UNIVERSITY OF CALIFORNIA
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Record of Creative Work

A comprehensive exam report submitted
in partial satisfaction of the requirements for the degree
Master of Fine Arts in the Department of Design Media Arts

by

Peter Hawkes

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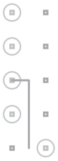
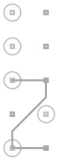
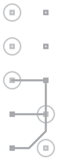

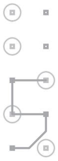
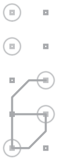



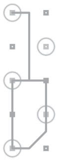
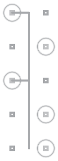

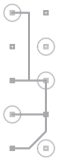

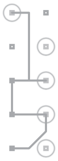
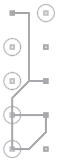
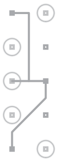
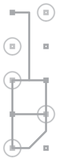
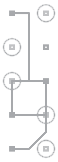
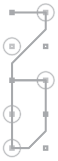
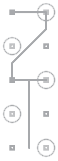


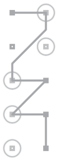
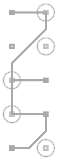
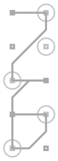

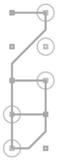
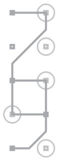

Thanks

To my ever-patient committee, for their encouragement, critique and guidance.

To my children, Molly and Ethan, for play-testing *everything*.

To Noa for pulling me through.

To Mr. G. and the many amazing teachers in my life—even Mr. Coe.

Binary Learning

Pete Hawkes

2012

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Introduction

My mind, eyes, arm, hand and pencil traversed the margins of the notebook, deep in focussed, calculated thought. The trajectory had to be just right. Certain, beautiful destruction was evident ... inevitable ... ***WHAM!*** *The textbook crashed down within inches of my arm. The pencil flew; blood drained from my face; neighbors snickered. Mr. Coe said, "Back to work, Mr. Hawkes."*

I love math, but it hasn't always loved me back. More specifically, I'm passionate about the application of math in the work I do and the art I create, but the bulk of the education I received shared little with me about its creative potential. A typical math education focusses on manual computation in a language of abstract symbols that are used less and less in modern careers. The way we access and process information has changed, yet students spend valuable classroom time—years—crunching numbers in isolation with pencil and paper. Children are intrinsically curious and creative. They enjoy playful interaction with their physical environment, and they learn even more by experimenting and exploring with their peers. Teachers need new approaches that bring abstract concepts into the tangible world, in ways that leverage the body and encourage lifelong creativity and passion.

Inspired by other efforts to improve math and science education, I began researching my own ways to contribute. My primary focus is on the needs of disengaged students, but I am mindful of hardworking teachers who are caught in the middle, doing their best to bring these students forward. Motivating this research is a hope to inspire designers to create simple, accessible solutions can make a difference even in areas of the educational system where resources are tight.

Underlying Numbers

I see a common disconnect in the current approach to teaching math. Children already embrace technologies that are capable of incredible computational power. Underlying these technologies are the very concepts and ideas that their teachers strive so hard to teach. If students could understand that the exciting systems that wait for them outside of school are built on numbers and sequences, maybe a new interest this simple, yet crucial relationship will arise.

The advent of personal computers and home gaming systems in the 1980s and 90s introduced new technical terms to children that provided a small glimpse into the inner-workings of computers. Marketing around the release of the Nintendo Entertainment System touted an 8-bit system. Playing with 8 bits was amazing; more colors, better sound. Several years later, the Super Nintendo and Sega Genesis arrived, both 16 bit systems. The games had shinier graphics and more complex gameplay. Then followed the Nintendo 64. The same patterns were clear as school-aged children compared processor speeds and graphics cards in personal computers. System names and marketing embraced the numbers behind the technology.

Now that we've approached computing speeds that provide astonishing frame rates in detailed 3D environments, we hear less and less about the underlying details of the machine. Those who remember the marketing simply recall that each fibonacci upgrade meant better-looking, faster games. And yet the reasons for those numbers provide valuable insight not only into the history of communication and modern computing, but into the methods programmers and engineers continue to use to solve complex problems.

I created a series of physical interfaces to help explain this hidden nature of computers. Intrigued by a friend who could count in binary on his fingers, I created a simple system to practice binary addition. Five inputs allowed for a simple set of numbers that even young learners could understand. Additionally, I aimed to create accessible, tactile interfaces where participants could explore sound, sequence, and pattern.

Binary Glove

Using the hand has many advantages. Our hands are natural tools for interacting with the world. Beyond using them to grab hold of and move objects in our environment, we use them for gesture, emphasis, and unspoken communication with one another. We also use them to count. The earliest counting systems on record involve sequential marks in soft clay[1] or knots on a string[2] (**Fig. 1**). Seeing a count or tally in an external medium helps our brains comprehend more complex reasoning. Essentially, we store the count into a physical system, freeing up room for the brain to deal with other problems. And when clay, beads and rope are not immediately on hand, we need only raise a hand and extend the appropriate number of fingers to gain the same advantage.

