. In this digital world, they are socially connected, presented with near infinite knowledge, and are natural users of smart phones and computers.

However, while children today are *users* of digital technology, they are lacking the fundamental understanding of how computers work and the underlying logic necessary to use them as powerful and creative tools. There is need to cultivate their ability to use digital tools to encompass a broader definition of digital fluency that extends beyond simply being digital users.

Everyone agrees that children from a young age need to learn reading, writing, and arithmetic. And we could add computational thinking to these core fluencies as a new form of literacy.[2] Still, the majority of classrooms do not teach computational thinking or concepts.[3]

Because computer science is not explicitly required for testing metrics such as the Common Core,[4] teachers must integrate it into their classrooms, either in creative applications across other disciplines, or as a separate subject matter. The latter is a difficult task for teachers with limited resources, limited class time, and pressure to teach for a test. For these reasons, and because computational thinking is practically implemented across disciplines, some suggest that computational concepts should be integrated within the existing curriculum, with such subjects as math and science.[5]

Computer science continues to be a male-dominated field, with limited inclusion of many minority groups. It is critical then to provide opportunities in computer science to a diverse range of students, though teachers struggle to overcome challenges of gender bias and misconceptions about what computer science is and why it is relevant. In older classrooms, there is a lack of qualified teachers to teach this subject matter. In younger classrooms, there are misconceptions about the challenges and reluctance to teach unknown subject matter.

Large-scale efforts from groups such as Code.org[6] and Google[7] offer support for

1 Prensky, M. Digital native, digital immigrants. On the Horizon 9, (October 2001), 1.

2 Wing, Jeannette M, "Computational Thinking," *Communications of the ACM* 49, no. 3 (2006): 33.

3 "Promote Computer Science." Code.org, accessed November 10, 2016, https://code.org/promote.

4 Center for Technology in Learning at SRI International, "Exploring Computer Science: Curriculum Mapping to Learning Standards," accessed May 8, 2017. http://pact.sri.com/downloads/ECS-Alignment-Common-Core-v-0-1.pdf.

5 Wilensky, Uri et al, "Fostering computational literacy in science classrooms," *Communications of the ACM* 57, no. 8 (2014): 24-28.

6 "Promote Computer Science." Code.org, accessed November 10, 2016, https://code.org/promote.

7 Google (n.d.), "Exploring Computational Thinking," accessed November 2, 2016. http://www.google.com/edu/computational-thinking.

computer programming instruction in schools;however, the challenges are still great and attracting diverse students in this way is still challenging.[8]

Still, many students do not know how to pursue computer science or understand clearly what exactly it is.[9] Perhaps one of the difficulties in teaching computer science is agreeing what it is, as many have different definitions and boundaries for what it includes. With the popularity of the term *computational thinking*, many use this term in order to broaden the definition to include skills of problem solving; and others, perhaps as a way of emphasizing the computer as a tool, not the end.[10]

Approaches for Computer Science Education

Considering the contemporary and changing landscape of skills necessary for children today, many large-scale efforts have been made to facilitate the instruction of computational thinking (most often through programming) in schools today.[11, 12] I outline some of these approaches here, categorizing them by those that do not use screens, those that do use computer screens, and those that demonstrate programming through robotics.

Computer Science without Screens

CS Unplugged. CS Unplugged is a set of online resources for teaching computer science without computers. CS Unplugged activities are suggested for elementary students and consist of fun, engaging activities that do not use a computer. Lessons are all done without a computer, through fun and cooperative activities that creatively incorporate games, play, and magic tricks. Developed by Tim Bell, Ian H. Witten, and Mike Fellows, one goal of CS Unplugged is to provide free access to computer science educational materials to students worldwide, in and out of schools.[13] The creators of CS Unplugged define "real computer science," as "algorithms, artificial intelligence, graphics, information theory, human computer interfaces, programming languages, and so on."[14] In this way, the aim is to extend computer science beyond programming to include other aspects of computational thinking and concepts.

A strength of this approach has been evident through the adoption by teachers,[15] by

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8 Wilensky, Uri et al, "Fostering computational literacy in science classrooms," *Communications of the ACM* 57, no. 8 (2014): 24-28.

9 Carter 2006; Mitchell et al. 2009

10 "CS Unplugged About," Bell, Tim et al, accessed May 2, 2017. http://csunplugged.org/principles/.

11 "Promote Computer Science." Code.org, accessed November 10, 2016, https://code.org/promote.

12 Google (n.d.), "Exploring Computational Thinking," accessed November 2, 2016. http://www.google.com/edu/computational-thinking.

13 "CS Unplugged About"

14 *Ibid.*

15 Bell, Tim et al, "Computer science unplugged: School students doing real computing without computers," *The New Zealand Journal of Applied Computing and Information Technology* 13, no. 1 (2009): 20-29.

providing them with resources, simple and fun activities, all independent of computers.

Some research has been done to evaluate the effectiveness of the CS Unplugged activities. In one study, researchers evaluated the effect of CS Unplugged on seventh-graders' views and attitudes toward computer science, and the ways in which the objectives of CS Unplugged are expressed through the activities.[16] The study was specifically concerned with the mindset and views that students had regarding computer science, its relevance in their lives, its scope—and how it changed (or did not change) after engaging with CS Unplugged learning activities. The results of the study suggested that the attitudes and views of the students did not change much after participating in the CS Unplugged activities.[17] The authors argued that the importance of computational thinking (which they consider broadly as problem-solving) as independent from computers was not explicitly stated and so the students did not make the implied connection.

Their conclusions suggest that for this age group (seventh grade) an explicit explanation of these ideas and their relationship to computer science needs to be a necessary discussion in order for the students to make the connection and understand its relevance on a personal level.[18]

Hello Ruby. *Hello Ruby* is an interactive storybook that breaks down the components of computational thinking into a playful story about a girl named Ruby and her friends. *Hello Ruby* was created by Linda Liukas, a Finnish programmer, author, and illustrator. The book walks children through various activities that frame these concepts within Ruby's world. It is cute, imaginative, and playful storytelling. Liukas' approach is unique in its lack of technology, but also the aim to explore computational concepts across multiple subject matters. In this way, she is attracting children with diverse interests at young ages while allowing teachers to feel comfortable introducing the content. Abstract computational concepts are nested in activities and stories, and children may or may not make any specific connection with actual computers.

Finland is unique compared to the United States, because computer science is now part of the curriculum, introduced at young ages. In the United States, programming is often taught as an isolated skill, whereas Finnish children are exposed to programming as a tool useful across many disciplines.[19]

Computer science through programming with computers

Scratch. Through its accessible and simple block programming language, Scratch breaks down the complexities of syntax and coding into basic concepts so that children can build and

16 Taub, Rivka et al, "CS unplugged and middle-school students' views, attitudes, and intentions regarding CS," *ACM Transactions on Computing Education* (TOCE) 12, no. 2 (2012): 8.

17 *Ibid.,*

18 *Ibid.,*

19 "Teaching Computer Science without Computers," The Atlantic. https://www.theatlantic.com/education/archive/2017/02/teaching-computer-science-without-computers/517548/?ref=ksrfb&__prclt=UdhBr8gw

create around content they are excited about and share it with others. Scratch demonstrates concepts of computational thinking through direct application in creative programming projects. Scratch is a project of the Lifelong Kindergarten Group at the MIT Media Lab, under the direction of Mitchel Resnick. As a free platform, Scratch is popular and accessible all around the world with more than 30,000 new projects added to the site each day by "Scratchers" who are on average between the ages of 8 and 16.[20]

Scratch is based on 3 design principles: tinkerable, meaningful, and social.[21] Its simple block programming language allows children to learn through immediate feedback of trial and error, with a low barrier of entry to get started, and develop more and more complexities as their skills improve. It is meaningful in that it provides an open environment in which children bring their own personal interests and projects. Scratch is unique in its social aspect, serving as a platform to connect users across the world with sharing and remixing projects.

Code.org. Code.org similarly uses a web-based computer interface, and like Scratch, focuses on programming through scaffolded exercises. Unlike Scratch, however, Code.org exercises are limited in that they do not allow for the same creative opportunity for individual projects. Exercises are highly prescriptive and directed; which allows for easy and controlled success, but without the same social or personally meaningful interaction. While Scratch is a creative tool, activities on Code.org tend to focus on instruction.

Robotics as tangible computational thinking

Another approach that embeds computational concepts within activities apart from screens is introductory robotics. Robotics activities take children away from sitting in front of a screen and allow them to develop fine motor skills and hand-eye coordination and opportunities to collaborate with others.[22] It can be a process of tinkering and play, using an active interaction with technology beyond the screen. I look here at two examples, Kibo and Cubetto.

Kibo. Kibo is a project by Marina Bers as part of the DevTech Research Group at Tufts University. Kibo introduces children to early robotics, allowing them to program their robot by scanning blocks that represent simple commands. Situating computational concepts within programming in a tangible way, the emphasis is away from screens and children are interacting together in real space.

Bers is specifically interested in early childhood education, targeting the Kibo for children as young as 4 and up to 7. Bers has tested this approach using the Kibo (formerly the Kiwi) and she concluded that younger pre-k students are able to master the foundational concepts of

20 Resnick, Mitchel, et al, "Scratch: programming for all," *Communications of the ACM* 52, no. 11 (2009): 60.
21 *Ibid.*, 63.
22 Lee et al. 2013

programming a robot, and that a 7-year-old can master programming a robot with conditional statements.[23] According to Bers, "Robotics offers a way to teach young children about the types of sensors and electronics they encounter in daily life in a hands-on and engaging way. Teaching foundational programming concepts, along with robotics, makes it possible to introduce children to important ideas that inform the design of many of the everyday objects they interact with."[24]

Cubetto. Cubetto is very similar to Kibo, and was released in 2016. It was widely popular, and raised significant funding on Kickstarter. Its deployment in the parent home market (rather than primarily in schools) is evidence of the desire on the part of parents to introduce their children to computational concepts, and in a hands-on way. It uses a robot similar to the Logo turtle, relating to a common lineage of children and programming, again with simple programming through blocks. There is no screen or computer involved. Children as young as 3 program the wooden robot to roll around using simple blocks that they arrange on a board, along with a specific mat for the robot's world and accompanying storybooks.

Models and Materials

Piaget believed that children construct their own knowledge in response to their experiences.[25] Likewise, Montessori also sought to situate learning in a child's life, as it practically and personally called to the individual.[26]

Most people can think back to a time in childhood and remember a specific toy or object that evoked a transformative experience. For me it was as simple as a set of pencils and my sketchbook. They were transformative because of the world they allowed me to create. Physical objects have the power to shape a child's learning experience and establish deep models that will serve them throughout their lives. Seymour Papert spoke of the "Gears from His Childhood"[27] and Frank Lloyd Wright was forever changed and inspired by Froebel's Gifts.

> Seymour Papert wrote about the gears:
> "I believe that working with differentials did more for my mathematical development than anything I was taught in elementary school. Gears, serving as models, carried many otherwise abstract ideas into my head. I clearly remember two examples from

23 Bers, Marina Umaschi et al, "Computational thinking and tinkering: Exploration of an early childhood robotics curriculum," *Computers & Education* 72 (2014): 145-157.

24 *Ibid.*

25 Piaget, Jean, Howard E. Gruber, and J. Jacques Vonèche. The Essential Piaget. New York: Basic Books, 1977.

26 Lillard, Angeline Stoll, *Montessori: The Science behind the Geniu,*. New York: Oxford University Press, Inc., 2007, 29.

27 Papert, Seymour, *Mindstorms: Children, computers, and powerful ideas.* New York: Basic Books, 1993.

school math. I saw multiplication tables as gears, and my first brush with equations in two variables (e.g., 3x + 4y = 10) immediately evoked the differential. By the time I had made a mental gear model of the x and y, figuring how many teeth each gear needed, the equation had become a comfortable friend."[28]

Papert writes about the importance of the gears in constructing his knowledge because they were part of his *natural landscape*, part of the adult world around him which allowed him to relate to others, and he could use his body to think about the gears—imagining how they work through understanding how his own body turns.[29] He called the gears an "object-to-think-with" because the gears contained information that allowed him to think about formal mathematical systems.[30]

In this sense, an experience with a physical material has the transitive quality to build the mental models in our minds. "Anything is easy if you can assimilate it to your collection of models," wrote Papert.[31]

Montessori Materials

The Montessori classroom is highly characterized by the traditional Montessori materials. They are elements in a carefully-prepared classroom, ordered neatly, and presented on the shelves as the children are prepared for them. Maria Montessori developed her original materials as a complete framework for the early childhood classroom. Based on her interpretation of the physiological and physical development of children, she divided her method into three parts: motor education, sensory education, and language and knowledge of the world. Motor education was included in practical life activities that referred to caring for the classroom, preparing meals, etc. Typically, the Montessori materials are characterized as self-correcting with control of error, simple without any extraneous or distracting information, and sensorial and tactile, in which discrete concepts are presented sequentially.

Montessori developed 83 materials for the primary (3-6-year-old) classroom, that incorporate practical life with the didactic materials that rely on sensorial demonstrations for language, writing, music, and arithmetic.

A quintessential example of this is the Pink Tower material, as Angeline Lillard describes: "The Pink Tower, for example, is not merely a tower of blocks of increasing size, but instead is a carefully calculated instrument to educate the senses and the motor system, and to implicitly introduce the decimal system and the notion of cubing...Each block

28 Papert, Seymour, *Mindstorms*, New York: Basic Books, 1993, vi-vii.
29 *Ibid.*
30 *Ibid.*, 11.
31 *Ibid.*, vii.

is 1 centimeter longer on all sides than the one that came before, and there are 10 such blocks, going from 1 cubic centimeter to 1000. The increasing size is reflected not only visually but also haptically and barically: Each block is heavier by an exponentially increasing magnitude."[32]

Materials are designed in an interweaving manner, so that they are all integrated and related to one another.[33]

Angeline Lillard has defined 8 characteristics ingrained in the Montessori Method and researched their effectiveness.[34] These characteristics inform the guiding principles of my work in creating new materials. They are:

Movement and Cognition: Movement can enhance cognition and learning.
Choice: Learning and well-being are improved when people have a sense of control over their lives.
Interest: People learn better when they are interested in what they are learning.
Intrinsic motivation: Extrinsic rewards are avoided, and can be disruptive to a child's concentration. It can negatively impact their motivation. Intrinsic motivation also fosters independence.
Collaboration: Learning with and from peers in mixed-age classrooms. Collaborative environments are conductive to learning.
Context: Learning situated in meaningful, practical contexts is deeper than learning in abstract contexts. Learning by doing, rather than being told.
Adult interaction: Child interaction with adults is associated with optimal child outcomes, particularly when adults (parents and teachers) provide clear limits but allow for freedom within those boundaries.
Order and the Environment: An orderly environment is beneficial to children. Montessori classrooms are physically ordered and conceptually ordered.[35]

Wildflower Montessori

Wildflower Montessori is a research project that grew out of the Social Computing Lab under Sep Kamvar. It is a model for innovative shopfront Montessori schools. They are a network of independent, teacher-led schools integrated into the community, with an emphasis on parent

32 Lillard, Angeline, "How important are the Montessori materials?" *Montessori Life* 20, no. 4 (2008): 21.
33 *Ibid.*, 22.
34 *Ibid.*, 22
35 Lillard, Angeline Stoll, *Montessori: The Science behind the Genius,* New York: Oxford University Press, Inc., 2007, 29-33.

involvement, nature, and beauty.[36] They are also designed as research lab schools; which means that each school is a research setting dedicated to advancing knowledge and innovation about the ways in which children learn in these schools. This provided an ideal classroom in which to test my materials. I have a close relationship with the teachers of these schools, and we have a shared vision about education that was developed together through this lab project. Working with Montessori trained educators in this research environment was invaluable.

36 "Social Computing Learning," Social Computing Group, Media Lab, accessed on May 2, 2017, http://social.media.mit.edu/areas/learning.

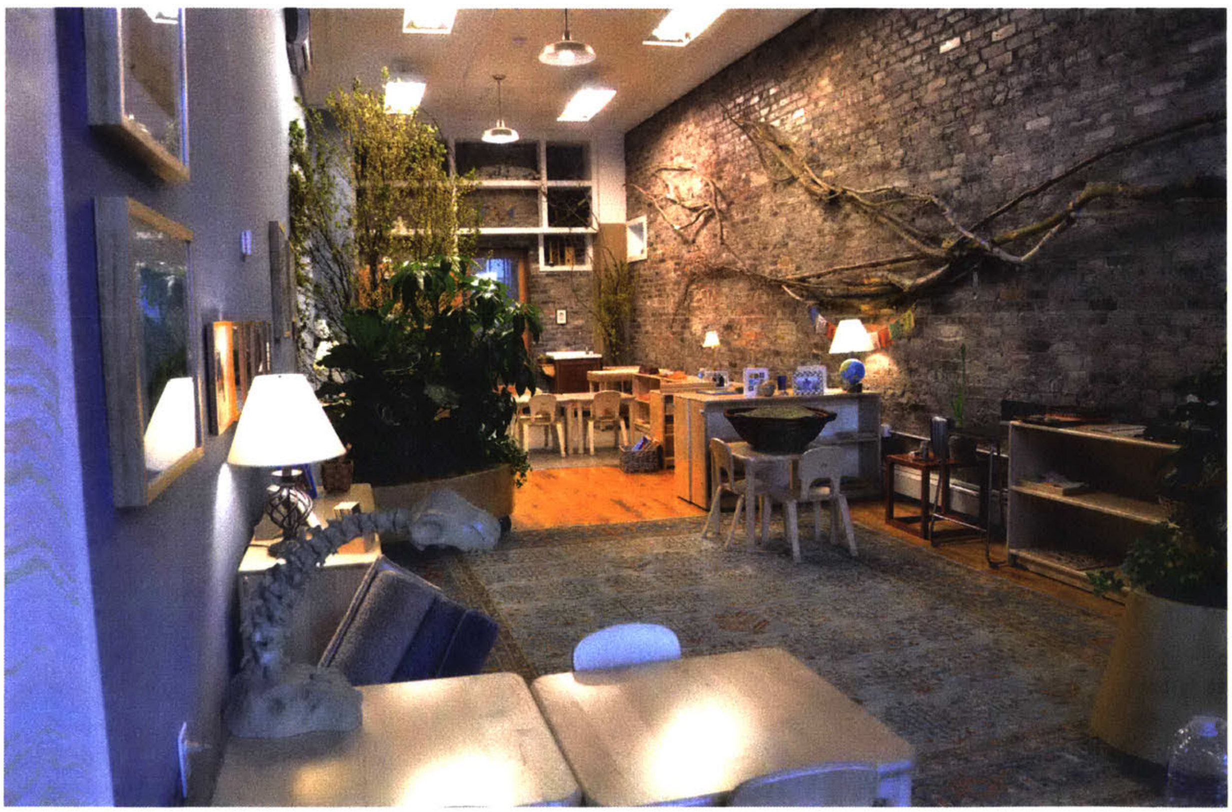

fig. 1. Interior of Wildflower Montessori School in Cambridge, MA. 2014.

Work

Defining Computational Thinking

The term *computational thinking* was first used by Seymour Papert in 1980, who spoke of it in relationship to the cultural significance of the time. In developing LOGO, Papert realized the need to create "objects-to-think-with" that connected people with engaging and shareable kinds of activities. As he experienced the rise of personal computers, he saw the need to integrate computational thinking into everyday life. He saw the role of the educator as one of an anthropologist, needing to consider cultural and social implications in order to implement educational reform.[1]

The term was later used and first popularized by Jeanette Wing and later Karen Brennan and Mitchel Resnick, and Marina Bers, among others. According to Wing, "Computational thinking involves solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science."[2]

Brennan and Resnick describe 3 dimensions of computational thinking: concepts, practices, and perspectives; which are implemented in Scratch. *Concepts* include: sequences, loops, parallelism, events, conditionals, operators, data. *Practices* include: experimenting and iterating, testing and debugging, reusing and remixing, abstracting and modularizing. *Perspectives* include: expressing, connecting, questioning.[3]

> In my interview with computer scientist Sanjoy Mahajan, he described it this way: "It is the argument of building broad schemas. So broad, and not a rote understanding of things. A skill I think is equally important, is the ability to make abstraction. To say, ok this problem divides into many layers, so there's gonna be a whole bunch of little processes, algorithms, that do this little transformations. One of the fundamental ideas is representation. And you can use numbers to represent all kinds of different entities in the world, whether it's pictures it could be algorithms or numbers themselves. Many things that you don't think that could be represented by numbers can be. Computational thinking is about that."[4]

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1 Papert, Seymour. *Mindstorms: Children, computers, and powerful ideas.* Basic Books, Inc., 1980,182

2 Wing, Jeannette M, "Computational Thinking," *Communications of the ACM* 49, no. 3 (2006): 33.

3 *Ibid.,*

4 Sanjoy Mahajan (Computer Scientist, Olin College, MIT), interviewed by Kim Smith at Cambridge, MA, October 2016.

Naming

In my interviews and conversations with both educators and parents, I learned that many were intimidated by the idea of teaching computer science, and understandably so. Computer science for many evoked something very foreign and unknown, and challenging beyond reach. Using the term computational thinking was a choice of broadening the scope, while also using a descriptive term that allows teacher to connect it to thinking, logic, and problem-solving. Many said, *ok, I understand what logic or problem-solving, and patterns, and representation means.*

One teacher suggested there was no real need to name this subject area when introduced to the Montessori classroom. Simply referring to them as their individual names was extremely unassuming and accessible for teachers. For example, presenting a material with its name, unattached to computer science, such as the *Logic Gates*, presents a simple representation of the concept of Boolean Logic, and is easily associated with language. It is represented in a way that is easy for very young children to understand, and in isolating these materials without attachment to computers, they become larger, broader, more accessible for educators. These ideas transcend computers, and opportunities to incorporate them into other disciplines has the potential to attract a variety of learners to play with these ideas.