Figure 1 A cuneiform tablet and an Incan quipu numbering system

The method my friend used for binary counting was difficult to follow. Rather than just raise and lower fingers, he used wrist rotations and awkward, if not impossible, hand gestures. It looked impressive, but was

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[1] James Gleick, *The Information* (NewYork: Pantheon Books, 2011), 42-43.

[2] Marcia Ascher and Robert Ascher, *Mathematics of the Incas: Code of the Quipu* (Mineola, NY: Dover Publications, 1981), 10-11.

difficult for an observer to follow and cumbersome to learn. I decided to reduce the motion to simply tapping fingers on a solid surface.

Early experiments with solid buttons felt too far removed from simple finger-counting. It was important that the interface be immediately responsive so that manner of use would feel as natural as counting with a bare hand. The first functional iteration used Force Sensitive Resistors (FSR's), small thin pads that detect changes in pressure, connected to an Arduino microcontroller (**Fig. 2**). The output from these sensors was displayed on a small 16 x 2 serial display. The FSR's were sensitive enough that the slightest pressure triggered an immediate response. A small piezo buzzer produced simple sounds to reinforce the interaction and enhance the tactility of the experience.

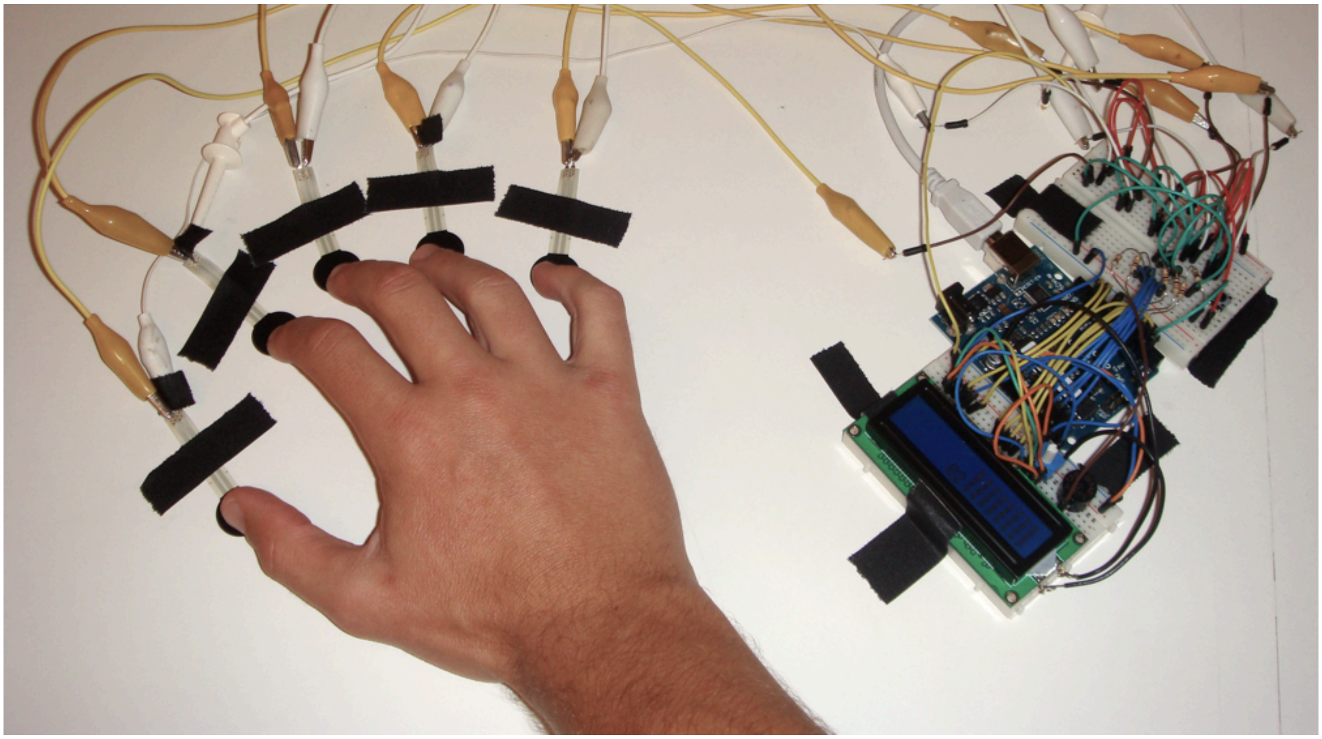

Figure 2 Force Sensitive Resistors connected to an Arduino

This configuration was then was built into a glove (**Fig. 3**). The sensors were positioned inside the finger tips of the glove at the natural point of contact when resting on a flat surface. The remaining electronics were enclosed on top of the wrist with the display facing upward. The system was powered with a small battery pack or via USB cable to a power source. Each digit represented a bit value in a simple binary sequence: 1, 2, 4, 8, and 16. The output from the pressure sensors registered each finger as on or off. The sum of each active bit was then displayed on the wrist along with a visual representation of the current combination. Five bits allowed the wearer to create sum totals from 0 to 31 on one hand.

Figure 3 Binary Glove

By default, the glove ran in a learning mode for experimentation and play; no instructions; no expectations. The serial display showed five prominent '+' characters that moved up and down when fingers were active. A large number showed the current sum, and a 4 x 8 grid of small dots quantified the 32 possible combinations. Each number combination played a different tone on a scale relative to its total value. The piezo buzzer created short staccato bleeps that provided gratifying feedback.

Unlike a piano keyboard, the tones changed in range when individual fingers were pressed individually in sequence. There was a small, incremental jump between thumb and index finger (1 to 2) and a much larger jump in tone between ring finger and pinky (8 to 16). Very quickly users discovered that pressing many fingers simultaneously produced higher notes; the highest note was only achieved by pressing all fingers together to create 31: the sum of 1 + 2 + 4 + 8 + 16. The range of sounds, correlating in pitch to the sum displayed, reinforced that the user was able to create more than just five sounds.

Once the user was comfortable with the learning mode, a button could be pressed to start a game mode to test the wearer's knowledge of the system. In this challenge mode, a random number from 1 to 31 was displayed with the simple instruction "ADD IT!" An incrementing timer counted up in hundredths of a second to create a sense of urgency. It also provided participants a benchmark for improving their reaction time. This was useful not just for individual play, but especially in a group setting where users could prove their mastery of the system to their peers. Addition was not the end goal for the Binary Glove. Beyond providing an engaging, positive experience, the glove teaches pattern recognition and an understanding of the efficiency of a bit-based system; through only 5 inputs, a computer could represent 32 unique outputs.

Binary Pad

The Binary Glove was fun to use and effectively trained users in simple binary computation. It also showed promise as a gestural instrument, but its fixed sized was a problem for different hand sizes. Young children were unable to have a seamless interactive experience; excess fabric got in the way of tiny fingers. In order to bring the system to a larger audience, I rebuilt the device as the Binary Pad (**Fig. 4**). The pressure sensors were replaced with simple push buttons, and a physical interface was designed that would accommodate a variety of hand sizes. The haptic experience of the larger buttons was less gratifying than the pressure sensors on the glove, but the form factor was effective; it even successfully accommodated left-handed users. The table-top interface allowed users to interact without the ceremony of donning the device, and multiple participants could use the pad simultaneously.