In one conversation that I had with the elementary teacher, she explained how much of Montessori didactic curriculum breaks down into Language and Math. Interestingly, I see computational thinking living in a unique space between both language and math. As Mahajan described it, "It's the use of numbers to represent data and how to process and change the data so that's the language. It's describing a language and describing the things that we talk about with the language, which can numbers do all of that."[5]

Computational Thinking Scope and Sequence

This Computational Thinking Scope and Sequence (fig. 2) was developed with my lab colleague, Yonatan Cohen and computer scientist, Sanjoy Mahajan. Through extensive research into the fundamentals of computer science and close collaboration with Mahajan and Montessori experts, we designed this scope and sequence to represent a broad foundation of computational concepts that are implemented in our computational thinking curriculum. These concepts are the basic ideas behind how computers work, and form the building blocks for a comprehensive understanding of computer science. The focus is on a broad scope of concepts, including, but not limited to, programming. These concepts are demonstrated as concrete models without computer screens.

The concepts in this scope and sequence are non-sequential. They form a network,

5 Sanjoy Mahajan (Computer Scientist, Olin College, MIT), interviewed by Kim Smith at Cambridge, MA, October 2016.

defined by larger nodes of ***bits***, ***structures***, ***algorithms***, and ***representation***. As a network, concepts relate to each other, and the materials can be used independently, and in some cases, integrated simultaneously with other materials.

In addition to concepts, computational processes such as checking for error, abstraction, representation, and iteration are embedded in the lessons. For example, the self-correcting materials allow children to check for errors and fix mistakes.

Designing Materials

After identifying the key concepts in the scope and sequence, the next step was implementing abstract concepts with physical, concrete models. Through sketching, conversations with computer scientists, and paper prototyping, designs cycled though quick iterations until creating a working prototype. The following design principles guided the development of these materials.

Design Principles

Montessori. Traditionally, Montessori materials are highly sensorial, self-correcting, and sequential through isolating concepts. I was very inspired by the ways in which Montessori used materials as artifacts that embody abstract ideas and allow children to use all of their senses in a way that is developmentally appropriate and thoughtful for their own periods of growth. She identified periods of sensitivity and created learning environments that met these needs and cultivated growth for the child. Through my conversations with teachers, I came to understand an important link between the process and correction of the materials and the child's ability to gain confidence through achievement. The Montessori materials allow children to reach a point of challenge, while providing them with the opportunity to succeed.

Scaffolded. Like traditional Montessori materials, these materials are scaffolded through isolating big abstract ideas into smaller steps or ideas that build off of one another. With the older students, one action or idea may be very singular because they have built the foundation already; however, with the younger students, that same single concept/action/idea may necessarily be broken down into smaller lessons, that build sequentially. So that the scaffolding for these materials builds on this idea, that big abstraction can be reduced to concrete smaller steps, and through mastering them sequentially, a child can build a larger idea.

Additionally, scaffolding is exemplified through multiple lessons for each material. And these lessons not only build ideas, but also can increase in challenge with new related concepts. For example, the Pixel Board demonstrates image representation. The younger ones may sensorially explore this material, placing the tiles on the grid and just playing. The next lesson may be matching the tiles with an image so that they recreate it. Next, they understand that a number can represent a color (black or white), and the next lesson will be connecting an image with numbered squares with the corresponding tiles. Then it becomes a matrix, and they use the matrix as a pattern for the tiles. And a more advanced lesson would be converting a decimal number into a binary one, and using the binary numbers as the code for the image. Scaffolding allows for multiple ages, and multiple levels of interaction.

Concrete. The materials provide tangible, physical engagement within the real world. These materials demonstrate abstract concepts with physical objects, through breaking down levels of abstraction into smaller, discrete ideas that can be represented tangibly. Not only does this appeal to a child's developmental stages, but it also allows them to build a model sensorially, with visual and spatial understanding. In the future, when a child is presented with more advanced ideas and applications in computer science, the ideas are already there in his or her mind. Concrete objects have the ability to engage children on multiple levels depending on their own individual learning styles. Concrete materials are unmediated by interface. So much of our interaction with computer science education is mediated by interface. These materials do not use technology or computer interfaces, so that the child's interaction with the concepts is simple, clear, and direct.

Cross-Contextual. Introducing computer science to young children in a variety of ways has the ability to engage children with all interests. Since computational thinking is really much broader than computer science, it can encompass a variety of skills that are shared across all disciplines.

Collaborative. Each material provides opportunity for either independent work or collaboration with peers. Since many of these materials are intended for a range of ages, allowing for different levels of engagement is an important part of meeting the child's interests. For example, from the observations in the classroom and the interviews with the teachers, I learned that the older ages are much more interested in learning with their friends and collaborating on projects, whereas in the younger classrooms, students typically worked independently, though sometimes taught the younger ones. The older ages are very interested in working socially, and according to one teacher, "Elementary kids are really interested in social. When they are little, they are learning how to become themselves, how to become an individual. And now during the elementary years, they are practicing becoming part of society."

Beautiful. It is important to me that these materials are aesthetically conscious. Visually, the materials should call to the children. The materials are created from natural materials, in very simple and carefully considered designs. They are simple without extraneous details, because extra information can be distracting for children, especially at young ages. Maria Montessori said, "The child should live in an environment of beauty."

Creating these materials was in iterative process in which feedback was gathered through early observations in the classroom. Materials were developed through quick iterations of prototypes, building from sketches to simple mock ups and then refined through digital fabrication processes such as the CNC, laser and vinyl cutting. As these fabrication methods become more common and accessible, others may use these techniques to create their own.

Curriculum writing

In addition to creating the materials for the key concepts, I also wrote individual lesson plans to support the curriculum. My lesson plans began loosely structured so as to equip the teachers with the knowledge necessary about how the materials may function, and the concepts they represent. In conducting the studies, teachers were provided these rough lessons, so that through this study process, I could gain their feedback to iterate and create new lessons. Revised lessons can be found in the Appendix. Since these were deployed in the Montessori classroom, I wrote these lessons as they would fit into the Montessori Method.

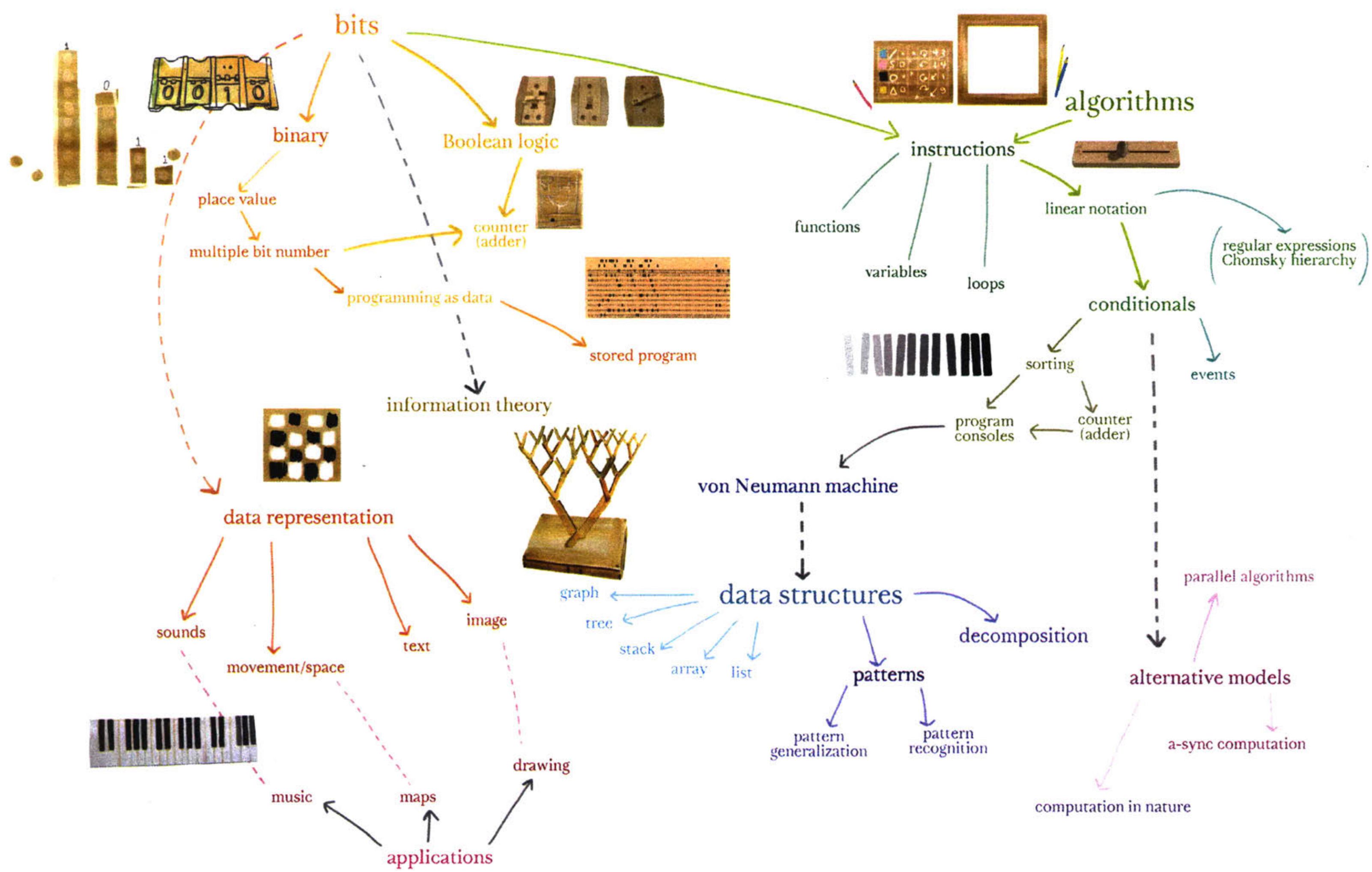

fig. 2. Computational Thinking Scope and Sequence.

The Materials

Binary Towers

fig. 3. Binary Towers in Montessori classroom, in Cambridge, MA. 2016.

The **Binary Towers** are an interactive activity to discover binary numbers for corresponding decimal values. The Binary Towers range from 8 balls-high, to 4-high, 2-high, and 1-high boxes, to represent place value for binary counting. The boxes are either filled completely to the top, or remain completely empty. When the box is full, the lid is shut and reads "1." When it is empty, the lid remains open and it reads "0." Children fill up the towers to discover how to count in binary, so that the lids of the towers read back the binary number for the corresponding quantity of balls.

This material is designed in such a way to be highly sensorial. Visually and spatially, the place values double in size, to physically demonstrate the doubling of the binary place values. Very quickly, children can see how the towers get larger, and begin to visualize the pattern. Towers that are 16- and 32-bit high approach the scale of the child and children begin to form a body connection to the scale of the quantity. The towers have holes like windows in the front, in order to see if they are filled and how much so.

Sound is also an important sensorial aspect of this material. The lids make a clapping sound and the balls make a clinking clunking sound that children enjoy. Sound is engaging and fun, and provides immediate sensorial feedback.

This material was designed to exemplify the exponential aspect of binary place value, as well as the idea that these boxes either are full or empty, 1 or 0. This either/or is an important idea in understanding binary.

This material was designed for younger and older children, and the earliest lessons are playful and exploratory for the younger ones, with the objective of understanding how to fill the boxes and close the lids, and make the connection that they can only be full or empty, and discover an association with the digit on the lid. Lessons for the older children allow them to convert from decimal values to binary, and physically count in binary. This material is designed for independent or collaborative work.

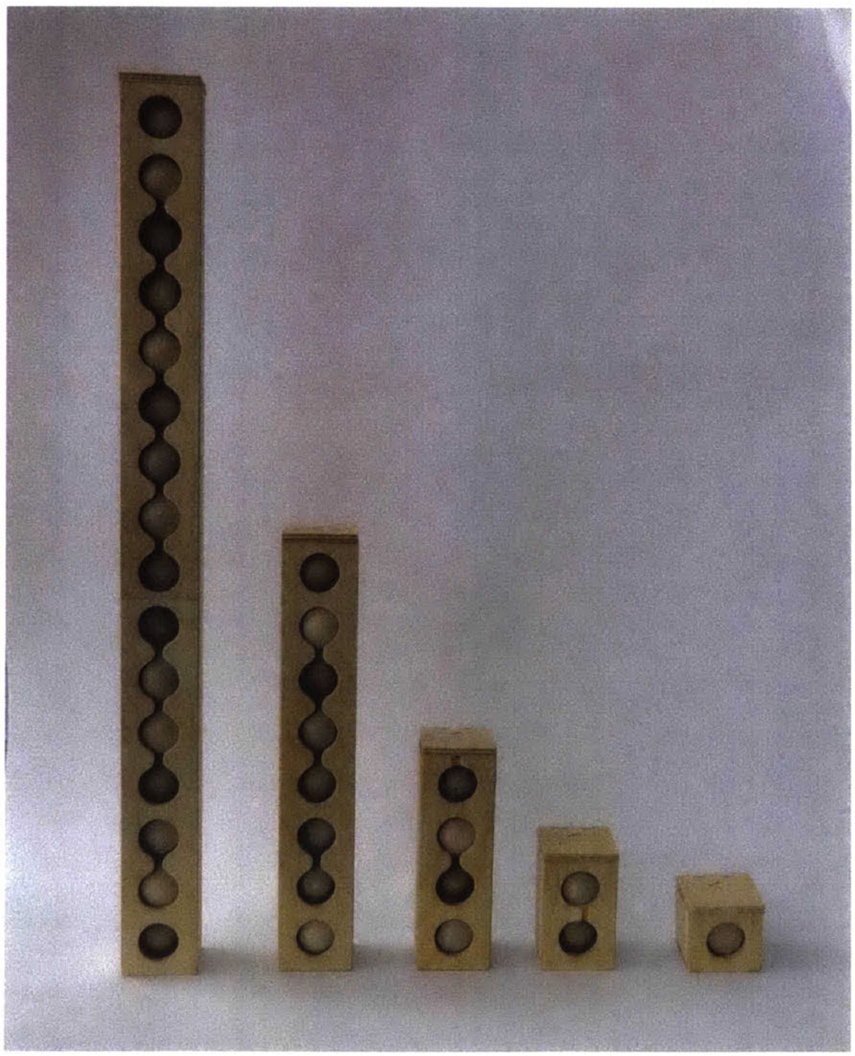

fig. 4. Binary Towers, up to a 16-bit tower, with each box filled to represent "1, 1, 1, 1, 1" which is equal to 31.

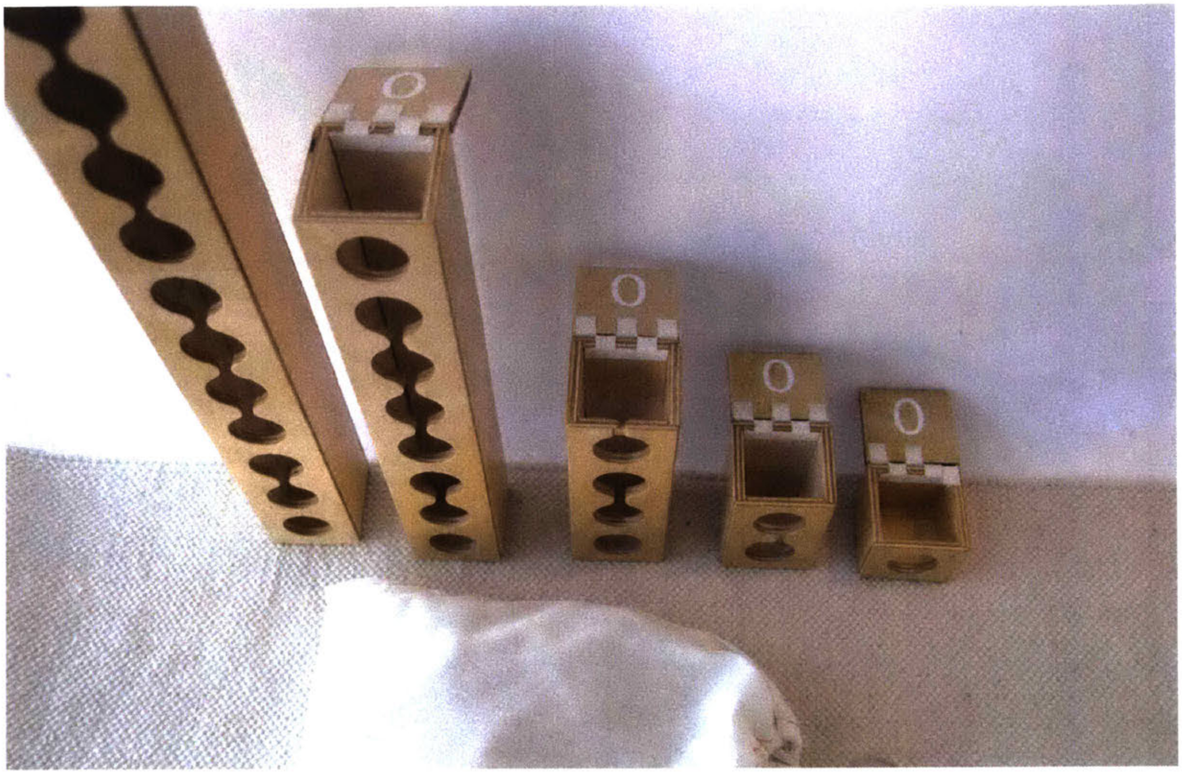

fig. 5. Binary Towers, with all of the boxes empty.

fig. 6. Binary Towers, representing "1, 0" in binary, which is 2.

Binary Cards

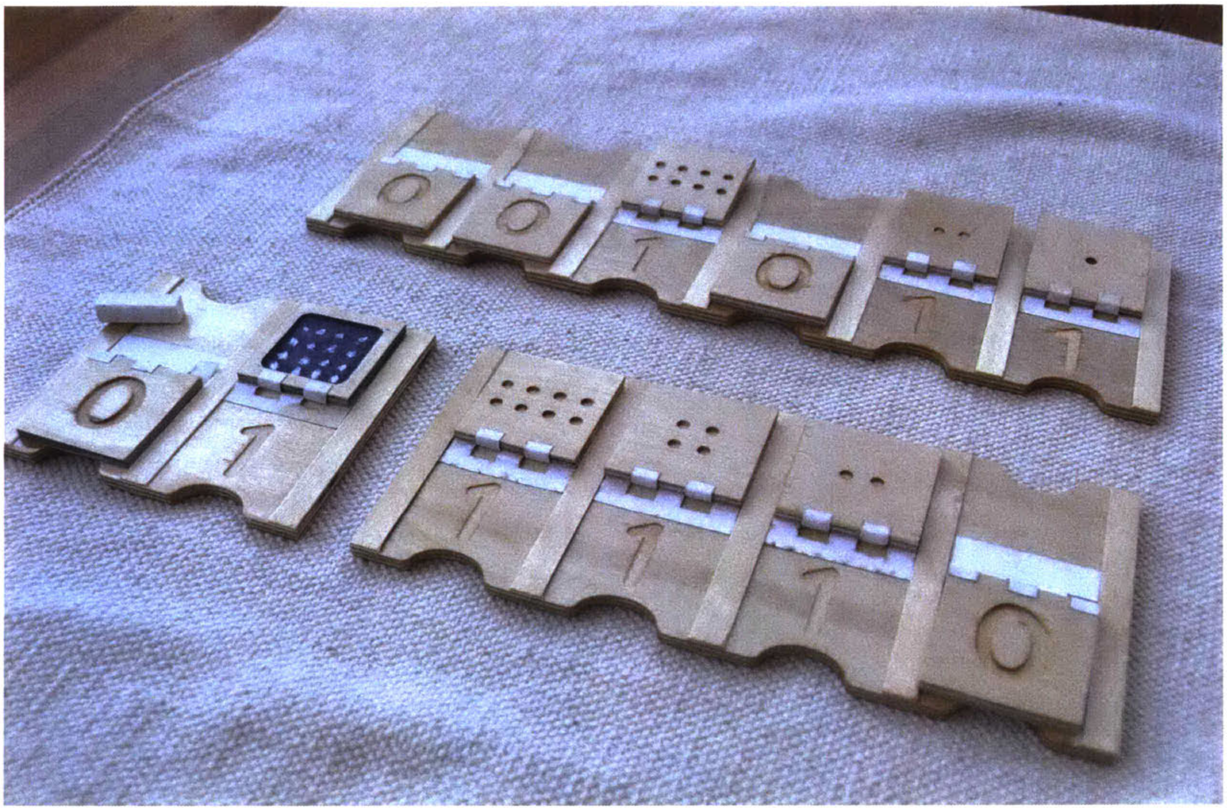

fig. 7. Binary Cards, in a Montessori classroom in Cambridge, MA, 2016.

The **Binary Cards** introduce children to binary counting and place-value. An abstraction of the Binary Tower, they demonstrate the correlation between quantities and their representation.