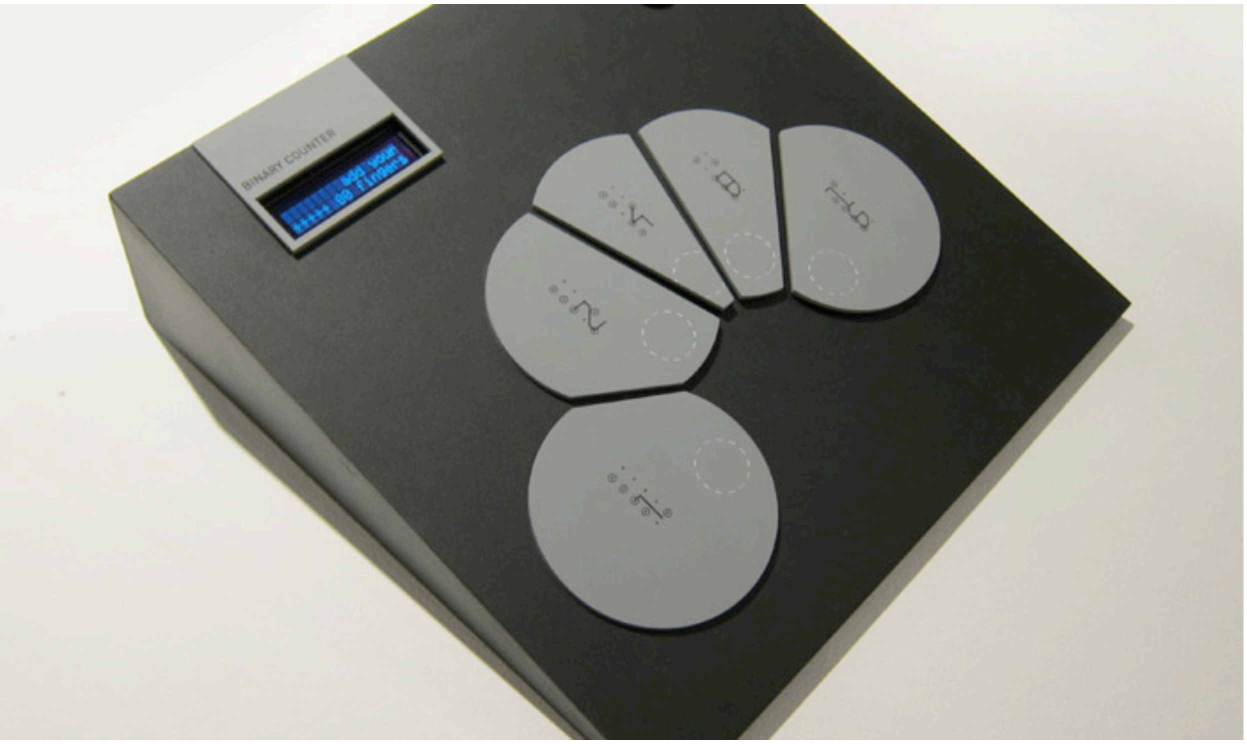

Figure 4 Binary Pad

The ability to test the system on a larger audience was most valuable. In December of 2010, I arranged to visit two fifth grade math classes to observe and document their interaction with the new system. Nora Sterry Elementary is part of the Los Angeles Unified School District, the second larges public school system in the nation. 62 students participated. I was graciously given a full hour with each class. I began each session with presentation on pattern and sequence in nature, with a particular emphasis on ways the students could discover these patterns in everyday objects from their own urban environment. I showed them a series of photos I'd taken on a walk around their school (**Fig. 5**) and asked them if they could identify what the objects were or where they were located. This got the students talking about personal observations and piqued the interest of those more resistant to math. Some were surprised by their ability to recognize the textures. Others expressed an interest to go seek out the patterns so they could take a closer look. We talked about how the textures were made, how they felt, and if they were reminiscent of other things. I then showed the same photos with overlays of earthquake data, generative drawings, and mathematic diagrams to illustrate that math, pattern, sequence and time are in everything around us—even the most ordinary things (**Fig. 6**). Their teachers helped draw parallels to the number sequences and patterns they were learning in school at the time. This provided a comfortable foundation to introduce them to the Binary Pad.
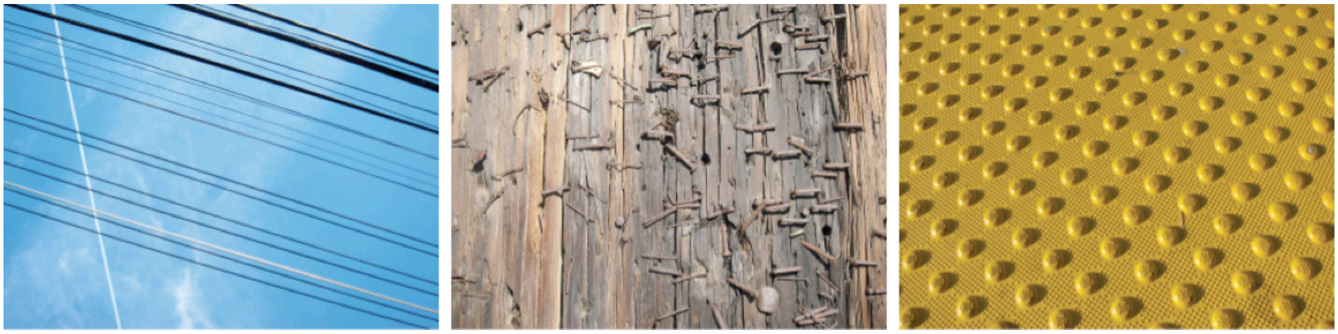
Figure 5 Textures around Nora Sterry Elementary

Figure 6 Textures with data, design, and math overlays

It was fortunate that I was able to present my work in two classes. When I set up the Binary Pad in the first class, it was clear that the teacher was concerned that students might break it. Clear rules were defined; students lined up to have a turn with the device. This meant each student would approach the interface for the first time under the watchful eye of two adults. Performing solo takes courage and is potentially embarrassing. And while I was interested in initial reactions, the teacher preferred to instruct them to hurry the process along. It was clear that the students were overwhelmed. Some seemed to watch for the approval of the teacher more than they watched the interface itself. Very few attempted to play or explore.

I took a different approach with the second class and this time the teacher understood my intent. Instead of lining students up one at a time, they were brought back in groups. Initially they still took turns alone with the device, but soon began approaching the interface in collaborative ways (**Fig.** 7). Those who had finished playing lingered nearby, enthusiastically coaching new participants on easier ways to think about the system. Crowding around the device, they helped one another complete combinations, teaching and explaining as they interacted together. They quickly discovered that they could achieve much faster times in the challenge mode if they worked together. Collaborative participation arose spontaneously. A spirit of play and collective problem solving lead to greater overall engagement and comprehension of the system.

Figure 7 Binary Pad with a 5th grade math class

The open atmosphere also lead to more questions. One student asked where he could buy his own device and how much it would cost. This provided the opportunity to explain that I had built it with simple electronics. I turned the system over and showed the students the sensors, wires, and Arduino micro controller. We talked about the accessibility of affordable DIY electronics and the many resources available online. They showed excitement about the possibility of building similar devices themselves.

Binary Dance

As an additional experiment, I led the students in my own full body computational exercise (**Fig. 8**). Instead of adding with fingers, I assigned the five bits from the counting system to a different appendage of the body, including the head, arms and legs. Each limb was given an on-state and an off-state: lowered or raised. After personally demonstrating each of the 32 unique body poses, I invited the class to stand and join me as I lead them in sequence through each pose (**Fig. 9**). The students found the dance humorous and fun. They referred to a few of the more sudden state changes as "Michael Jacksons"—the shift from 11 to 12 and from 17 to 18—because of the unique way the head would drop as an arm and a leg jutted out to the side. Learning the sequence in a large group allowed students to comfortably observe their classmates while attempting the combinations themselves. Students reported understanding the underlying patterns that emerged as they physically acted out the sequence; they could *feel* the patterns in ways different from the Binary Pad. Months later, I was stopped by some of the original participants so they could demonstrate that they still remembered the dance sequence.

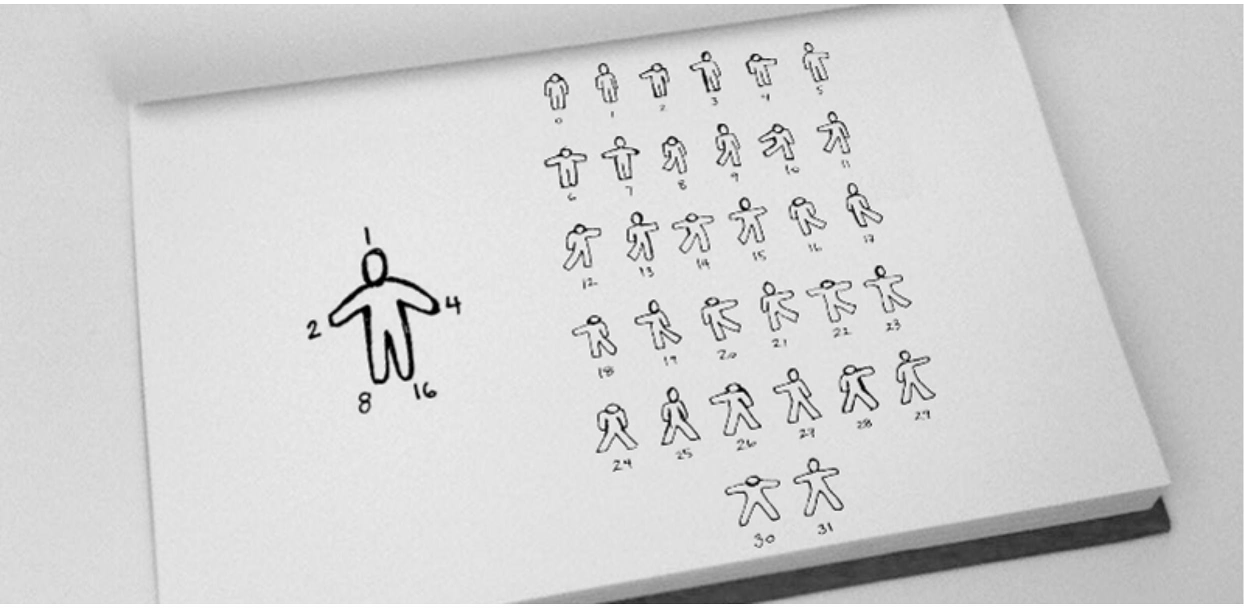

Figure 8 Binary Dance diagram

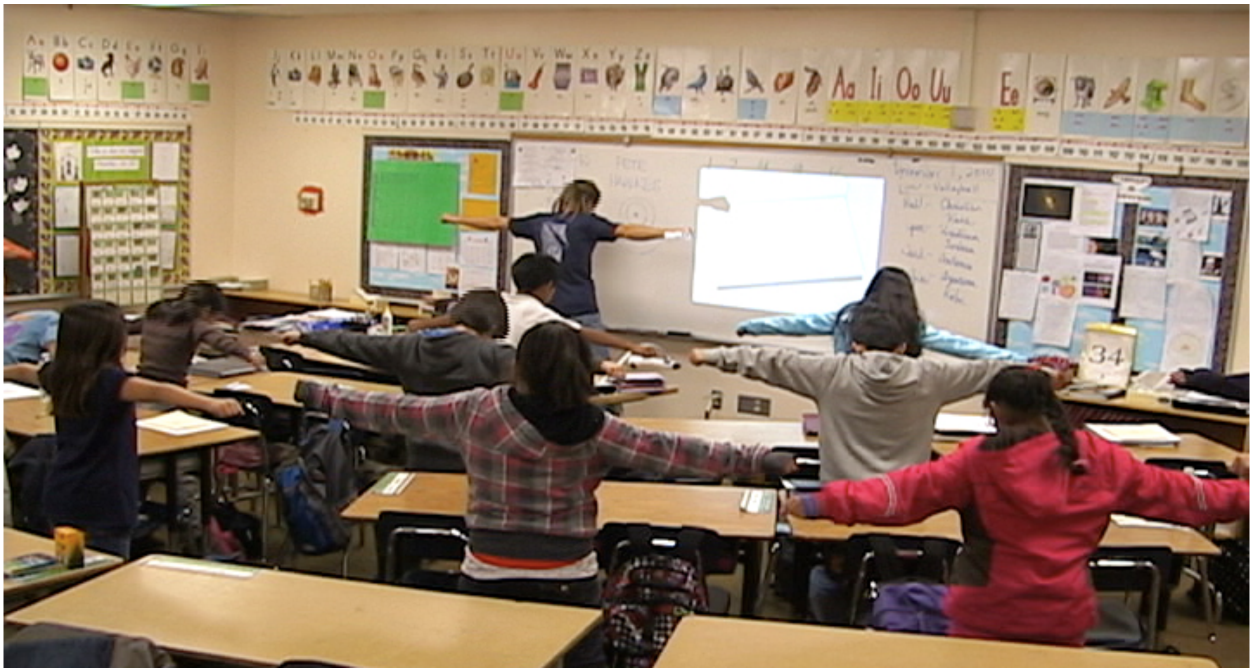

Figure 9 Binary Dance instruction

Binary Face Off

Following the visit to Nora Sterry, I created Binary Face Off (**Fig. 10**). The Binary Dance had been effective enough that I drastically increased the size of the device and expanded its ability to accommodate more users. Two opposing body-sized interfaces were connected by an Arduino board to game software written in Processing. As in previous iterations, the pitch of interface sounds, which were linked directly to each combination, played an important role in the experience; I wanted the sound to carry through a larger crowd. Screen visuals provided instructional messaging and pattern diagrams.

Figure 10 Binary Face Off

As participants approached the installation, they saw a series of large, hand-sized buttons and a screen with a simple invitation to play. Each side functioned independently in this state. It was suggested that I merge the input of both sides to build larger sums, but I felt it was important to keep the initial experience as simple as possible: the same five inputs, the same 32 possible combinations. With two sides installed in the center of the gallery, many more people could interact simultaneously.

I also introduced a more considered competitive game experience. The Green side could press a button to challenge the Blue side to a binary face off. If Blue accepted, Green was asked to create a combination and hold it for a full second. Once the challenged number was submitted, Blue was then timed to see how long it would take to create the 31 – [Green's number]. Green earned more points the longer Blue took to complete the problem. The process was then reversed and repeated over three rounds of play.