The cards are hinged to the board, and can be flipped one of two directions. The blank side represents a 0, and the side with dots represents a 1. The children count the circles (or insert small marbles) on the turned-over cards, and that number represents the decimal equivalent.

The binary cards allow children to convert large numbers into binary values rather easily, and less cumbersome than the binary towers. The binary cards clearly illustrate the concept of 1 or 0, like a switch, that is either one or the other, and this is demonstrated with the hinged card that flips back and forth and makes a slapping sound that children enjoy.

In designing these materials, sound was a consideration, as the flipping of the cards creates a clapping sound that appeals to children. The dots are intended to hold marbles, so that children physically place a quantity and count this value when converting to binary. With the binary materials, the connection is between the visual and physical quantity (as seen here with small marbles) rather than the decimal number as an abstraction. This is intended to further reduce the levels of abstraction for young children, with the intent that very young children can begin to gain an understanding of number systems and how they function as abstract representations.

Additional lessons, as seen in fig. 7, allow children to fill in the number of dots on a small chalkboard for the quantity in the specified binary place value. Working back and forth in this way, further tests for a child's understanding of the concept. If the child is able to work backwards in this way, and fill in the correct number of dots, he or she understands and can predict the pattern of binary numbers.

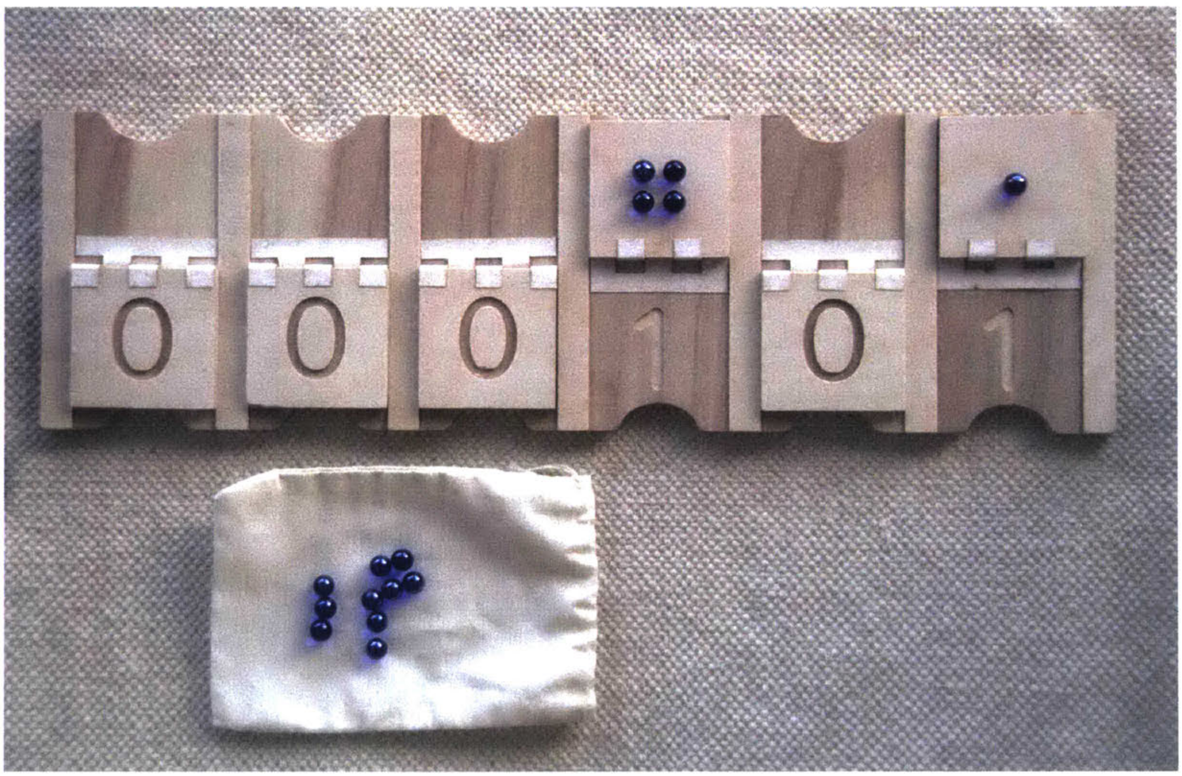

fig. 8. Binary Cards, representing 5 marbles here as "0, 0, 0, 1, 0, 1" in binary.

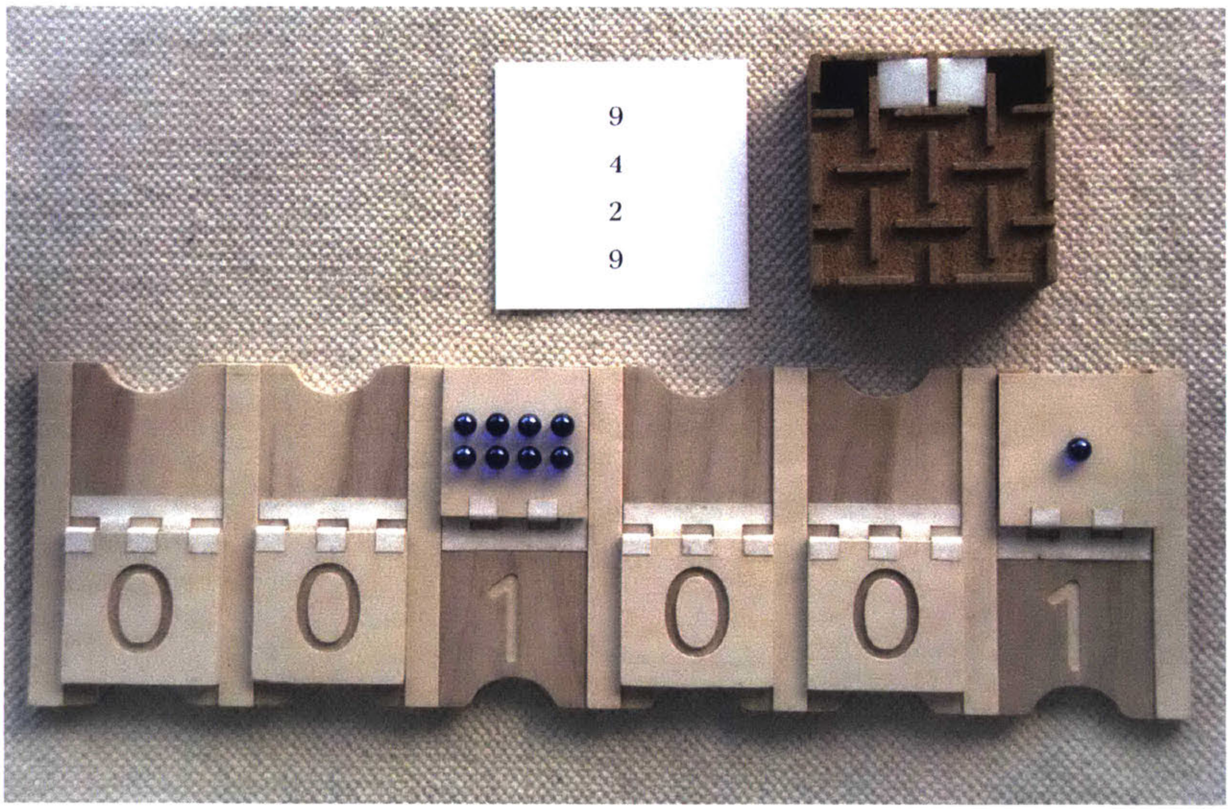

fig. 9. Binary Cards, and the Pixel Board. Here, the Binary Cards are used to convert decimal to binary, which are then implemented on the pixel board, seen here as partially filled in.

The Pixel Boards

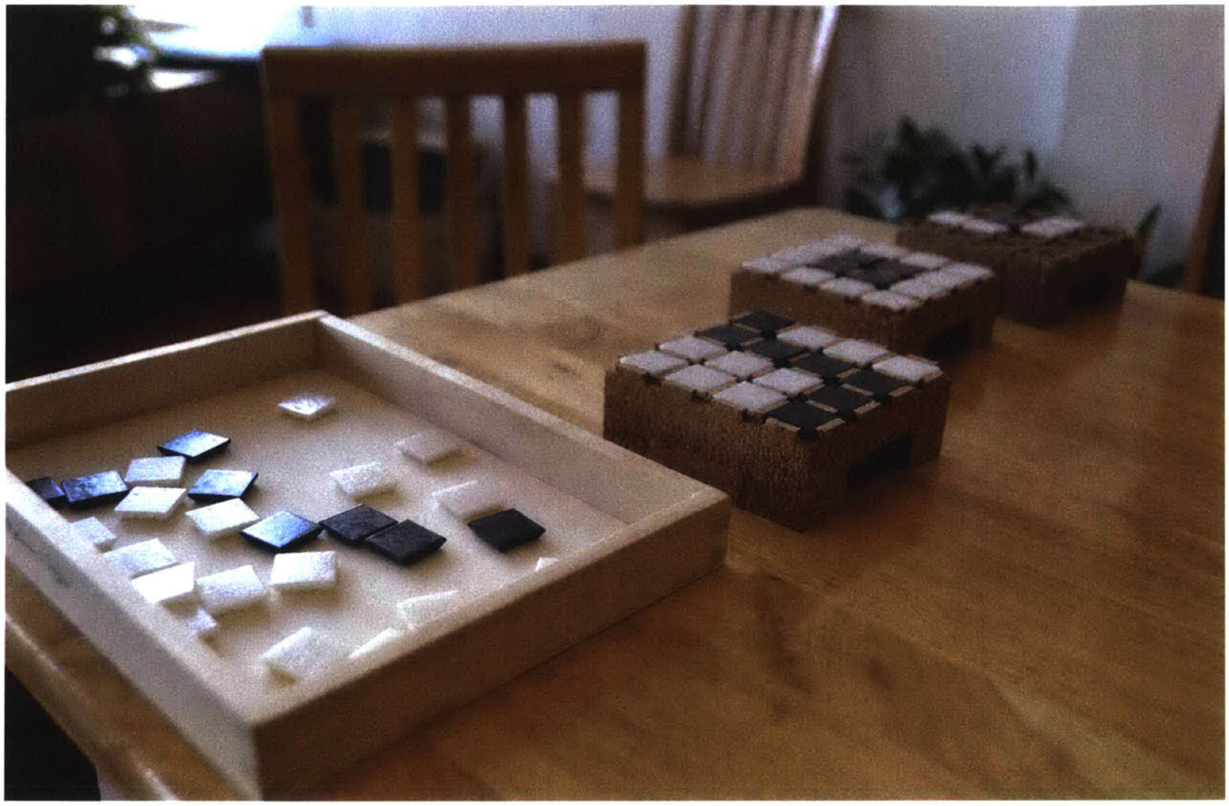

fig. 10. Pixel Boards in a Montessori classroom in Cambridge, MA.

The **Pixel Boards** demonstrate representation, specifically how computers represent images through numerical codes. Images can be represented as pixels, and these pixels can be represented with numbers. Children create images based on numerical representations, and then create and code their own.

The Pixel Boards consist of mosaic tiles, in black and white, which represent pixels. There are 2 different sized cork boards, a 4x4 grid and an 8x8 grid. The tiles are placed onto the cork board to create images. The key concept of this material is image representation. Images can be represented by numerical codes. This introduces children to the idea that numbers can represent images, and presents various levels of abstraction.

Pixels represent bits of data; and as the number of pixels increase, so does the data or information. Children construct a visual understanding of resolution. Resolution is the amount of information in a given area. In this context, it is how many pixels (tiles) there are on the board. The fewer pixels, the less information, and it has a lower resolution. Higher resolution means there is more data (information), and so there are more pixels. They will see that it is easier to make more detailed images or letters when they use the bigger board and have more pixels.

As an introduction, this could be contextualized as the way in which computers make pictures. For older ages, especially those who have learned binary, lessons continue in difficulty to that the child converts decimal values into binary numbers that represent the image.

This material can be used collaboratively, either in creating images together, or having students write codes for their friends. While there are a variety of activities with this material, they do follow a sequence in which they get progressively more difficult.

Lessons for this work demonstrate image representation through providing codes to implement, and allowing children to construct their own coded designs. For the youngest learners, age 3, they begin with exploring the work through placing the tiles on the cork board, and nothing more. At this age, they are developing the pincer grip, and creating patterns visually. Shortly after they may simply copy an image of black and white squares onto the cork board with the tiles.

The next step, suggested for age 4, is understanding that numbers represent a colored tile, and in this case, either a 0 or a 1 represents white or black. During this lesson, the teacher associates the number 0 with the white tile and the number 1 with the black tile. This is implemented with a small card, the same size of the tile, with the corresponding number on it. Through dialogue and directed questions, the child learns the association, and understands that a number can represent a color.

The next lesson consists of a same size grid that contains the digits 0 and 1, inside boxes similar in size to the tiles on the cork board. Children follow the boxes in order to set up the pattern on the cork board with their tiles.

This prepares them for the next lesson, in which the grid is replaced with a matrix. Children read a pattern of 0s and 1s listed in a matrix and create the corresponding image.

After a child understands binary numbers, and often in conjunction with using the binary cards, the latest of the lessons features a card with decimal numbers on it that children then convert to binary values of 0 and 1, and then use these binary numbers to create the image with the tiles.

This material provides opportunity for creative application in which children can design their own images and create corresponding codes. Collaboratively, there is opportunity to then share their codes, or decode their friends, or collaboratively work on 4 boards that can be joined together to form a larger board.

Black and white tiles were chosen as the most basic dichotomies of color (or rather lack of color). Throughout the materials, a common language exists, so that there is no confusion. In this case, whenever a 1 is represented it is always with black and a 0 is always white. Small tiles were chosen because of the fascination that children have with small, precious things, as well as the way they feel to touch. They must be placed carefully on the cork board, which is designed to hold the tiles just so, without their falling out if the board is tilted or carried. The cork boards are squares without proper orientation. Accompanying lesson cards contain many activities as we developed them to closely mirror systems and processes in computation. These cards are provided with a small arrow that indicates the orientation, and all of the cards include self-correction with the "answer" or the corresponding representation on the other side. The process of error checking is a necessary process in both computer science and the Montessori Method.

Further work on the pixel boards, based on teacher feedback, will incorporate larger scales. Children enjoy working together on this work and the added challenge of incrementally gaining complexity.

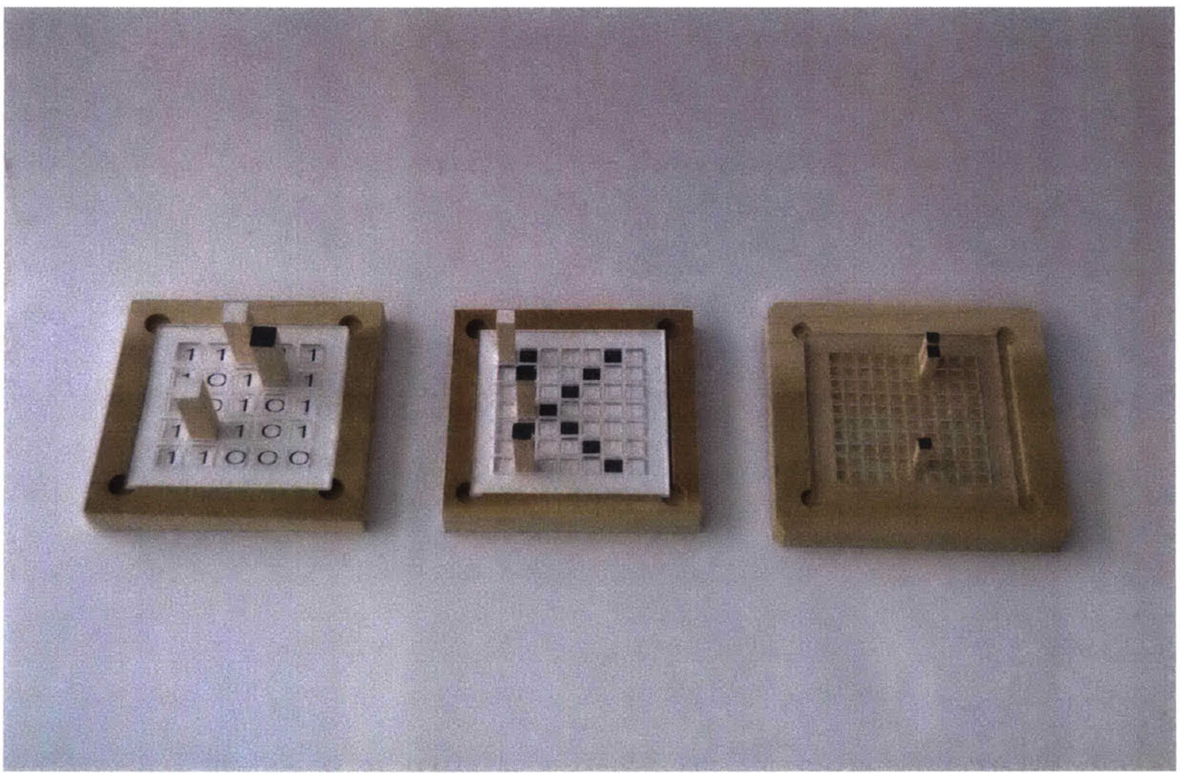

fig. 11. Early iteration of the Pixel Boards, seen here with pegs that represent pixels and resolution.

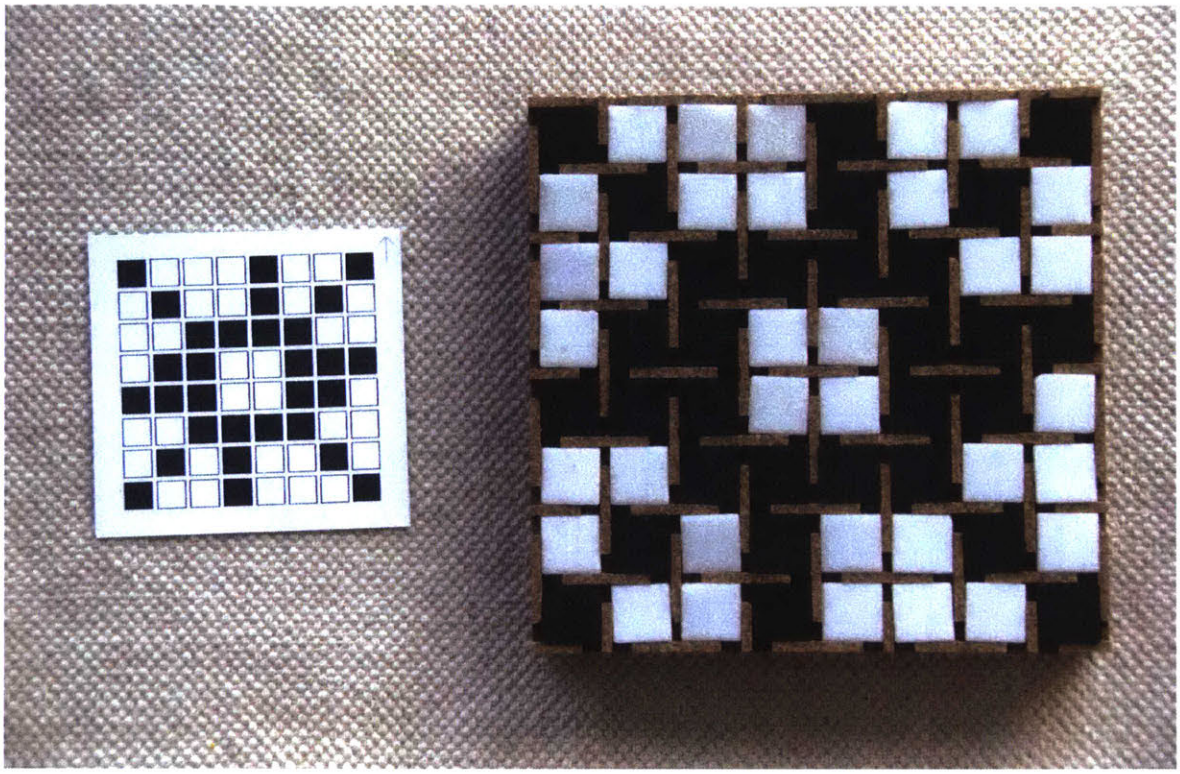

fig. 12. Pixel Board, with an 8x8 image replicated on the cork board.