I observed three strategies to completing the challenge. The first and least effective was usually attempted by new-comers who hadn't spent much time learning or observing: randomly hitting and holding buttons. The second approach was to complete the simple math problem displayed on the screen: 31 – [Green's number] = [Blue's number]. The third and simplest solution was typically achieved after players had played a few times: Blue need only create the inverse combination, the buttons Green had not pressed.

Game play was not very intuitive, and the interface itself could have been improved, but I found that some mystery only encouraged further group participation. The added stress of public gameplay and running timers flustered some players. Fortunately, bystanders would often come to the rescue, understanding in their pressure-free context on the sidelines what needed to be done. As in with the math students at Nora Sterry, I observed players who had mastered the system linger to help others or return later to train and then challenge their friends.

The buttons were strategically placed to force participants into full-body gestures, some of which were particularly awkward when playing alone. The smaller, more frequently used numbers 1 and 2 were also positioned low on each side to encourage the use of knees, feet or crouching. This introduced a performative aspect that also brought comedy to the experience. When players—particularly small children—struggled to connect more difficult combinations (**Fig. 11**), they asked for help from others nearby. I also built the structure from sturdy materials and designed the buttons so that they could withstand considerable abuse. Participants could kick, slam and jam buttons with significant force—and many did (**Fig. 12**).

Figure 11 Binary Face Off in action

Figure 12 A well-used button

This series of gesture-based learning systems demonstrated an effective approach to teaching abstract math concepts. More importantly participants enjoyed the experience and often went further to help and teach their neighbors and friends, increasing the likelihood of knowledge retention. By utilizing open-ended play and game components, users were free to experiment and explore the system and then challenge their knowledge. Additionally, the use of full-body interaction and gesture expanded the teaching potential of the interaction in ways that are underutilized in education.

Had my grade school math curriculum leveraged these principles to teach abstract concepts, the margins of my notebook would likely have been filled with more math than mayhem. Teachers are struggling not only to hold the attention of a rapidly changing student population, but to meet the urgent needs of a system that falls short in math and science. Rather than push standardized testing and outdated practices, they need tools and approaches that incorporate creative, engaging, physical systems.

Math Problems

In 2006, Richard Cohen of the Washington Post called attention to a particular problem in mathematics. The Los Angeles Unified School District had changed a policy to require that all students pass a year of algebra and a year of geometry in order to graduate. On the surface this may sound entirely reasonable; the United States has fallen behind other developed countries in math and science. The measure, which was already a requirement in 17 other states, was meant to help close that gap and make the U.S. more competitive. Unfortunately, it has resulted in an increase in the number of high school dropouts in the Los Angeles area—which now loses more graduates on account of algebra than any other subject. Cohen writes of one student, Gabriela Ocampo, who after failing algebra six times in six semesters, finally gave up during the seventh, "gathered her textbooks, dropped them at the campus book room and, without telling a soul, vanished from Birmingham High School."[3] It is important to note that many of these failures are not a result of lower intelligence or a lack of trying. The students excel in other subjects but remain stumped on algebra.

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[3] Richard Cohen, “What is the Value of Algebra,” *The Washington Post*, February 16, 2006, accessed September 12, 2012, http://www.washingtonpost.com/wp-dyn/content/blog/2006/02/15/BL2006021501989.html.

Cohen himself confesses that he hated math and only barely passed algebra through some "divine intervention."[4] His salvation was a typing class and an eventual career as a writer. I empathize with Cohen on some levels, but I didn't hate math. Geometry and trigonometry excited me because of the parallels they had with my own creative impulses, but algebra and much of the rest of my math education often felt monotonous and even pointless. Fortunately, I entered high school in the dawning age of the graphing calculator. I busied myself writing simple programs on my TI-81 or graphing equations that made unexpected patterns in the pixels on my screen. That's where the magic was; that's where math felt real. But I was playing outside of the curriculum, and it often led to trouble.

Today's teachers are struggling to hold the attention of students like me. New gadgets—smart phones, media players, and handheld gaming devices—have supplanted the TI-81 and calculator watch. Eric Patterson teaches algebra to ninth-graders in a low-income neighborhood and asks himself why so many of his students fail algebra. On average, only half pass in their first year of high school. He wonders "what is going through their minds as they sit there, knowing they are going to fail."[5] Not surprisingly, Patterson points to the competition; immersive technologies engage his students in ways that traditional computation with pencil and paper cannot. The landscape has changed, and it continues to change so quickly that teacher and textbook are left behind. I'm not advocating a dumbing-down of the curriculum, or that math needs to be digitized or simply more entertaining, but I submit that the current system misses important opportunities for engagement that relate directly to a fundamental desire for learning.

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[4] Richard Cohen, "What is the Value of Algebra."

[5] Eric Patterson, "Why Do High School Students Fail Algebra?," *Yahoo! Contributor Network*, November 26, 2008, http://voices.yahoo.com/why-high-school-students-fail-algebra-2232214.html.

Diana Laufenberg, an advocate for education reform in the United States, cites a key change in the availability of information over the last century. The great-grandparents of today's children relied almost exclusively on schools to receive information. Teachers imparted knowledge to the student who then took that knowledge out into the world for direct experimentation. Children were more actively engaged in the testing of that knowledge in the real world. A generation later, resources like the World Book Encyclopedia arrived, and there was no need to go to the library because the information was now accessible inside the home.[6] But this pales in comparison to today's landscape. This shift from information scarcity to information surplus compounded exponentially as the internet entered our homes and our pockets.

Laufenberg points to this shift to emphasize that our approach to education needs further change. The educational paradigms of the past—one right answer bubbled in on a multiple choice test—are no longer effective because the information landscape has changed. She advocates instead an embrace of the surplus.[7] The time and effort we spend drilling details and facts should instead be used to push children toward hands-on experimentation, inquiry, play, and failure.

The field of mathematics in particular stands to benefit from this approach because of dramatic advances in computing technology. The gap between how children use math in school and how it's used in the real world has never been greater. In a TED talk in 2010 technologist Conrad Wolfram summarizes the situation well; "No one's very happy. Those learning it think it's disconnected, uninteresting, and hard. Those trying to employ them think they don't know enough. Governments realize that it's a big deal for

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[6] Diana Laufenberg, "Diana Laufenberg: How to learn? From mistakes," filmed November 2010, TED video, 10:06, posted December 2010. http://www.ted.com/talks/lang/en/diana_laufenberg_3_ways_to_teach.html.

[7] Diana Laufenberg, "Diana Laufenberg: How to learn? From mistakes."

our economies but don't know how to fix it. And teachers are also frustrated."[8] Wolfram expands the definition of math education beyond simple computation into four primary steps:

1. Pose the right questions of the real world.
2. Convert real world problems into math formulations.
3. Compute the answer.
4. Take the formulation and verify the findings back in the real world.

He argues that rather than spend an estimated 80% of our time doing step 3 by hand, we should leverage computers and have students focus instead on steps 1, 2 and 4. "Math has been liberated from calculating. But that math liberation didn't get into education."[9] He does not advocate that we no longer teach the basics; he argues instead that there's a fundamental misunderstanding of what the basics are. Hand calculation is as fundamental to math as knowing how to sharpen a quill is to writing. Wolfram believes that fields like calculus—which demand a high level of computational ability—could be taught to a much younger audience if we simply took the focus away from computation. Ideas like this fly in the face of conventional wisdom.