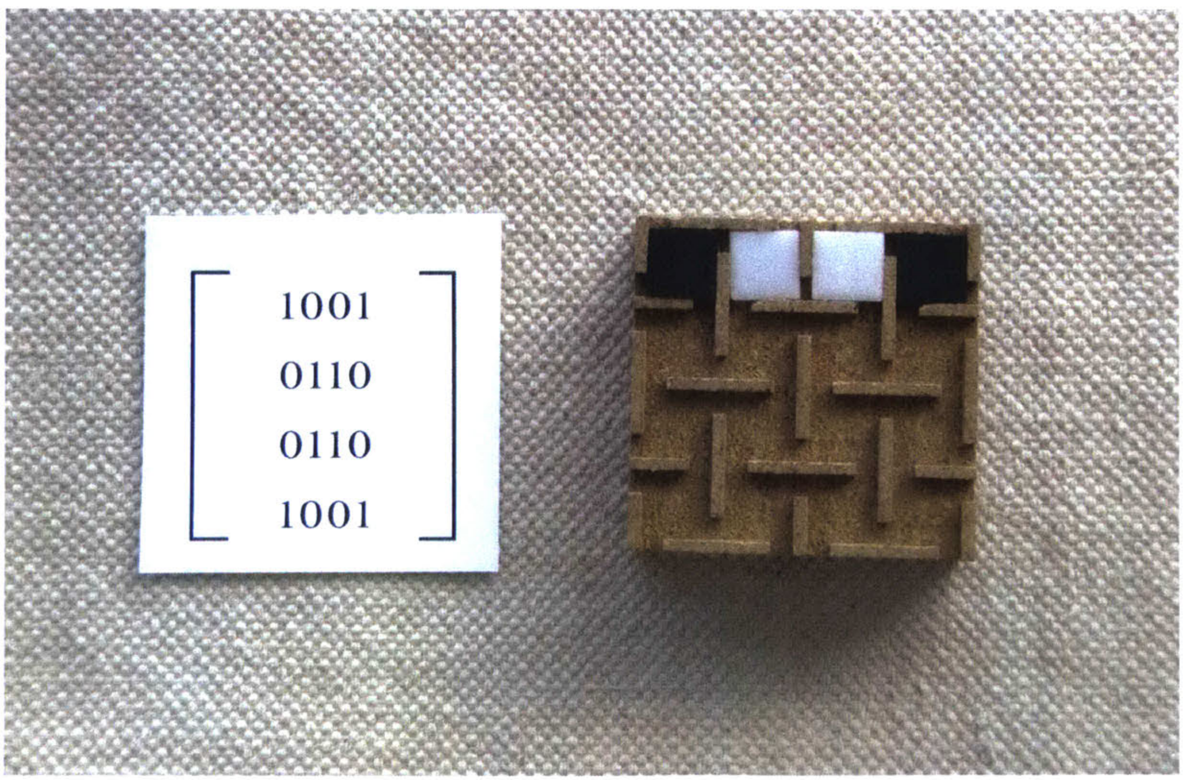

fig. 13. Pixel Board, with an 4x4 image represented as a matrix, which is then transferred to the cork board, seen here with only the first row completed.

Logic Gates

fig. 14. Logic Gates, represented here with AND and OR gates in which a marble passes through.

Logic Gates are the building blocks of computers and the first step in changing bits into data. These materials are physical representations of Boolean logic (input/output; truth tables) and logical operations. Boolean gates perform logical operation on bits, such as AND, OR, and NOT gates.

This learning material breaks down the ideas of Boolean logic, into concrete mechanical representations of this concept. For this material, the basic operations AND and OR are represented and combined to create simple equations, or logic statements. It is the foundation for further exploration in materials that demonstrate the remaining logic gates.

There are several iterations of the logic gates, beginning with single operations, and then evolving toward piecing them together to form more complex and combined logical operations.

As seen in the later version (fig. 14), children slide levers to create logical statements for AND and OR. With the AND gate, the marble passes through when the left *and* the right gate are open. And with the OR gate, the marble passes through when the left *or* the right gate are open. A marble then runs through the gates to represent the logical operation. Future work could incorporate language with this activity, so that children are able to create logical stories or situations that connect with real or imagined life scenarios. In this way, wider applications for logic can be expressed beyond applications solely related to computer science.

Boolean logic can be difficult to understand. It is often introduced at later ages, and the intent with this material is to present it early with physical models so that children become familiar with it. Early iterations of the materials (fig 15) were purely didactic and each logic gate was a singular entity. The thinking here was to create the most simplistic representation of each of these gates. Seeing them together, as discrete entities also helps to clarify their differences.

As we began to develop and iterate on this material, we saw opportunity to connect the logic gates together, and begin to form half adders. In this latest iteration (fig 14) gates are connected in a combination of ways in order to set up simple logical statements. This can be playful and exploratory, as the marble passes through the operation. Additionally, teachers expressed interest in lessons that connected this work to language, so that children are constructing representations of story problems, or specific logical scenarios. Future work can build on this further, so that children are actually building a series of logic gates that become simple operations for computation.

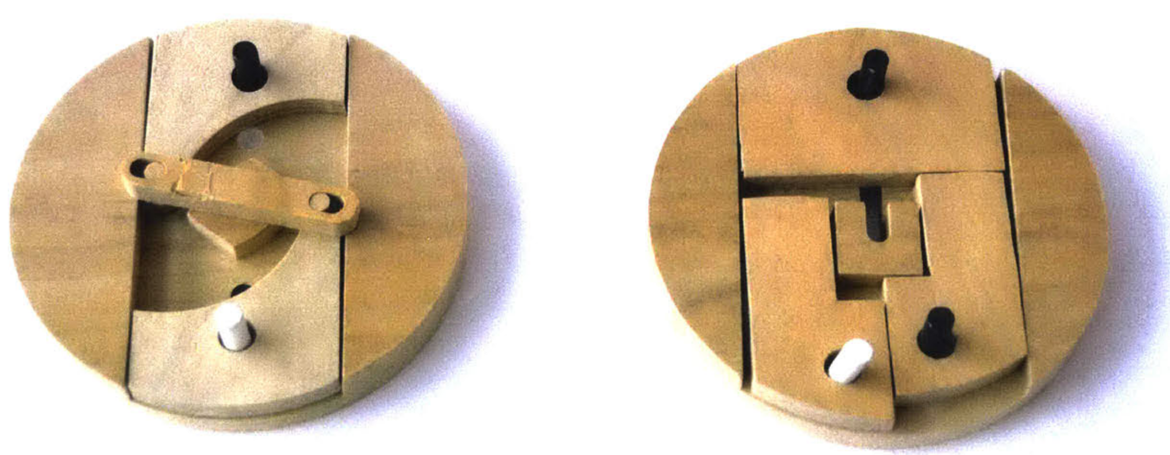

fig. 15. Logic Gates, seen here as discrete operations, on the left a NOT gate, and on the right, an OR gate.

Programming Board

fig. 16. Programming Board.

The **Programming Board** introduces children to the basic concept of programming, through the use of simple blocks. Children write their own lines of instructions using blocks that are categorized as definition fields and action fields. The following fields (in this order) compose each line of code: color, shape, location, size, direction, number of times.

This could be thought of as similar or a precursor to block programming languages such as Scratch. The blocks are meant to simplify the specifics of code syntax, so that they are thinking at both a high level and simplified way about what the code does. This lesson uses similar ideas, but without the digital interface. The commands are created from physical blocks, and implemented by hand. Children use this material as a way of coding instructions that are then implemented on their drawing paper. When codes are created, the child (or a friend) follows the instructions to draw the code on the paper (screen), starting at the top, and reading left to right. Additionally, the drawn image can then be shared with another child who would decipher the image by recreating the lines of block code from the drawn image.

The Programming Board also introduces children to composition in art and design. Composition is the way in which objects are arranged in a given space, in this case, how drawings fit within the piece of paper. This is referred to in art and design as the figure/ground relationship; where the figure is the marks on the page, and the ground is the background. In art and design, the marks on the page are considered of equal importance as the negative space that is created from the marks. So when children use the programming board, they understand their drawings as how they relate to the shape of the drawing board.

Through color-coded dots on the blocks, children have a control of error on their placement. Colors were chosen to correspond to the Montessori color system for grammar. For example, the object a child is drawing from the code, corresponds to nouns in the Montessori system. This was designed so that the material subtly integrates into the Montessori system without any added confusion, and that teachers can point out the connection to language structure.

Variables are used to store information to be referenced in a computer program. It is helpful to think of variables as containers that hold information. Their sole purpose is to label and store data in memory. This data can then be used throughout your program.

In this case, the variables are represented on the blocks with identifiers such as (a), (b), (c), and (d). Meanwhile, blank cards with corresponding labels allow the children to draw or write anything they want on them. The information for their program is stored on these cards, and the code includes the variable, so that when the code is "run" with a variable block, the image on the card is substituted for the block.

While computers rely on extremely basic instructions that do not allow for interpretation, this material exposes the fact that no two drawings will look alike, although they follow the same code. This could be a starting place for discussions as to why. For example, in what ways are the programming blocks imprecise? And why does one child's drawing of a circle look different from another?

fig. 17. Programming Board.

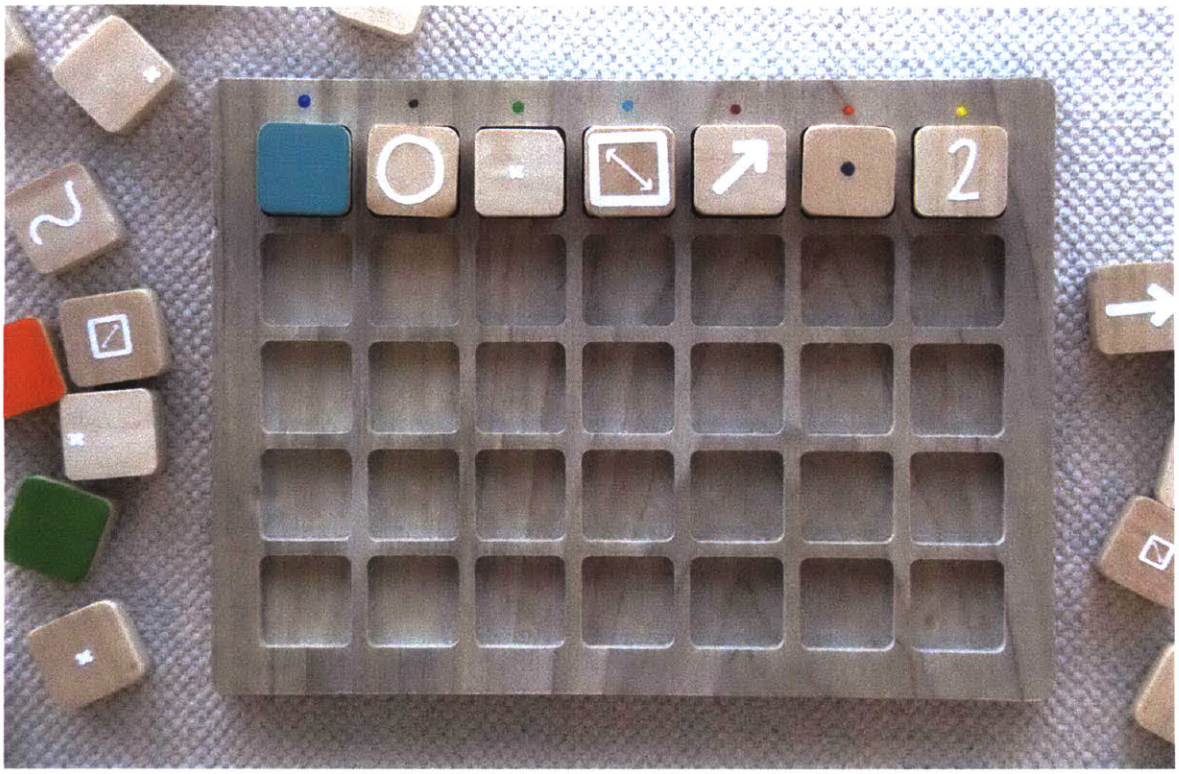

fig. 18. Programming Board, seen here with the first line of code created.

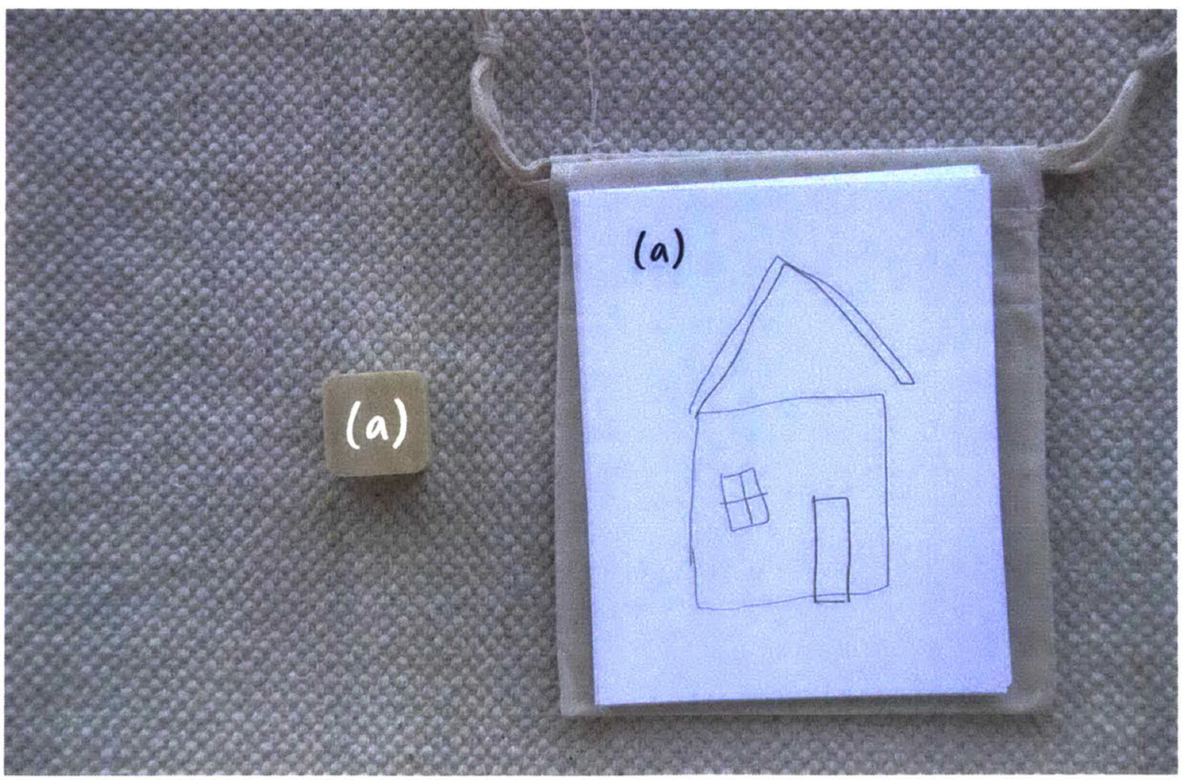

fig. 19. Variable Card, children can use a variable block to represent their own drawn images.

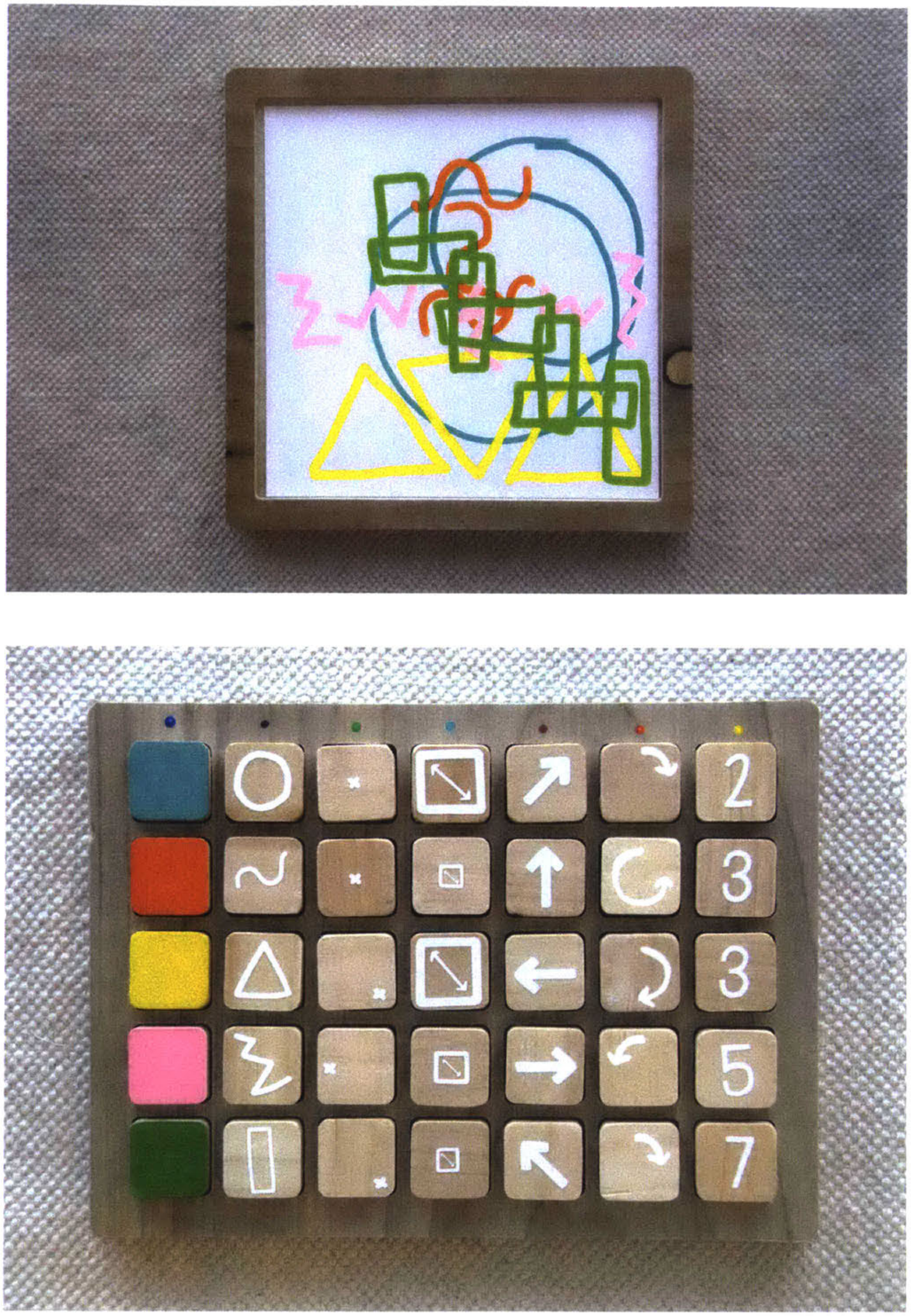

fig. 20, 21. Programming Board, here with an example of a drawing based on the corresponding algorithm.

Binary Tree

fig. 22. The Binary Tree, in a Montessori classroom in Cambridge, MA. 2016.

The **Binary Tree** introduces the concept of tree data structures. The child uses the branches and connectors to construct a tree that mirrors the abstract concept of a binary tree. This also introduces the child to the concept of exponential sequences.

Children construct this tree, whose branches get progressively smaller, and grow by a power of two. They can work together or independently. This material was designed with a control of error in that when all the pieces are assembled they can only fit and balance if completed correctly. Also, each size branch is a different color which helps visualize the progression.

This material was designed with consideration for creating a three-dimensional, spatial representation of an abstract idea. In this way, children create a relational model of how this tree grows. It loosely connects to a natural tree, growing upward, and painted with brown and green.

fig. 23. Early iteration of he Binary Tree.

Sorting Rods

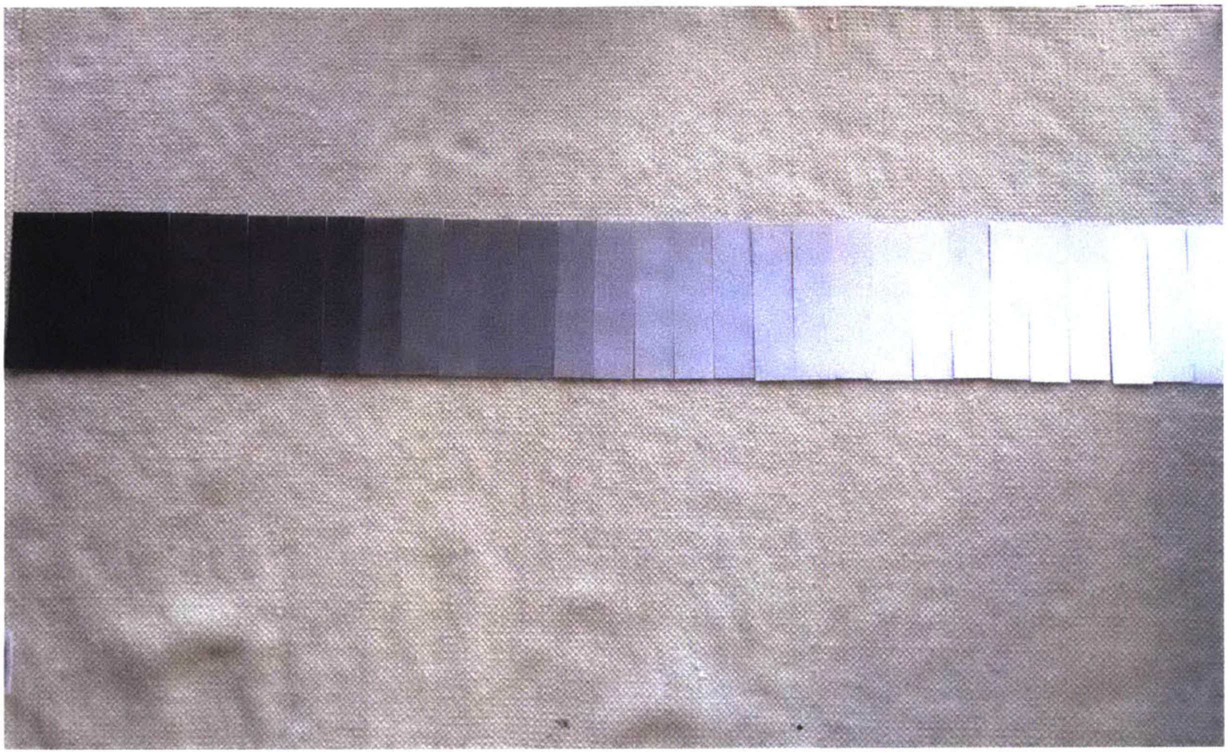

fig. 24. Sorting Rods, forming a gray scale.

The **Sorting Rods** demonstrate sorting algorithms such as bubble sort and merge sort. They are designed to integrate within the Montessori classrooms; they follow a similar design pattern of other Montessori materials, demonstrating slight variation across a group of objects. These rods vary by a gradation of 10%, ranging from black to white. Using these rods, children sort them as a gray scale, using a sorting algorithm.

They were designed to heighten the child's visual perception of value, while demonstrating these algorithms. The rods are all the same weight and size, only varying in color. They are quite challenging to differentiate when using them all; and the lessons can be scaffolded by omitting rods to a smaller number and then adding rods to increase difficulty. The rods are numbered on the back, so that children can see check for error.

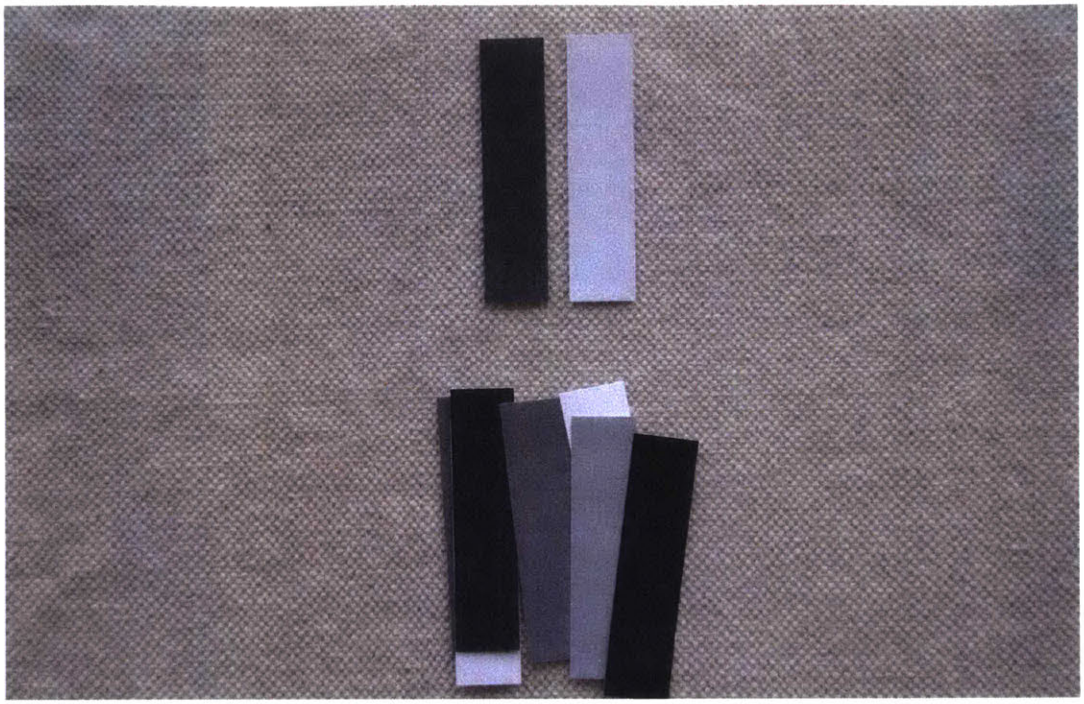

fig. 25. Sorting Rods, demonstrating comparing two rods in order to sort.

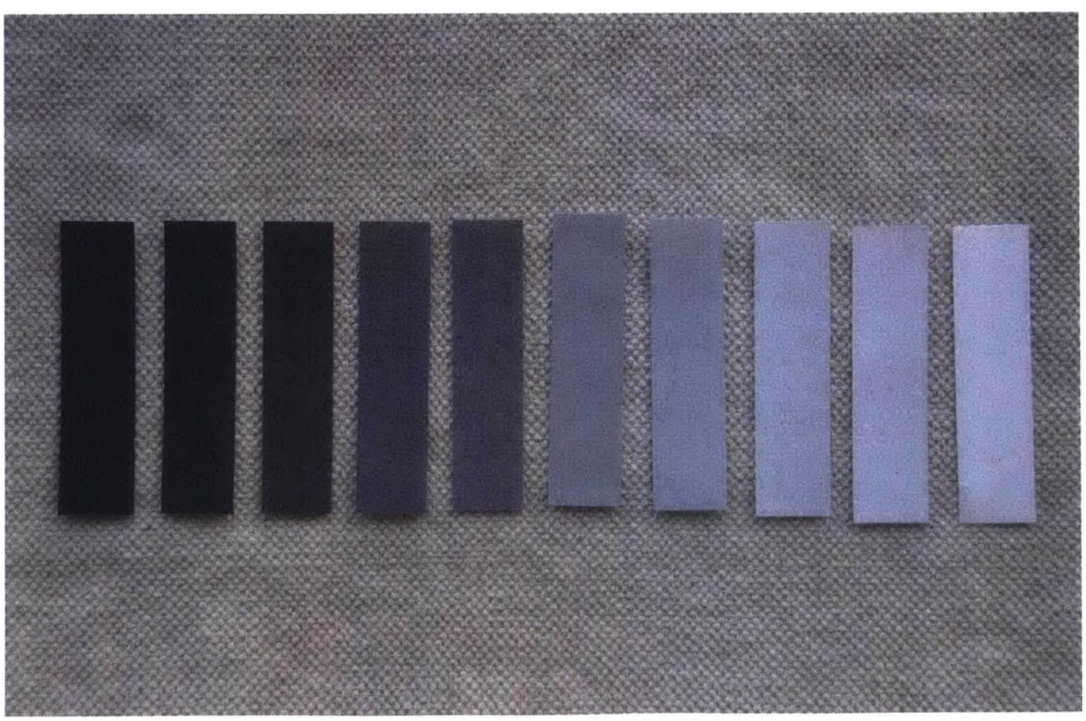

fig. 26. Sorting Rods, with a limited number for beginning lessons.

Evaluation

Testing in the Montessori classroom, especially the primary classrooms (3-6 years) is not common. Evaluation of student performance is based on observation, and interaction with the child that reflects their progress over time and engagement with the materials. Since the Montessori materials are typically self-correcting, and with a correct way to use them, they often tell the students when they are making an error, and this is an observable way to measure a child's mastery over the material.

So it is fitting to evaluate these materials in the Montessori classroom, and to do so through direct observation. It is important to understand the ways in which children interact with the materials, and through observing their work in the classroom. In conducting this study, it was important for me to observe and reflect, while using this process for design iteration, and use it as an opportunity to learn everything I could about how children learn and play—what motivates them, what engages them, and as the teachers say, "what calls to them."

It was also a process of learning from the teachers. I wanted to learn how to best equip them with new content, while also providing them the infrastructure they could build on, in order to advise new lesson plans, and feedback as to how to use these materials in a very specific way. I learned as much from my conversations with the teachers as I did from observing the children. The purpose of this evaluation was largely to learn and keep an open mind.

Research Questions

How do children engage with these materials?

This question is answered directly through careful observation. For this study, however, it is helpful to simply measure and observe if a child uses the material, and for how long. Do they use it again? Or with repetition during one interaction? And how frequently over the course of the 4-month study? Does the material call to them in such a way that they are intrigued and interested in playing with it? Are they concentrating in such a way that is enabled by the interplay between challenge and success? Are the materials too easy so that the children are bored? Or are they too difficult, in which case they will be frustrated? What kind of improvisation they bring to the materials? How do they use the materials collaboratively?

What resources do teachers need to feel comfortable with these materials?

Computer science is often not included in classrooms because teachers do not feel comfortable teaching this content. Perhaps they are not trained or educated or have limited understanding of how this would be integrated into their classroom. Teachers trained in the Montessori Method undergo a rigorous training in which every lesson is taught to them in a very rigid methodical way. Teachers first observe the lesson presented to them, and then they rehearse it over and over on their own before practicing with someone else. By the time teachers are giving a lesson in the classroom, they feel very comfortable with both the process and the ideas. In conversations with both teachers and parents, many revealed an unease about teaching this subject matter.

For this study, I wanted the teachers to teach me and advise how best to structure the lessons around these materials.

Are the children learning concepts from these materials?

Since testing is not formal at this age or in the Montessori classroom, this process is somewhat qualitative. The first step was to identify the key concepts of the lesson. This is a very basic concept for young children, and I quickly learned from the teachers that what I thought to be one lesson, was actually several, that broke the ideas down even further. Through this process of breaking down and isolating concepts, I identified the most basic and age appropriate concepts for each material.

One of the challenges with this work in evaluating their effectiveness, is that the entire premise of their value is based on the proposed long-term effects, so that when a child does get older, and they do have exploration into computer science, the ideas are already there as concrete models in their head. They are ahead because they have the building blocks necessary and the fundamental ideas are not new. They can build upon them. So ideally, this could be measured over a very long time period with many children. For our purposes, we used a series of uniform lessons, with a selection of same-aged children, observed their lesson, and tested their understanding through a) directed questioning and b) observing their ability to complete the lesson objective independently.

How do children of different ages learn and engage with these materials?

There were some initial hypotheses about what ages would be best; however, through observing these materials with a range of ages, I sought to understand how they were used differently for different ages, and how also these materials could be scaffolded. There were multiple levels of challenge within one material that either allowed for different ages, or sequential development for a given student. I wanted to observe the ways in which children learn these ideas simultaneously with language and math; and given their understanding of the decimal system, how then do they interact with the concept of binary?

Methods

In order to evaluate these materials in the classroom, I gathered qualitative data from 2 studies:

Study 1

The first, a 4-month open qualitative study in 3 classrooms. This was a very open procedure, with the intent of observing the classroom and learning from both the children and the teachers. This is akin to the approach of Dr. Montessori—starting with an idea (children can learn the basic of computer science with these tactile methods), observing the children using them, and then adapting the materials or procedures accordingly (future work and design iterations).

Study 2

The 2nd a smaller, directed study isolated two new materials with uniform lesson procedures among same-aged children in order to observe their ability to demonstrate an understanding of a concept introduced through the material and the lesson.

Classrooms were chosen because of:

- Montessori
- Proximity
- Ages (3 primary classrooms ages 3 - 6; and one lower elementary ages 6 - 9)
- Continued relationship through Wildflower. It was important that I had already had a familiarity with these classrooms and that they trusted me.

I used two different age groups for testing these materials: 3-6 classroom, and the 6-9 classroom.

The materials

For these two studies, I used four of the materials from the computational thinking curriculum. I chose these four materials because they are the most developed at this point, and represent a range of concepts in the curriculum. Each is quite different; however, the same questions apply to each one. Each presents potential for a variety of lessons, and range in uses. Lesson plans for each can be found in the Appendix.

The four materials used in these studies:

Binary Towers
Binary Cards
Programming Board
Pixel Boards

Qualitative research process

In order to analyze the data from these two studies, I used an approach of *open coding*, as described by Anselm Strauss and Juliet Corbin in their book, *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Through this process of qualitative data gathering and analysis, "coding represents the operations by which data are broken down, conceptualized, and put back together in new ways."[1]

The process I used is as follows:

1.Observation

For these two studies, I worked with six teachers in four classrooms, observed approximately 25 students for approximately 30 hours, with detailed note-taking. I conducted several interviews with three of the teachers (leads in the classroom for this study) in order to gather their observations of the children with the materials. I also recorded approximately two hours of video of several children with the materials in order to review later.

2. Labeling phenomenon

From my notes, teacher feedback, and recorded video, I carefully interpreted specific actions or events and apply labels to broaden and define their meaning.

3. Defining categories

From these labeled phenomenon, I created categories from these labels, actions that were associated in some way.

4. Naming categories

I then named these categories, to create higher level themes based on patterns.

5. Reflections

I reviewing observations in light of these labels and categories, and provided ideas about

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1 Corbin, Juliet M., Anselm L Strauss, *Basics of qualitative research : techniques and procedures for developing grounded theory*, 57

these patterns. Based on this process of pattern finding, I then reviewed all of the notes and data again, in order to provide reflections on these themes.

Teacher Instruction

At the start of the study, I conducted a two-hour training information session with all of the teachers. During this meeting, I showed them the physical materials, walked through how they demonstrated the concepts, and explained the basic concepts behind the materials. I provided them each with a book that contained information about the fundamental computer science concepts and suggested lesson plans for each material. One aim of the study was to develop these lesson plans further, particularly how they relate to traditional Montessori lessons. I provided them with the structure of how the materials function to demonstrate the basic concepts, with the intent for a collaborative process with the teachers in which they could suggest additional ways to use the materials, how to incorporate them with other materials in the classroom, and provide feedback as to the authenticity of this approach in the Montessori context.

During the study, teachers were asked to keep simple observations (as they normally do) and record them in order to relay through interviews. One or two interviews with each teacher was conducted during the study. Another interview was conducted with each teacher at the end of the survey in order to summarize their thoughts and experiences teaching with the materials and provide their own insights and observations as to how the children used the materials, and suggest critical feedback.

Of the classrooms in the study, two teachers had some training in computer science, both with an engineering background, and the other two had none at all. Of the four, none were currently teaching computational concepts in their classroom, although each expressed a desire to do so.

Observations from 2nd Study

The observations for this study focused on indicators of comprehension through direct observation, directed questions, the child using verbal cues and nonverbal cues such as pointing, showing, emulating, and then finally observing the child work independently with the lesson to see if he or she completes it successfully.

Classroom 1, primary classroom
Material: Pixel Boards
Key objective, for this study: The child will understand that a numerical code can

represent an image
Number of Students: 5
Ages: 4.1 - 4.3

For these two days of observations, the teacher gave the same lesson, with the same language and materials to five different students, all aged four. The detailed lesson plan can be found in the Appendix.

The material used was the Pixel Boards. Each of the five students demonstrated understanding of the objective through independent work and answering directed questions. Four of the five deviated from the lesson in some way.

Classroom 2, primary classroom
Material: Binary Towers
Key objective, for this study: The child understands how to fill the boxes with the balls, understanding that they must only be completely full or completely empty.
Number of Students: 3
Ages: 4.1 - 4.6

For this observations, the teacher in this primary classroom gave the same lesson to three different children, all aged four. The lesson plan, including the language she used can be found in the Appendix.

Each of the three children demonstrated that they comprehended the objective of the lesson. They demonstrated this through verbal explanation, independent work, giving correct answers, and teaching another student the lesson.

Reflections

The following are my reflections based on the patterns and categories I observed during these studies. They lead to further questions and potential research.

Watching and decoding the world

At this age, especially in the 3 - 6 year olds, they displayed several indicators of watching. These included copying, watching with anticipation, finding patterns, displaying focus, curiosity, and intently watching. Often children, especially in the younger classrooms, would simply watch another child using one of the materials.

The children were eager to listen for the lessons, and frequently displayed indicators of anticipation: they appeared eager to find out what happens next, and were excited when something was revealed to them, like an ah-ha moment. They watched the teacher carefully, and then they frequently emulated what was taught to them. According to one teacher, "so much of what they do [is] deciphering the world. And reading, encoding and decoding...The whole world is like a puzzle for them, a world that they are trying to decode."

With the younger children, I observed and gathered from the teachers that their decoding process is more individual than that of the older children. According to another teacher in the elementary classroom, "They like to be secret agents!...We're going to have a secret code, and we'll be able to talk to each other. I think that's intriguing, but the other things is they really have a mathematically active mind, and they just love puzzles and solving things."

The older children liked to create codes for their friends, using the Pixel Boards. They would also make drawings and ask their friends to code the image.

Achievement

Achievement and success was a significant theme I observed in the Montessori classroom. The idea of achievement, however, is contextualized within the intrinsic motivation of the child. Since the materials are self-correcting and with a control of error, a child can receive immediate feedback as to whether or not she has achieved the desired outcome. However, even with the younger ones, or a challenging task, often the emphasis (although still with a correct outcome) is one the completion of the task, and so the act of completion often indicates a sense of achievement on the part of the child.

As one teacher stated it, "It's all intrinsic reward. In the beginning, that looks like just being able to be successful. So, take the pink cubes, [a Montessori stacking material in which 10 blocks are arranged from biggest/heaviest to smallest/lightest] Success for them is getting them all back to where they started. Not biggest to smallest, not equal, just back to where they started, they just have the visual discrimination, it just makes sense to them no matter what. They moved all of them here, and they moved all of them back. In the beginning they feel successful because they completed a task. Over time they become more interested in what's right, when they have visual discrimination, when their sense are more developed."

I observed a pattern in which the methodical procedure of the lesson created a structure by which they could on some level feel successful. Part of the Montessori Method, is the ordering of the materials and the process of a child doing work. Typically, a child chooses the work he or she will set out to do during their 3-hour uninterrupted work time. She will identify her work space, either choosing a small table, or rolling out a rug on the floor in order to prepare the space. She will then take the work lesson from the shelves and place it on the defined work space. She will do the lesson, for however long, or as many times as she chooses. When she is done, she carefully arranges the lesson to its original state, returns it to the shelf, and rolls up the rug, or cleans the table.

Simply integrating these rituals in the learning process, allows the child to feel a sense of accomplishment on their own, not just as it relates to the content of the work, but rather the entire process of choosing, defining work space, working, and then completing it and putting it away. According to a primary teacher, for some children, either younger or still in a period of sensorial exploration, simply using the materials (even if "incorrectly") and then deciding when they have completed the task, is an extremely individual and intrinsically-motivated activity that brings about a sense of independence and accomplishment.

Important for all ages is the space between challenge and success, creating a challenge so that they are not bored, but provided a way for them to feel successful so that they are not frustrated. For example, with the older classroom, the 4x4 Pixel Board was too easy, and they completed it quickly and became bored. They were more interested in larger boards, or challenging codes. Alternatively, with the younger classrooms, the 4x4 Pixel Board was challenging for most 3- and 4-yearl-olds, and they felt a sense of accomplishment after working with it.

Sensitivity to order, small things, and details

Maria Montessori outlined 6 periods of sensitivity in a child's development, and two of them are Sensitivity to Order and Sensitivity to Small Things. As it relates to the materials, the children often displayed patterns of organizing and ordering the materials. One student stacked and unstacked the pixel cards over and over several times, and most of the students would arrange the materials in the ordered fashion as they were set out, in the middle of the lesson or after they had completed it. In the younger students, this structure seemed quite important for their ability to grasp the basic concept. I observed this to be less important with the older classroom. In the primary classrooms, I observed the teachers very carefully and methodically arranging the lessons and breaking down the steps. It seemed important for the child's comprehension, because the act of physically ordering created clarity in the concepts. For example, when one teacher in the primary classroom gave a lesson about the Pixel Boards to a 4-year-old, is was necessary to first create order and lay out the pieces thoughtfully. By organizing the materials, the teacher created a sequence, a hierarchy, and association. In this example, the first concept she explained was that the white tile represented the 0 digit and that the black tile represents the 1 digit.

Improvisation

In the elementary classroom, the children discovered new ways of engaging with the materials. For the Pixel Boards, they connected it to their peg board, which is a typical Montessori material. Using the pegs as pixels, they created patterns with color. In order to code the colors, they represented red, green, and blue with binary digits.

Also, they began creating drawings on paper, using the same ideas. The teacher explained: "Some of it just came about from the kids themselves. I think one of the things about a Montessori classroom is that the materials are limited. You don't want to have a pixel board for every kid. Even if you could, we would never do that. So because they are limited, it kind of forces students to be creative."

In the younger classrooms, the children would deviate from the lesson, in fact many of them did this with the pixel boards. I think that is because the pixel boards provide a lot of opportunity for multiple kinds of exploration and play. All still within the framework of the concepts, children frequently adapted this lesson for their own play, either alone or with others. Especially in the younger classrooms, the children used the image codes differently, seeing patterns and not necessarily reading codes left to right, or completing the pixel board from top to bottom. Many developed different ways of filling it out, either starting in the middle, seeing the number of the same, consecutive pixels, or immediately choosing to create their own patterns. The children in the younger classrooms were challenged by the 8x8 board, and they often worked in teams of two to work out the code, one child calling out the numbers or colors, and the other one placing the tiles.

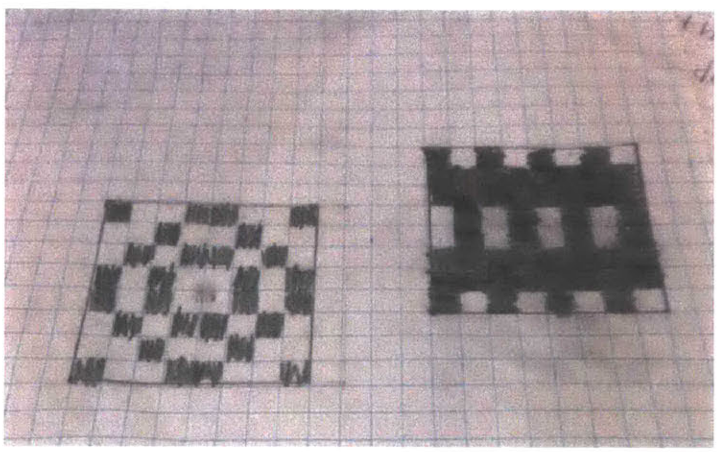

fig. 27. Children's drawings of pixel designs on graph paper.

Collaboration

In the elementary classroom, the children were much more collaborative. They enjoyed creating new lessons together, and exchanging codes with their friends. They were very social. All of the materials in the study include opportunity for collaborative learning. With the primary classroom, the children did collaborate some. Often one child would give the lesson to another child. I observed two young boys working on the Pixel Boards together, first one teaching the other how to use it, and then they both worked on a large board together, dividing up tasks. Additionally, working together allows the children to determine whether or not they agree that others are using it correctly. For example, in the elementary classroom, several children were counting in binary together using the binary towers. Together they would agree or error check each time they created a number.

> "Montessori is opposite to traditional school environments in which preschoolers often play in groups and older children in elementary work independently on tests, problem sets, and papers. Montessori is more in line with what child developmentalist know: younger children are more apt to play side-by-side but not necessarily together, whereas elementary-age children are intensely social."[2]

Sensorial Experience

For the younger ones (such as age three), playing and exploring with the material is the goal. Two of the primary teachers expressed that the sensorial connection for the younger ones is enough and that this is foundation for them to explore further as they develop. They are building a model in their heads. As one teacher said: "They just get the rules about it and you know they're doing it sensorially, they don't necessarily understand the concepts behind it."

And related to the sensorial experience of learning, all of the children I observed were fascinated by sensorial play. I observed very frequently, the child simply playing with the material in a very sensorial way. For example, every child that I observed with the pixel boards in the primary classroom, displayed enjoyment with handling the tiles that were piled in little boxes. They would run their hands through them, and then drop the tiles from above. They seemed to enjoy the feel of running their hands through it as well as the sound when they dropped in the pile.

With the binary towers, each of the 3 children I observed in the primary classroom displayed enjoyment when they opened and closed the lids of the boxes. They would open and close and open and close them to hear the clapping sound. Additionally, they displayed enjoyment when they dropped the balls in the boxes, as again, there was a sound of them falling down the inside of the box.

With the binary towers, I observed similar interactions in the elementary classroom; however, there was less playing with the materials for the sake of sensorial play and rather excitement when the time came to drop the balls down the tallest tower (16-high).

As the elementary teacher explained: "[Sensorial experience], first of all, is way more fun, but it's also more meaningful. So I think, manipulatives and being engaged by more than

2 Lillard, Angeline Stoll, *Montessori: The Science behind the Geniu,*. New York: Oxford University Press, Inc., 2007, 31-32.

just your brain or your ears or you eyes, but being engaged in other ways is really important for learning. You can't learn if you're not having a good time. Those Binary Towers were just fun. I think fun is important."

Ages and content

In studying two different aged classrooms, both the primary (3-6) and the lower elementary (6-9) observations revealed the differences in lesson presentation, interaction with the materials, and contextual background. In general, the materials were equally effective across the classrooms. Ideally, the materials should address multiple levels of both difficulty and conceptual understanding. For example, the younger students were often simply exploring with the material, engaging with it sensorially, without specific guidance for a lesson. One teacher in particular really used this approach. Speaking about the Pixel Boards, she said, "For a three-year-old just putting the pieces on, would work. Total exploratory..." And she used this approach also for the Binary Cards, so that the youngest were simply interacting with the material and understanding how it works. They are exploring and building sensorial relationships.

Another teacher in the primary classroom said that the children are "figuring it out in a sensorial way but they don't really know what it means yet."

Each of the lessons, are designed this way, with scaffolding and different levels of understanding. For example, with the Pixel Boards, simply working with the tiles and having the youngest ones matching the pictures was appropriate for them. However, the lessons build in difficulty, complexity, and concepts—first using a matrix code to create and image, to deciphering a decimal number to binary in order to make an image, and then creating one's own image with the code. With the older students in the elementary classroom, they created completely new lessons and integration with existing materials. There was much more collaboration in the elementary classroom. The children were very social with the materials and enjoyed gamifying them. In the older classroom, children in groups of three would use the binary towers, counting up to 31. They would each take turns, counting from 0 - 31 by using the towers to figure out the binary number. This collaboration was an effective way of self-correcting the group, since all of them had to agree on the answer. This allowed them to work together and figure it out, without the teacher. The older students really enjoyed making their own designs, writing their own codes, and then giving them to their friends. They were very eager to decode their friends' patterns and discover if they figured it out.

The younger students were much more individual. According to the elementary teacher, "Elementary kids are really interested in social. And they're interested in being part of the group, and this idea of belonging to a society. When they are little, they are learning how to become themselves, how to become an individual. And now during the elementary years, they are practicing becoming part of society." Often, a child would receive a lesson with the material, and then work with the material independently. Many times, another student would come up and observe, but not necessarily engage in the activity. On a few occasions, and including in the younger classrooms, I observed a student giving another student a lesson with one of the materials.

On binary

There was interest in studying how children learn binary, as a new number system, and how it relates to their understanding of the decimal system. Initially, the idea arose that a child should have a firm understanding of the decimal system, before introducing the binary system. However, through these studies, I suggest that it is possibly effective to introduce the binary number system at younger ages. Perhaps it is like learning another language. The children did not display confusion, but rather simply interacted with the concepts. In studying the binary towers in the younger classroom (with three 4-year-olds), they were able to quickly understand the following basic concepts: a.) the box must be filled to be closed b.) the box must be completely empty to be open c.) a closed box represents a 1 d.) an open box represents a 0.

One primary teacher said, regarding learning binary at young ages, "[It is] much easier for the children to do this because they don't have the preconceived notion of quantity, of base 10, of any of the things that clouds our vision as adults. It's so fresh for them." In learning more than one number system, perhaps children can understand that these are abstractions, and that there are more ways to represent quantities.

> According to Sanjoy Mahajan:
> "It's really easy when you just learn base 10 place value to not realize the fundamental idea of place value. It just seems like there is some magic, there's a one here and this one is worth 10, and this one is worth 100, and this one is worth 1000, and you can just go through just mindlessly saying ok 2 x 100 plus 100 plus 3 x 10 is 230—without realizing, well how were those one? What's the relationship between 1, 10, 100, 1000? And the Montessori materials try to teach that, and I look at the binary materials as extending that idea—so forcing the students who have already understand it to some extent to really abstract out what the core idea of place value is—that it is not tied to 10, it's tied to any number. So that you could do place value with any number, so it deepens your understanding of place value. That's one reason to do binary."[3]

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3 Sanjoy Mahajan (Computer Scientist, Olin College, MIT), interviewed by Kim Smith at Cambridge, MA, October 2016.

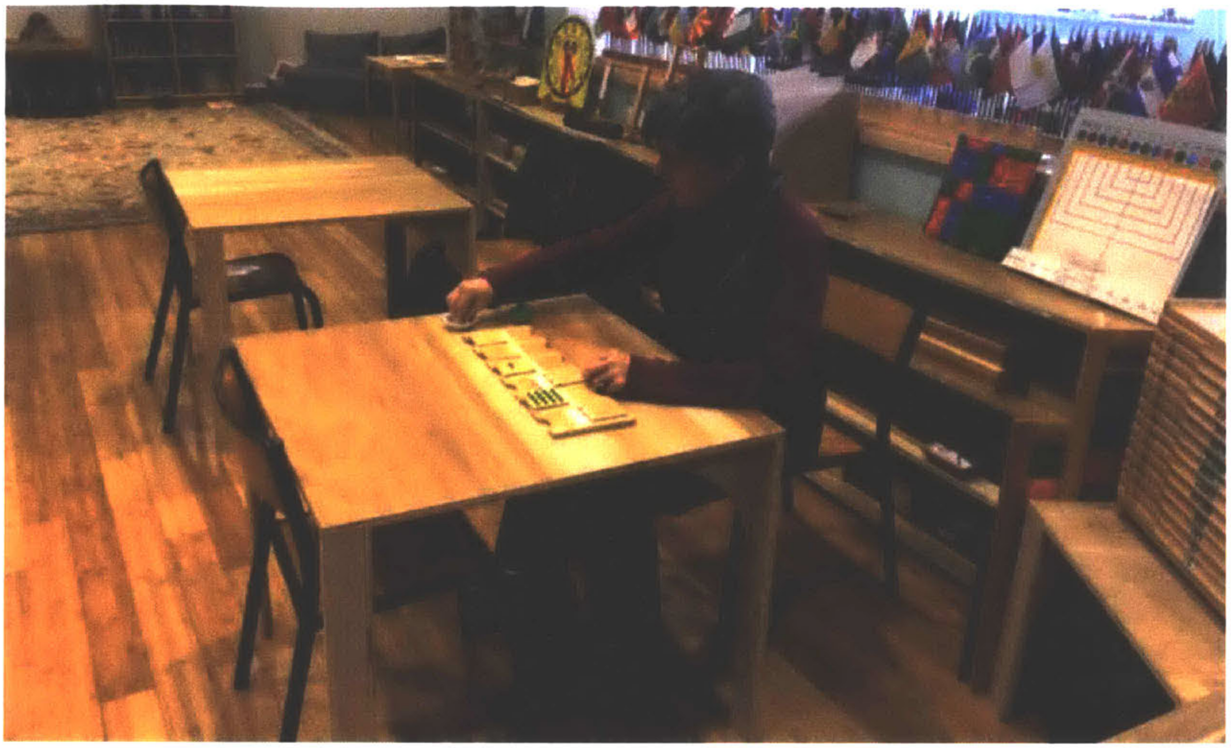

fig. 28. Elementary teacher practices a lesson before giving it to the students, in an elementary Montessori school in Cambridge, MA.

Importance of repetition

All of the teachers, especially in the younger classroom, relied heavily on repetition during their lessons. They made associations over and over, and repeated vocabulary several times. Similarly, the child during independent work would often emulate the teacher's specific action and then repeat the exercise over and over. This is a characteristic of Montessori materials. The act of doing something sensorially over and over, I would imagine, is building understanding and mental models through movement.

Teacher comfort levels

All of the teachers I worked with expressed some amount of intimidation about using new computer science materials in the classroom. I believe this is for two reasons that they explained to me. The first, is that they did not feel comfortable with the subject matter because it was foreign to them and seemed complicated. The second reason is the way in which they are traditionally trained. Montessori teachers undergo rigorous training for every lesson, first observing another give the lesson and then practicing it many times.

Comfort with the materials is extremely important. They must feel very comfortable. They achieve comfort through receiving a lesson from someone else trained in it; and then practicing on their own. How teachers felt about a material (whether they understood, or liked it, or were confused/intimidated, or did not like it) affected its place in the classroom and how the children interacted with it.

Breaking down steps into very small, single ideas and processes

This was especially important in the primary classroom. The teachers explained to me that concepts that I thought were only one lesson, could be broken down much further into several lessons. This makes a lot of sense when considering the larger goal of the curriculum: which is, taking something large and abstract, and breaking it down into smaller discrete parts.

Limits

This was a four-month study in four Montessori classrooms. In order to gain a better understanding of children's engagement with the materials, a larger number of classrooms would be useful. There were three primary classrooms for this study, and one elementary classroom. More study in additional elementary classrooms could provide greater insight into how the interaction with the materials changes among different age groups. Ideally, it would be best to evaluate a child's understanding and development of computational thinking over an extending time, even as long as ten years, with the use of these materials. Since these materials are designed as building blocks for a strong foundation, it would be useful to measure outcomes across a longer time period.

fig. 29. Teacher giving a lesson for the Pixel Boards to a 4-year-old in a Montessori classroom in Cambridge, MA.

fig. 30. Teacher giving a lesson for the Binary Towers to 2 4-year-olds in a Montessori classroom in Cambridge, MA.

fig. 31. Children working collaboratively with the Binary Towers at an elementary Montessori school in Cambridge, MA.

fig. 32. A 4-year-old working independently with the Pixel Boards, Montessori classroom in Cambridge, MA.

fig. 33. A 4-year-old working independently with the Pixel Boards, Montessori classroom in Cambridge, MA.

fig. 34. A 4-year-old teaching a 3-year-old how to use the Pixel Boards in a Montessori classroom in Cambridge, MA.

fig. 35. Two elementary students working together on the Pixel Boards.

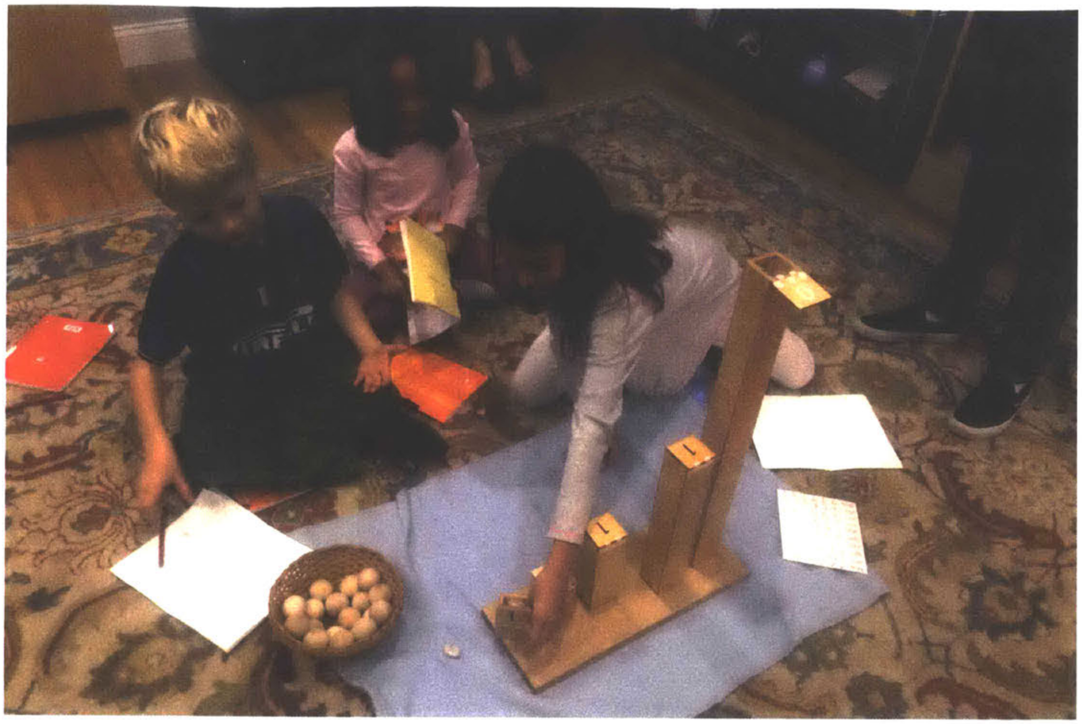

fig. 36. Three elementary students working together on the Binary Towers.

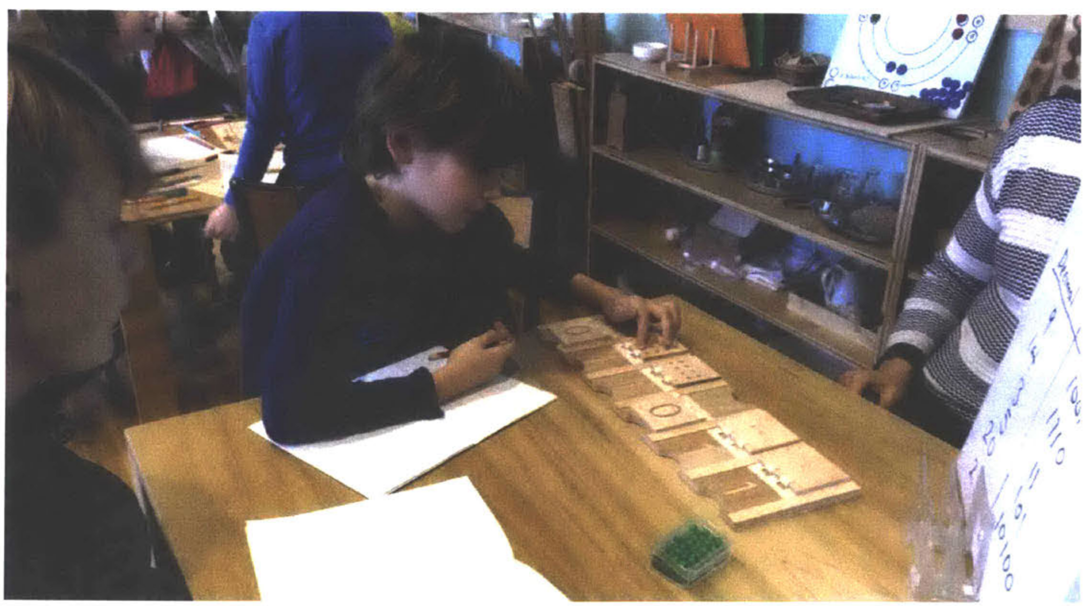

fig. 37. Two elementary students working together on the Binary Cards.

fig. 38. Computational materials arranged on the shelves beside traditional Montessori materials in the elementary classroom.

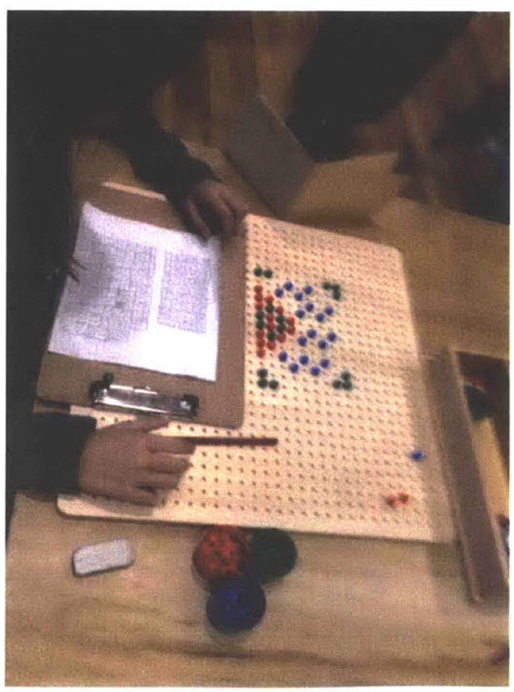

fig. 39. Adapting the pixel boards to represent colors in binary numbers, then implemented on the peg board, a traditional material in the Montessori classroom.

Contributions

New Montessori Curriculum for Computational Thinking

This work builds upon the methodology of Maria Montessori, to extend her approach and key insights about the ways in which children learn, in order to include a curriculum for computational thinking. This includes creating additional materials and lessons to demonstrate computational concepts, while also utilizing existing materials to demonstrate computational concepts.

This work has the potential to expand the Montessori curriculum to include computational thinking and concepts. Further development could lead to use of these materials in Montessori classrooms, and potentially be added to the Montessori standard curriculum.

Validation of this Method in Computer Science Education

Research has shown the effectiveness of the Montessori Method.[1] This evidence in support of the Montessori approach, coupled with the early evaluation from this work, suggest the potential effectiveness of this approach in teaching computational thinking to young children. And while the real value or effectiveness may not be evident for years to come, small studies from this work suggest that children do in fact understand big abstract ideas when they are broken down into smaller scaffolded steps in concrete ways. As children develop these ideas sensorially at young ages, they will already have a familiarity and a base, and a deeper understanding of the building blocks for this learning when they explore computer science more deeply at later ages. A 2007 longitudinal study showed that students at a public high school who had attended a Montessori program from the ages of three to eleven, performed significantly higher on mathematics and science tests than other high school students at the same school who had not attended Montessori school.[2] This suggests that early Montessori education has positive long-term effects on a child's education, specifically with math and science subjects. In light of this, further longitudinal research could evaluate the long-term effects of this approach to teaching computer science.

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1 Lillard, Angeline, and Nicole Else-Quest, "Evaluating Montessori Education," *Science* Vol. 313, Issue 5795 (2006): 1893-1894.

2 Dohrmann, Kathryn Rindskopf, Tracy K. Nishida, Alan Gartner, Dorothy Kerzner Lipsky, and Kevin J. Grimm. "High school outcomes for students in a public Montessori program." Journal of Research in Childhood Education 22, no. 2 (2007): 205-217.

Insights into the Ages Children Learn Computational Concepts

For this research, I tested four new computational learning materials in four different classrooms: three primary (ages 3-6) and one lower elementary (ages 6-9). One of the benefits for this research is the fact that Montessori classrooms are mixed-age groups. Dr. Montessori believed that children can both learn from and teach other children of other ages, and also that children develop at their own unique time-lines. And while it is true that children learn at their own unique pace, there are trends and patterns that can suggest appropriate ages for certain content.

Evaluation from this research suggests the ways in which content is understood at various ages. For example, through observation and teacher interviews, it was apparent that the younger students (ages 3-4) engaged with the materials differently than the older students (ages 5-7). The approach for the younger students was highly exploratory, sensorial, and independent. Their introduction to the materials was very basic, isolating the most simple and first steps in understanding the content, often without any broader contextual background. While they did demonstrate understanding of discrete concepts, their engagement with the materials was more open-ended and sensorial.

The older children would engage with the same materials; however, their process was much different. Often, particularly in the elementary classroom, they were given contextual background for the content, connecting it to other big concepts they were studying. For example, in the elementary classroom, the teacher introduced these materials with a lesson in communication: how humans developed language to communicate with others, how humans developed the language of math in order to communicate through numbers, and lastly, how humans have developed technological tools. Since older students naturally enter at a later point with the materials, their work was quite different, and exploratory in different ways. For example, with the Pixel Boards, the older children connected it to the Binary Cards - converting decimal values to binary numbers to then create images. After that, they created new ways of using the materials, using it in a much more collaborative social way through coding images for their friends.

I suggest that these materials offer an effective approach to teaching young children, at a broad age range (3-9) through two methods: 1) Scaffolded lessons: Children build on ideas, using the Montessori approach that breaks down and isolates bigger abstract concepts into very small pieces they build upon; so that children can learn and grow with the material. 2) Multiple entry points: Creating materials that allow for different level of understanding across different ages. A very young child may engage with it in ways effective for her age and level of understanding; and simultaneously, an older students may use the materials and lessons in ways that are appropriate for their levels of understanding.

Open-Source Materials

This work provides resources for others to build on these materials, or fabricate them for themselves. Designed for digital fabrication, their accessibility will increase as others gain more access to fabrication facilities. Lessons are available and provide a framework to build upon.

Future Work

Additional research could measure the effectiveness of these materials across many more classrooms, with more students. Testing children from diverse background in a variety of other contexts beyond Montessori could yield interesting results about these materials as they are decoupled from the Montessori classroom. This could suggest additional work to be done in order to extend this beyond Montessori.

Additional materials can be made for this specific computational thinking curriculum. I would love to see more emphasis on play, and cross-contextual associations with art and storytelling, perhaps at the older ages, after beginning with these materials.

Longitudinal studies could suggest interesting insights about the effectiveness of this approach. Since the assumption is that many of the benefits may be long-term and developed over time (even when the child later begins pursuing computer science) and so not immediately apparent, following the development of children using these materials from an early age could suggest more about their effectiveness, role, and even ability to attract students to this subject matter.

This approach could be applied across other subject areas such as design, physics, or architecture, etc. Through the lens of the Montessori approach, one could create new learning materials to address other contemporary fluencies—the skills and ideas relevant for today's learners—that can create a strong foundation for a child's future.

Appendix

Lesson Plans

Binary Towers

Objective

The child understands how to fill the boxes with the balls, understanding that they must only be completely full or completely empty.

Using the towers, the child can recite the binary number for a given quantity of balls, from 0 - 7.

Materials

Binary towers (there are 3 towers)

7 wooden balls

Children's work journals or notebooks, if appropriate to write these conversions down.

(above) This is how the binary towers are arranged; note that for this lesson the two towers from the left are omitted. The remaining 3 towers, from left, are called: 4-bit (4 balls fit in), 2-bit (2 balls fit in), and 1-bit (one ball fits in).

Procedures

Lesson A: Understanding the filled box and the empty box
Ages 3-6

For this lesson, the teacher only uses 3 of the towers (4-bit, 2-bit, 1-bit...in order to count from 0 to 7) and 7 balls in the bag.

The teacher takes the child to the tower lesson (or to the shelf to take the binary towers). They sit down together, at a table or on the ground.

Today we are learning the lesson of the Binary Towers.

The teacher sets up the towers, (or they are already set up), with the towers ranging from the left with the 4-bit, the 2-bit, and the 1-bit.

She starts from the left, points to the 1 on the 4-bit tower, and then flips open the lid, and points to the zero. She traces this digit with her finger. And then leaves the lid open.

She then points to the 1 on the 2-bit tower and traces it with her finger, and then opens the lid. She points to the 0, and traces the zero with her finger.

Leaving it open, she then goes to the 1-bit, points to the 1, traces it with her finger. She opens the lid and points to the 0, and traces the zero with her finger.

She then takes 5 balls out of the bag, and sets them down in front of the towers. She takes 1 and sets it apart from the others.

She places one ball in the 1-bit tower (furthest right).

The balls go inside the boxes.

She closes the lid.

When a box is filled all the way to the top, and no more balls can fit inside, we close the lid.

If there are no balls in the box, the box is empty, and we leave the lid open.

She points to the open box. *These boxes cannot be half-filled.*

They are either completely filled to the top, with the lid closed. Or else they have none inside, and are completely empty, and the lid is open.

She takes the ball out of the box, leaving the lid open. She places 2 balls in the next box (the 2-bit box). It fills to the top, and so she closes the lid.

She then takes the balls out of the box.

She holds 3 balls, and shows them to the child.

She places them, one by one, in the 4-bit box (the furthest left) and it does not fill to the top.

What do we do now?

She pours them out of the box on to the ground. And then moves to the next box, the 2-bit box. She drops one in, and then another.

Since it is filled to the top, she closes the lid. She hands the remaining ball to the child.

Can you show me where this one goes?

The child attempts this. And if trouble, the teacher states the rules again, that a box must be completely filled to the top, or completely empty, and that when a box is empty the lid is open, and when the box is filled the lid is closed.

Then the teacher takes all of the balls out of the boxes, and places them in front of the towers, in front of the child. Together, they go through 1 - 7 balls, the teacher prompting the child to fill them by his or herself.

(The teacher and the child will soon discover, that in order to fill the boxes completely to the top as they go through the numbers, they will have to 'carry' the balls over across different place values. For example, with one ball, it is placed in the 1-bit box, furthest to the right, with the lid closed. And then to add another ball, to represent 2 balls, the teacher/child may place the ball in the 2-bit, with the single ball still in the 1-bit box. They will notice that the 1-bit box is still filled to the top; however, the 2-bit box is half empty. So, they must carry the single ball from the 1-bit box over to the 2-bit box in order to fill it to the top.)

If trouble, she reminds the child how the rules work - either completely filled with the lid closed or completely empty, with the lid open. (It is helpful to walk through the rules, and start from the left and move to the right, with each quantity of balls.)

The teacher does this with several quantities of balls, up to 7. The student has successfully accomplished the lesson when he or she can place the balls correctly in the boxes, from 0 - 7.

Lesson B: Understanding Binary Number Representation
Ages 3-6

This lesson continues from the previous, after the child understands how the towers work, how to fill them and how the lids are open and closed.

This lesson shows us another way to count. We will fill these boxes with these balls in order to count in this new way, we call it binary.

She hands one ball to the child. *Do you remember how to put this ball in the box?*

The child attempts, and after help if necessary, places it in the 1-bit box (furthest to the right), and closes the lid.

The teacher then point to the digits on the lids, from the left to the right, they should be open, open, and closed, or 0, 0, 1.

And then points to the single ball.

Pointing, *When the boxes are empty, empty, and closed, the lids read: 0, 0, 1. And there is one ball in the box.*

So in this new way of writing numbers in binary, '0, 0, 1' is equal to one ball.

She hands the child another ball, and the one ball still remaining in the box.

Do you remember where this one goes?

The child will likely place it in the 2-bit box. And then the teacher asks if this is correct, because the box is not filled to the top.

The child may remember that they need to carry the ball from the 1-bit over. The teacher helps, and so 2 balls are placed in the 2-bit box.

So when the boxes are empty, full, empty, they read: 0, 1, 0. (pointing) *And that is how many balls?*

Yes, so in binary, '0, 1, 0' (pointing to the digits on the lids) *is equal to 2 balls.*

Together, they continue this process, gauging how the child is comprehending this through questions. They continue up to 7.

The teacher asks the child to do as much as he or she is able. After placing the balls in the boxes, the teacher asks the child to read back the digits in binary. It is important that he or she reads the binary number as "one, zero, zero," rather than "one hundred."

The teacher can also go out of sequence with the number of balls.

The child has successfully completed the lesson when he or she can count from 0 to 7 by placing the balls correctly in the boxes, and reading back the binary values for each.

Lesson C: Contextual Understanding of Counting in Binary
Ages 6+

Materials

Binary towers (there are 5 towers)
31 wooden balls
Children's work journals or notebooks

Today we are learning about the binary number system. The binary number system is how we talk to computers. Why do you think it is called binary? Can you think of any other words that have 'bi' in them. (bicycle, bilingual, bifocul) And can you think what these words have in common? They mean 2.

We have learned so far about the decimal system, which means base 10. Our number system is based on the number 10. Hold up your hands. Recall the great lesson about the history of numbers. Why do you think we use the number 10 as the basis of our numbers? We have 10 fingers, and this was useful for early humans to count. But we could count using other systems, such as the one we are learning today: binary.

Now we are going to use this game to learn how to count in binary so we can communicate with computers. Remember that computers don't use base 10 - they don't have hands! They use base 2, or binary.

I have these wooden balls, and that is my quantity. I will place them in these towers in order to find out how to write the quantity in binary.

Have the children take out their notebooks. Ask them to write the quantities 1 - 10 on their notebooks. Check their work. Explain that this is base 10 counting.

Ask them to start a new page, and title it Binary Counting.

Back to the towers. I will be placing the balls in these towers in order to find out how to write in binary. Now there is a very important rule in this game: the towers must be completely full or completely empty. They cannot be filled partially. When a tower is filled completely, and no more balls can go in, we close the lid. If the tower is completely empty, meaning there are no balls inside, the lid remains open. Show them that there are numbers on the lids; explain that when the lid is open, it says '0'. Show them that when the lid is closed, it says, '1.' Remember, the tower must be completely full or completely empty.

Demonstrate how to represent one ball, by placing it in the first tower from the right

Notice that the binary number represented is 0 1. The quantity is one ball. Since the first tower is empty, it reads a 0 on the lid. And since the second tower is full, the lid is shut to read 1.

Hold out two balls. Where do these go? Have them try and figure it out. As you go through the numbers, 1 - 31, have the children notice the corresponding numbers on the lid and write the binary numbers in their work journals. Have the children take turns with each number, counting up to 31, see that you don't interject and see if the others can jump in and help when one makes a mistake.

After you have completed counting to 31, explain that you can use this system to write all of the numbers, including 32 and 50 and 100 and 146, and 1000, etc. We just need to add more towers. Can you guess how many balls will fit in the next tower? The answer is 64. Can you see a pattern?

Binary Cards

Objective
The primary purpose of this learning material is to introduce children to the binary number system, which is the fundamental system on which computers are built. This material can work in conjunction with the binary towers, as an additional way to think about binary.

The secondary purpose of this learning material is to deepen the understanding of place value, through the representation of a new number system: base 2.

Materials

- 2-bit binary cards
- 4-bit binary cards
- Small beads
- Students' workbooks

Procedure

Lesson A: 2-bit base 2 counting

Materials

- Binary cards
- 3 marbles

Introduce the lesson by framing it as a new number system; a simple system or language that we use to communicate with computers. It only uses zeros and ones to represent quantities. Just like decimal counting has place value for tens and ones and hundreds.

Place the cards with the zeros up.

Hold in your hand 3 marbles and show them to the children. Ask them how many marbles you have. And how would you write this amount? Children write it on their notepads. This is the 'decimal' or base ten way of writing this quantity. But if we want to talk to computers, we have to use a different way of describing this quantity. And this new way to talk to computers is call 'binary'. Today I am going to show you how to count using the binary number system. Just like you wrote the number 3, you will be able to express this value in binary. But, in binary, we only use zeros and ones to represent all of our numbers. It is like a code.

There are two place values here. Show the cards, with the two zeros up. This is a value of zero. There is nothing here.

Flip the right card over so that there is a "1" showing, and a single hole. Place the marble on this hole.

How many marbles do I have here? The answer is one; explain that the cards read: "0 1", and that this is a value of one marble. The marble is useful because it is a tangible concrete way of demonstrating numbers, instead of confusing it with another abstraction of decimal system.

In binary, each place value can hold a certain number of marbles. Show them that the first column (the one on the right) can hold one marble. Flip the card over to show them that the second column (from the right) can hold 2 marbles. Explain that it is two because it is twice as much as one. When a card is flipped, we have to use all of the holes for the marbles. We cannot fill a card up halfway - if the card is flipped over, then it must be filled.

Now I have 2 marbles. How do I flip the cards to represent 2 marbles? Let one of the children try by flipping the cards over and placing the marbles in the holes. You may have to remind them that a card cannot be half full; if it is flipped, all of the holes must be filled with the marbles.

Do the same for the quantity 3. Have the children take turns counting from 0 - 3, using the binary cards, so that they see how the system works and begin to understand patterns.

Lesson B: 4-bit base 2 counting

This is an extension from Lesson A; the only difference is now there are 2 more place values. You will need:

Binary cards
15 marbles

Review the basic concepts outlined above. This is binary counting, or base two counting. Just like we have been learning about base 10 or decimal counting. These cards are going to show us the place value for base 2 counting.

Place the binary cards with the zeros up. Review. The cards read "0 0 0 0". How many marbles do I have? They should answer zero. Review how to represent 1-3 by having the children demonstrate.

But what if I want to represent 4...or 10...or other numbers? I need more places to hold the marbles.
Flip the 3rd card over (3rd from the right) Show them that this place value holds 4 marbles. Review from the right the place values: How many can this place hold? And this place? Before you flip over the 4th card, as them to guess how many it can hold. The right answer is 8. Flip it over and they will see that there are 8 holes for marble on the 4th place value.

Ask them how to represent the quantity 3, by giving them 3 marbles.

Now, give them 4 marbles and have them represent 4. You can have them work together, or take turns. Have them do this for the remaining quantities, which is up to the number 15.

Now suppose I want to represent 16 or 20 or 1000. I would need more place values. Can you guess what the next place value would be? The answer is 16. Do you see a pattern in the place values. (Each place value is double the one previous)

Pixel Board Lesson

Objective:
Children will learn that numbers can represent an image.

Materials:

4x4 cork board
16 black tiles, in bag
16 white tiles, in bag
4x4 Matrix to Image cards, in bag

3 Lessons: (not shared with the child, for reference)

Representation: Understanding the relationship between 0 and white; 1 and black.
Tile Card (with numbers): Precursor to the matrix represents the cork board.
Matrix: Numbers in a matrix represent an image on the cork board.

Procedure

Lesson A:

Today we will work with the Pixel Board.

And takes the child to the shelf and takes the Pixel Board lesson: the cork board, the cards (4x4 matrix to image), and the tiles (both black and white, in bags).

Together, they sit on a rug, and lay out the materials very carefully. The teacher takes the cards from the bag, ensuring that they are all facing the same direction, places the stack back on the bag, with the tile-matrix (numbers in grid-boxes) side up (ones and zeros).

She takes the two number cards (small tile-sized squares that read 1 and 0), and places them in front of the child.

She then opens each of the tile bags and shows the child that one has black tiles, and the other has white tiles. The teacher point to the numbers on the card.

This card contains the numbers zero and one, which look like this.

This is a zero, and this is a one. (Pointing to the number cards).

During this process of checking the child's understanding, the teacher can switch the placement of the tile-sized cards so that the child is not simply remembering the placement.

Can you show me which card represents a one? And a zero?

The teacher then takes a white tile from the bag.

This is a white tile. And she places it on the rug.

She then takes a black tile from the back. *This is a black tile.*

(Pointing at the one card) *A one represents a black tile* (touching the black tile).
(Pointing at the zero card) *A zero represents a white tile* (touching the white tile).

Do you know what represent means?
She allows the child to answer.

'Represent' means to stand for or take the place of, so when I read a zero on the card, it means a white tile.

And when I read a one on the card, it means a white tile.

The teacher points to a zero on the card, and asks: *What color tile does this represent?*

The teacher points to a one on the card, and asks: *What color tile does this represent?*

Lesson B:

The teacher then takes a single card, the tile-matrix (gridded boxes with 1 and 0) and places it in front of the child, with the number side showing.

She then places the cork board in beside the card. She points to the card and then to the cork board. She touches each gridded box on the top row of the card, and then touches each square on the top row of the cork board, left to right. She does each row like this, from top to bottom, and left to right, so that the child sees the connection between the two.

The picture on this card 'represents' this cork board.

This picture with numbers gives us instructions about where to put the tiles on the cork board.

Do you remember what color tile this ONE represents? (pointing to a one on the tile?)

She points to the first number on the top left of the card. *What number is this? What color tile does it represent?* She then takes the appropriate tile and places it on the cork board.

Lesson C:

The teacher picks up the cork board and places it in front of the child. The black and white tiles fit on this board.
(Picking up the card) *This card is a set of instructions. It tells us which tiles and where to put them on the cork board.*

The teacher sets the card next to the cork board. The teacher touches each number on the top row of the matrix card, left to right. Then she touches each square on the top of the cork board, left to right. She does the same for each row, touching the second row of the card, left to right and then the cork board, etc.

Then she touches the first number on the card (top row, left column).

What number is that? Do you remember which color tile it represents?

The child answers.

So I put a white (or black) tile on the top, left square, just like the card.

The teacher points to the second number (top row, second column from the left). And then points to the corresponding square on the cork board. She picks up the correct tile and places it on the cork board in the appropriate spot.

Can you show me which tile is next and where it goes?

She allows the child to pick a tile and place it on the cork board. If correct, acknowledge that it is correct and she asks the child to place the next one. If incorrect, the teacher asks why the child put the certain color tile there. She then completes the first row, pointing at the card first and then the corresponding cork square, before placing the tile down.

When the first row is completed, the teacher touches the second row on the card, left to right. She then touches the second row of squares on the cork board, left to right.

Can you show me how to complete the second row of tiles on the cork board, by following the instructions on the card?

If the child cannot complete it correctly yet, the teacher completes another row as the child observes. She touches the number on the card first, then picks up the corresponding color, and places it on the cork board. She then touches the tile on the cork board and then touches the corresponding number on the card, so that the child sees the connection between the two.

Can you show me how to complete the last (bottom) row?

After the teacher has completed one board with the child, she flips the card over to reveal an image that corresponds with the black and white tiled cork board.

Now we check to see if we completely the card correctly. Does this image look like the cork board?

She shows the child how to check by touching the black/white square on the card, and then the corresponding tile on the cork board.

Why not, where is the mistake(s)?

The child corrects any mistakes.

If it is correct, the teacher says, *We have completed it correctly.*

Now we can take the tiles out of the cork board, and place them back in their piles. *Can you do that?*

She puts the card away and then asks the child to take another card, with the matrix side up. *Can you now create an image on the cork board with the instructions on this card?*

The lesson is complete when the child can successfully place the tiles on the cork board according to the matrix card. The child can flip the card over to check for errors.

VI Materials

4x4 cork board

8x8 cork board

Wooden number tiles

64 white tiles

64 black tiles

5 Bags of Cards:

- 4x4 Image to Matrix
- 4x4 Image to Binary
- 8x8 Image to Matrix

- 4x4 Blank Cards (with grid on one side)
- 8x8 Blank Cards (with grid on one side)

VII Procedure

Activity 1

Introduce the material by explaining how computers represent images. *When we look at a screen, that image is made up of tiny little pieces. Does anyone know what those are called? They are called pixels. When you have lots and lots of pixels, you can make a picture with them. Each pixel on the screen is its own color. But in order to tell the computer what picture it should make, we have to communicate with the computer in a language it understands. So today we are going to learn new way of creating images, using numbers.*

Set out the 4x4 cork board and the tiles, separated into black pieces and white pieces.

This is my screen, showing the cork board. And these are my pixels, show the tiles.

Using the 4x4 Image to Coordinate cards, have the child recreate the image, by simply following the corresponding places on the cork grid. This is especially good for young children, and a quick introduction for older children.

When the child has completed a card, he or she can check for accuracy by holding the card next to the cork board, and seeing if they look the same.

B. Activity 2

Materials:

4x4 cork board

16 black tiles

16 white tiles

Bag of 4x4 Image to Matrix cards

Students will use the matrix cards to create an image. They should be familiar with the introduction and the contents of this lesson. Provide a brief review in introducing this activity. Students will be following codes to create images.

Show the child the 4x4 Image & Matrix cards. Explain that they will be starting with the side with the code on it, and that the other side of the card has the image, or the answer. They should wait to look at the image until they have completed the code on their own.

Explain the matrix. A matrix is a collection of numbers arranged into a fixed number of rows and columns. Looking at a card together, show the student how to read the card by placing the appropriate tiles on the corresponding location on the cork board.

1 = black
0 = white

Using the matrix card, the student places the tiles on the cork board, following each line, so that each row is read left to right, and then filled out with the tiles on the corresponding rows. Lastly, when the tile board is completed with all of the tiles, the child can flip the card over to reveal the image.

Checking for error, the student can look at the image card and their own cork board in order to determine if he or she filled it out correctly.

C. Activity 3

Materials:

- 8x8 cork board
- 8x8 image + matrix Cards
- black tiles > 32
- white tiles >32

This activity is the same as Activity 1; however, this time with and 8x8 grid as opposed to the 4x4. So the introduction is the same; however you can emphasize how there are more pixels on the 8x8 grid. How many more pixels are there? Is this more or less information? Explain how the more pixels you have, the more information you have, and the more detailed a picture can be.

The student draws an 8x8 image card and fills in the cork board corresponding to the picture. Looking at both the picture and the board, the student can determine if the pattern is filled in correctly or not.

D. Activity 4

Materials

- 8x8 cork board

- 8x8 image + matrix cards
- black tiles > 32
- white tiles >32

This activity corresponds to Activity 2, only now they are working with an 8x8 grid. It is a natural transition to move from the 4x4 grid when they have mastered it to this board. The introduction is the same.

Walk through one card, showing them that it is the same procedure as the 4x4, only with more rows and columns, more pixels, more information

The child completes a picture using the coordinate card.

When completed, the child flips over the card to reveal the picture on the other side. The child can compare this picture to his or her cork board and determine if it is completed accurately.

E. Activity 5

Materials

- 4x4 cork board
- 16 black tiles
- 16 white tiles
- 4x4 image + binary cards
- Binary Cards Materials (optional)

This activity continues on the idea of using a code to represent an image, only this time it relates directly to the work with what the student learned about binary (with the binary cards and binary towers) in order to use binary codes to represent images.

Review binary. *What is binary counting? It is a base two number system that we use to communicate with computers. If we want to tell a computer a picture we want it to make, we are going to use binary numbers to represent our pictures.*

Bring out the Binary Cards material (optional) to review how to write a few numbers in binary. You create binary numbers such as 0001, 0101, 1101, 1111, etc.

Back to the cork board. *We will be using binary codes on these cards (show the binary cards) in order to create pictures.*

Show them a binary card. *On this card are numbers, are they written in binary?* (No) *What system are they written in? (Base 10 or decimal). But now you know how to write these numbers in binary, right?*

Have the student use his or her work journal to make notes and computations.

Start with one card, with the first number. Assisting the child, using the Binary Cards, if necessary, ask the child to write the decimal number as binary.

Do this for each number, there will be 4 rows of numbers.
They will have a list of binary numbers that should look like this:

9 = 1001 (= black, white, white, black)
1 = 0001 (= white, white, white, black)
3 = 0011 (= white, white, black, black)
5 = 0101 (= white, black, white, black)

Now you have written your code for the picture! You can now use this code to create a picture on the cork board. Explain that the black and white tiles represent 1's and 0's. 1's equal black; and 0's equal white. The child then uses the binary code for each row to place the corresponding black and white tiles on the board.

F. Activity 6

Materials
4x4 cork board
8x8 cork board
4x4 blank cards
8x8 blank cards
White tiles
Black tiles
Pencil

1. Using a 4x4 board or an 8x8 board, the child designs his or her own image.
2. Based on the image, the student writes the code in the matrix or binary/decimal system.
3. The student may also or opt to create the code for his or her image using binary (and for this, the 4x4 board should be used, and the child can use the 4-bit binary cards for reference)
4. The child can color in the squares for his or her image on the cards, so that they have new cards that he or she created that has the image + code (coordinates or binary)
5. The child then gives this card to a friend, and the friend can make the picture.

Programming Board

I Primary Purpose

Key Concept: The Programming Board introduces children to the basic concept of programming, through the use of simple blocks. This could be thought of as similar or a precursor to block programming languages such as Scratch. In Scratch, children arrange simple blocks in order to form codes. The blocks are meant to simplify the specifics of code syntax, so that they are thinking at both a high level and simplified way about what the code does. This lesson is similar, but without the digital interface. The commands are created from physical blocks, and implemented by hand. Children use this material as a way of coding instructions that are then implemented on their drawing paper.

Key Terms

Programming: Programming is the process of taking an algorithm and encoding it into a notation, a programming language, so that it can be executed by a computer

Program: A computer program is a list of instructions that tell a computer what to do

Algorithm: a process or set of rules to be followed in calculations or other problem-solving operations, especially by a computer; it is like a recipe.

Code: In computing, code is any collection of computer instructions, , written using a human-readable programming language.

Syntax: In computer science, the syntax of a computer language is the set of rules that defines the combinations of symbols that are considered to be a correctly structured document or fragment in that language.

Field: A single entry type on the programming board

Screen: The part of the computer where information is displayed to the user.

Variable: Variables are used to store information to be referenced in a computer program. It is helpful to think of variables as containers that hold information.

Attribute: In computing, an attribute is a specification that defines a property of an object, element, or file.

Rotation: The action of moving around an axis or center.

Angle: The amount of rotation of an object, measured in degrees.

II Secondary Purposes

Concept: The Programming Board also introduces children to composition in art and design. Composition is the way in which objects are arranged in a given space, in this case, how drawings fit within the piece of paper. This is referred to in art and design as the figure/ground relationship; where the figure is the marks on the page, and the ground is the background. In art and design, the marks on the page are considered of equal importance as the negative space that is created from the marks. So when children use the programming board, they understand their drawings as how they relate to the shape of the drawing board.

Key Terms:
Shape: A shape is an enclosed space, the boundaries of which are defined by other elements of art (i.e.: lines, colors, values, textures, etc.). Shapes are limited to two dimensions: length and width.
Composition: Composition is the term used to describe the arrangement of the visual elements in a painting or other artwork.
Figure-Ground Relationship: Figure–ground organization is a type of perceptual grouping which is a vital necessity for recognizing objects through vision. In Gestalt psychology it is known as identifying a figure from the background. For example, you see words on a printed paper as the "figure" and the white sheet as the "background"

Additionally, the programming board relates to Language Syntax. While this is a secondary concept, and extremely subtle, it could be a useful way to create a cross-context understanding of programming and language, in that it breaks down instructions into categorical fields, that relate to basic grammar. We can think of programming as instructions, or recipes. Instructions are simple commands in which we explicitly tell the computer what to do. In this case, these instructions can closely align with language in that the command fields break down into adjectives, subject (noun), prepositions, and adverbs. In Montessori, parts of speech are given colors (and shapes) in other lessons.

D. Key Terms:
Subject
Verb
Adjective
Preposition
Adverb

III Age

The Programming Board is recommended for ages 4 - 9. Younger children may need more assistance, and the emphasis may be on simple understandings of color matching, holding a pencil, and drawing simple shapes. Since the programming board uses very simple icons to express information, it is not necessary that children can read. Later more advanced activities such as starting with the image and reverse-coding it, may be better for older students, such as 7+. The lessons incorporating the use of variable may be best for ages 6+.

IV Prerequisite

There are no strict prerequisites for this material. An introduction lesson to computer science is helpful in order to place this activity in a meaningful context. For language associations, it is good that the students understand basic grammar and how to differentiate parts of speech. Basic drawing skills and holding a pencil are useful, although this could be a lesson that exercises that skill.

V Notes

Scratch: Scratch is a beginning block programming language for children. In block programming, simple blocks represent complex programming syntax, so that children can focus on the broad concepts versus the details. With Scratch, you can program your own interactive stories, games, and animations — and share your creations with others in the online community. See: www.scratch.mit.edu

Variable Cards: Variables are used to store information to be referenced in a computer program. It is helpful to think of variables as containers that hold information. Their sole purpose is to label and store data in memory. This data can then be used throughout your program.
In this case, the variables are represented on the blocks with identifiers such as (a), (b), (c), and (d). Meanwhile, blank cards with corresponding labels allow the children to draw or write anything they want on them. The information for their program is stored on these cards, and the code includes the variable, so that when the code is "run" with a variable block, the image on the card is substituted for the block.

Open to Interpretation: While computers rely on extremely basic instructions that do not allow for interpretation, this material exposes the fact that no two drawings will look alike, although they follow the same code. This could be a starting place for discussions as to why. For example, in what ways are the programming blocks imprecise? And why does one child's drawing of a circle look different from another?

VI Materials Included

Programming Board
Drawing Board (Screen)
Colored Pencils with tray
Paper
Blocks (coded by colored dot on back) in bag
Object (subject or noun) blocks (dot color=black)
Variable blocks
Color Blocks (dot color= Royal Blue)

Action Blocks (dot color=Red)
Location Blocks (dot color=Green)
Size Blocks (dot color=teal)
Direction Blocks (dot color=red)
Rotation Blocks (dot color=orange)
Number Blocks (dot color=yellow)
Variable Cards

VII Procedure

Activity 1: Program, Then Draw

Materials Required:

Programming Board
Drawing Board
Paper
Colored Pencils
Blocks

1a: Writing a Program

Introduction. *Today we will be writing simple programs.* Explain how programs are a series of instructions. These instructions are like recipes. *What are recipes? Why do we create recipes? Like recipes, we can create instructions for the computer.* This activity allows us to create instructions for how to make drawings. Show the board and all of the materials, defining key concepts along the way. These are the materials we are using today.

Show the child the way in which the blocks are assembled on the board. Note that each column has its own color. You can mention the association with the parts of speech if this is appropriate to your other lessons or age group. Explain which block goes where, and what each block does. This block represents color, this block represents location, etc.

Set up a row of blocks, according to the appropriate field, and then talk through and demonstrate how the child will implement the instruction. Talk through the commands before making any marks. This is important so that the child can first visualize it and see that it makes sense. (For example, sometimes, the code may need to be adjusted, if logically the command does not work; i.e. draw a large circle 10 times on the right side of the paper moving right--you would run out of space. So simple planning and spatial understanding is necessary.) First, I see that pink block, so I know I will be using the pink pencil. Next I see that the object I am drawing is a triangle. (don't make a mark yet). I see that I will begin drawing in the lower left hand corner. This shape will be small in size. I will draw 3 of this shape, each time moving upwards, and rotating this much each time I draw the shape(show the arrow on the block, which represents 90, 180, and 270 degrees. Depending on the age level of the child, you can draw the line of code yourself.

Explain how each line is a command. There are 6 fields, represented by 6 columns. You can make 5 lines of code. Together, this makes a program.

Together, "write" the program, by creating each line of code. Assist the child in locating the appropriate block for each field. After creating a line of code, ask the child to verbally talk through it. *Does this make sense? Can you imagine what that would look like?*

1b: Drawing the Program

Now you have written a program! Here is our screen. This screen is a drawing pad that works like your computer does. When we give instructions to our computers, the computer can create this instructions on the screen. Today, we will be doing the work of the computer, and we will follow the instructions by drawing on the screen, like a computer does. It is important we read carefully and follow each instruction one at a time.

Have the child draw the first line of code. Let he or she make any mistakes. It's ok. Ask them to re-read the line of code, and agree or disagree that it looks like his or her drawing. Have the child complete the rest of the lines of code, talking through each line before he or she draws, and checking after each line to determine if it is correct. When each line is finished, the child has run (drawn) the program.

Activity 2 Program then give to another to draw

Materials Required:
Programming Board
Drawing Board
Paper
Colored Pencils
Blocks

Activity 2a: Writing a Program

Introduction: This activity follows the previous, Activity 1a/1b in which the child learns about what programs are, how to create a program on this programming board, and then draw the program on the drawing board (screen). For this activity, the same concepts are explored, only this time in a collaborative manner. One child "writes" the code and then shares with another child who draws it. Review the key concepts and materials of the activity with the child, if necessary.

If the child writing the code needs a review on the lesson, go through it together, and please see Activity 1a. For this step, one child writes the program, by creating 5 lines of code (commands) on the programming board. As the child writes each line, he or she should talk through it to themselves, and make sure that it makes sense; the child can also self-correct the placement of the blocks into the correct field, but checking that the dot on the back of each block matches the dot at the top of the corresponding field column.

Activity 2b: Drawing the Program

After the first child has completed writing the program, he or she shares it with another child. The second child is now the computer, running (drawing the program) on the screen (paper).

Before drawing each line, the child talks through the line of code, in order to understand what is happening and visualize how it will fit on the paper. Then the child draws each line of code, using this process: talk through it first for comprehension and visualization, draw the line of code, check the drawing to the line of code to confirm he or she implemented it correctly. The child completes the 5 lines of code. *Was there any part of the program that was confusing to you or difficult to draw?* The child then shows the drawing to the programmer, and they can discuss the process together.

Activity 2C: Multiple Children's Drawings of the Same Program

And additional step for this activity would be to have more than one student draw the program. Several could follow the same program simultaneously or without seeing the others' drawings. Follow the same steps from Activity 2b for each child. After multiple children have completed drawing the program, collect them all and gather up the children.

Place the drawings on the wall, or ground, so that everyone can see them and that they are orientated the same way. (In order to ensure the orientation of the drawing, have the child draw and arrow on the back indicating the top, along with their name.) Take a moment to look at the drawings, all of them together

What do you notice about all of these drawings? What do they have in common? What differences do you notice? Why do you think there are differences even though we all used the same program?

Activity 3 Draw, then program themselves

Materials Required:
Programming Board
Drawing Board
Paper
Colored Pencils
Blocks

This activity follows the previous activities, at least Activity 1, so that the child is familiar with this material and understands the key concepts. Particularly, the child should be familiar with the specific blocks, what objects there are, and how the different blocks in the set work.

This activity is the reverse process from the previous. Review with the student the key concepts of the programming board, and its parts (if necessary). For this lesson, we will be moving backward; instead of writing the program first, we will be making a drawing first, and then trying to decode it, by creating a program for it. *Why would we want to do this?*

Give the child the paper and the colored pencils. Include the blocks, laid out, so that the child can see if he or she needs help remembering or getting started drawing. It is important to note that the child is not just drawing whatever, but it is directed toward what can be programmed with this set. It is still interesting in terms of reducing an image down to simple steps, or abstracting it, and this could prompt discussion. Also note/remind the child that this program only has 5 lines of codes, so the drawing should also have only 5 distinct parts, that can be written as lines of code.

After the child has created a drawing, the child will write the program using the blocks in the appropriate fields on the programming board. *Was this difficult or easy? What were the challenges? In what ways is the programming board limited?*

Activity 4a Draw then another programs

Materials Required:
Programming Board
Drawing Board
Paper
Colored Pencils
Blocks

This activity is similar to the previous (Activity 3) and should follow after the child understands the key concepts of this material and has completed at least Activity 1. As with the previous, the child should be familiar with the specific blocks, and it is most helpful if he or she has completed Activity 3.

Now, for this activity we will work backwards. We start with a drawing, that is drawn by someone else, and then "decode" it to figure out how we would represent it in a program on the programming board.

Have one child create a drawing that will be programmed by another child. So remind the child drawing that there will be 5 distinct lines of code. What can you draw that can be written as a program with our programming board? It is helpful to lay out the blocks and the board, so that the child is reminded of how the blocks work, and what is specifically represented. After the first child creates a drawing, he or she shares it with another child, who uses the blocks and the programming board. Look at the drawing. Imagine the steps he or she took to make it. Can you create a program that gives the instructions to draw this picture? What is challenging about programming this drawing? Can you accurately recreate it with the code?

Activity 4b

You can take this even further by continuing Activity 4a to then take the programmed board, based on the first drawing, and then share it with a completely different child, who is not familiar with the original drawing. Have the new child draw the program (using the same procedure as mentioned above and throughout)

Layout the original drawing, the program board, and the new drawing. Gather the three children and have a discussion about the results. *In what ways are the two drawings similar? How are they different? Why do you think that they look different?*

Activity 5 Program Using Variable cards

Materials Required:

- Programming Board
- Drawing Board
- Paper
- Colored Pencils
- Blocks, including variable blocks
- Variable Cards

This activity can be incorporated into all of the previous, however it requires some additional content and may be best for older ages, such as 6+. The new information and key concept demonstrated in this material are variables. Students should have completed at least Activity 1, and understand the key concepts and procedure for the programming board.

For the object block, which is labeled with a black dot on the back, there are four variable blocks: (a), (b), (c), and (d). There are corresponding cards with these labels on them. Explain to the child what a variable is. Variables are stored information that the code references. We can draw on these cards, and when we use the variable block, it means that we can substitute what is on the card for that variable.

Have the child draw an image, object, text, on the variable card.

The child can then use the variable block in the program to call the image drawn on the card.

Bibliography

American Academy of Pediatrics Council on Communications and Media. "Media and Young Minds." *Pediatrics* 138 (5) e20162591 (2016): doi: 10.1542.

Anderson, Daniel R., and Tiffany A. Pempek. "Television and very young children." *American Behavioral Scientist* 48, no. 5 (2005): 505-522.

Barr, Rachel. "Memory constraints on infant learning from picture books, television, and touchscreens." *Child Development Perspectives* 7, no. 4 (2013): 205-210.

Barr, Valerie, and Chris Stephenson. "Bringing computational thinking to K-12: what is Involved and what is the role of the computer science education community?" *Acm Inroads* 2, no. 1 (2011): 48-54.

Bell, Tim, Jason Alexander, Isaac Freeman, and Mick Grimley. "Computer science unplugged: School students doing real computing without computers." *The New Zealand Journal of Applied Computing and Information Technology* 13, no. 1 (2009): 20-29.

Bell, Tim, Ian H. Witten, and Mike Fellows. "CS Unplugged About." Accessed May 2, 2017. http://csunplugged.org/principles/.

Bers, Marina Umaschi, Louise Flannery, Elizabeth R. Kazakoff, and Amanda Sullivan. "Computational thinking and tinkering: Exploration of an early childhood robotics curriculum." *Computers & Education* 72 (2014): 145-157.

Blikstein, Paulo, "Computationally Enhanced Toolkits for Children: Historical Review and a Framework for Future Design," *Foundations and Trends in Human-Computer Interaction*, v9 n1 (2015): 1-68.

Brennan, Karen, and Mitchel Resnick. "New frameworks for studying and assessing the development of computational thinking." In Proceedings of the 2012 annual meeting of the American Educational Research Association, Vancouver, Canada, 1-25. 2012.

Center for Technology in Learning at SRI International, "Exploring Computer Science: Curriculum Mapping to Learning Standards." Accessed May 8, 2017. http://pact.sri.com/downloads/ECS-Alignment-Common-Core-v-0-1.pdf

Code.org. “Promote Computer Science.” Accessed November 10, 2016. https://code.org/promote.

Computer Science Education Coalition. “Computer Science Education Coalition Press Release.” Accessed November 10, 2016. http://www.csecoalition.org/Computer-Science-Education-Coalition-PressRelease/

Corbin, Juliet M., Anselm L Strauss. *Basics of qualitative research : techniques and procedures for developing grounded theory.*

Duch, Helena, Elisa M. Fisher, Ipek Ensari, and Alison Harrington. "Screen time use in children under 3 years old: a systematic review of correlates." *International journal of behavioral nutrition and physical activity* 10, no. 1 (2013): 102.

Google (n.d.). “Exploring Computational Thinking.” Accessed November 2, 2016. http://www.google.com/edu/computational-thinking.

Google (Firm) Gallup (Firm). "Images of computer science: perceptions among students, parents and educators in the US." (2015).

Guzdial, Mark. "Education Paving the way for computational thinking." Communications of the ACM 51, no. 8 (2008): 25-27.

Kabali, Hilda K., Matilde M. Irigoyen, Rosemary Nunez-Davis, Jennifer G. Budacki, Sweta H. Mohanty, Kristin P. Leister, and Robert L. Bonner. "Exposure and use of mobile media devices by young children." *Pediatrics* 136, no. 6 (2015): 1044-1050.

Knuth, Donald. *The Art of Computer Programming.* Upper Saddle River: Addison-Wesley, 2005.

Lee, Irene, Fred Martin, Jill Denner, Bob Coulter, Walter Allan, Jeri Erickson, Joyce Malyn-Smith, and Linda Werner. "Computational thinking for youth in practice." *Acm Inroads* 2, no. 1 (2011): 32-37.

Lillard, Angeline. "How important are the Montessori materials." Montessori Life 20, no. 4 (2008): 20-25.

Lillard, Angeline Stoll. *Montessori: The Science behind the Genius.* New York: Oxford University Press, Inc., 2007.

Lillard, Angeline, and Nicole Else-Quest. “Evaluating Montessori Education.” *Science* Vol. 313, Issue 5795 (2006): 1893-1894.

Lin, Ling-Yi, Rong-Ju Cherng, and Yung-Jung Chen. "Effect of Touch Screen Tablet Use on Fine Motor Development of Young Children." *Physical & Occupational Therapy In Pediatrics* (2017): 1-11.

Liukas, Linda. *Hello Ruby.* New York: Feiwel & Friends, 2015.

Montessori, Maria. *The Absorbent Mind.* New York: Dell Publishing Company, 1984.

Montessori, Maria. *Dr. Montessori's Own Handbook: A Short Guide to Her Ideas and Materials.* New York: Schoken Books, 1965.

Montessori, Maria. *The Montessori Method.* Radford: Wilder, 2008.

Nisan, Noam, and Shimon Schocken. *The Elements of Computing Systems: Building a Modern Computer from First Principles.* Cambridge: MIT Press, 2005.

Papert, Seymour. *The Children's Machine: Rethinking School in the Age of the Computer.* New York: BasicBooks, 1993.

Papert, Seymour. *Mindstorms: Children, Computers, and Powerful Ideas.* New York: Basic Books, 1993.

Piaget, Jean, Howard E. Gruber, and J. Jacques Vonèche. *The Essential Piaget.* New York: Basic Books, 1977.

Prensky, Marc. "Digital natives, digital immigrants part 1." On the horizon 9, no. 5 (2001): 1-6.

Resnick, Mitchel, John Maloney, Andrés Monroy-Hernández, Natalie Rusk, Evelyn Eastmond, Karen Brennan, Amon Millner et al. "Scratch: programming for all." Communications of the ACM 52, no. 11 (2009): 60-67.

Social Computing Group, Media Lab. “Social Computing Learning.” Accessed on May 2, 2017, http://social.media.mit.edu/areas/learning.

Sullivan, Amanda, and Marina Umaschi Bers. "Robotics in the early childhood classroom: learning outcomes from an 8-week robotics curriculum in pre-kindergarten through second grade." International Journal of Technology and Design Education 26, no. 1 (2016): 3-20.

Taub, Rivka, Michal Armoni, and Mordechai Ben-Ari. "CS unplugged and middle-school students' views, attitudes, and intentions regarding CS." ACM Transactions on Computing Education (TOCE) 12, no. 2 (2012): 8.

Turkle, Sherry, Evocative Objects: Things We Think With. Cambridge: MIT Press, 2011.

Wilensky, Uri, Corey E. Brady, and Michael S. Horn. "Fostering computational literacy in science classrooms." Communications of the ACM 57, no. 8 (2014): 24-28.

Wilkinson, Karen, and Mike Petrich, The Art of Tinkering. San Francisco: Weldon Owen, 2014.

Wing, Jeannette M. "Computational thinking." Communications of the ACM 49, no. 3 (2006): 33-35.

Wing, Jeannette M. "Computational thinking and thinking about computing." Philosophical transactions of the royal society of London A: mathematical, physical and engineering sciences 366.1881 (2008): 3717-3725.