Educational advisor Sir Ken Robinson critiques current education paradigms because they were designed and conceived for a different age. The economic demands of the industrial revolution created a necessity for public education. Robinson points out clear remnants of that model in existence today: "Schools are still pretty much organized on factory lines. Ringing bells, separate facilities, specialized into separate subjects." And the model hasn't improved. Increases in standardized testing may be cause for real damage. According to Robinson, the rate of ADHD in the US has risen in parallel with the growth of standardized testing.

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[8] Conrad Wolfram, “Conrad Wolfram: Teaching kids real math with computers,” filmed July 2010. TED video, 17:19, posted November 2010. http://www.ted.com/talks/lang/en/conrad_wolfram_teaching_kids_real_math_with_computers.html.

[9] Conrad Wolfram, “Conrad Wolfram: Teaching kids real math with computers.”

Instead of changing the curriculum or the manner in which its taught, many children are heavily medicated (**Fig. 13**).[10] Others make it through without serious psychological harm, but instead fall far short of their potential through simple loss of interest.

Figure 13 RSA Animate still from "Ken Robinson: Changing education paradigms"

The Ignorant Schoolmaster

The French philosopher Jacques Rancière proposes a solution through the idea of *The Ignorant Schoolmaster*. In the current model, well-informed teachers seek to bring ignorant students up through the ranks of education toward academic equality. Rancière proposes a reversal of this mentality that equality should be seen as a starting point rather than a destination. All are equally intelligent and capable of virtually limitless

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[10] Sir Ken Robinson, "Ken Robinson: Changing education paradigms." Filmed October 2010. TED video, 11:40. Posted December 2010. http://www.ted.com/talks/lang/en/ken_robinson_changing_education_paradigms.html.

growth.[11] Unfortunately, it's not necessarily easy, and potentially risky, for a teacher to put these ideas into practice.

In the 5th grade I met an outlier at Northfield Elementary. Mr. G. was not your typical teacher. He had a quick smile, wore flip-flops and comfortable shirts, and the walls of his classroom were covered in Calvin and Hobbes clippings. An entire section of the chalkboard was dedicated to a carefully hand-drawn *Far Side of the Week*. Mr. G. was one of the few teachers who sat with students at lunch and regularly led games of ultimate frisbee during recess. I never remember being more excited to get to school. It wasn't all fun and games; there was plenty of work, but his approach to learning was vastly different from anything I'd experienced prior. Our desks were arranged in small groups instead of gridded rows, and he would often gather us together on the floor for impromptu discussions. More than a few times, he took the entire class outside on the grass to continue a lesson in the sun. He had a wry sense of humor and would even occasionally share his own failed attempts at dating. Students in his class felt comfortable. We could ask questions about anything.

On the surface, you might say Mr. G. didn't care much for standard practice, but he certainly cared for his students. He approached teaching in ways that encouraged exploration and kept each of us excited about learning. At one point he confronted three students who were known trouble-makers. They were the cool kids with perfect flat-tops, smug looks, and a general disinterest in school. He asked them what they cared most about. Unabashedly, they responded that they just wanted to play Nintendo. Thoughtfully, he set aside time each day for the three to work together and design their own Nintendo game. It was like flipping a switch. I remember them on their knees, taping sheets of paper in a long line that spanned the width of the classroom many times. They carefully designed a long side-scrolling series of levels, complete with all

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[11] Jacques Rancière, *The Ignorant Schoolmaster*, trans. Kristin Ross (Stanford: Stanford University Press, 1991), 43-44.

the bad guys, obstacles, guns, bombs, dialogue and big bosses. After a month of work, he helped them package the entire project along with a proposal they'd written and mailed it off to Nintendo. Before the year ended, they received a polite rejection from Nintendo, but the letter was loaded with praise and encouragement for their future careers as game designers. Mr. G. read it proudly to the entire class.

His value as a teacher was in understanding that conventional measures of intelligence were inadequate. He saw potential in each of his students. Sadly, it was clear that Mr. G. was not popular with everyone. The grade shared an open area without classroom doors, and we all saw the occasional raised eyebrows and disapproving looks from neighboring teachers. Maybe we were having too much fun. He was released from the school after only a few years of teaching and was sorely missed by his students. He was the kind of teacher you wanted to go back and visit; to say thank you and to tell him about what you'd done with your life. He epitomized in my mind the hero teachers popularized by Hollywood like Professor Keating in *Dead Poets Society* and Jaime Escalante in *Stand And Deliver*. But the educational system doesn't take these outliers seriously. They inspire us for an evening but are not a model for rethinking education.

Play and Collaboration

Keating, Escalante, and Mr. G. share an uncommon ability to inspire a passion for learning in students by bringing excitement and a spirit of play into an otherwise dull classroom. Play is more than mere games and entertainment; it is central to the way we learn and develop. Dutch historian Johan Huizinga "argues that play is a most fundamental human function and has permeated all cultures from the beginning."[12] And according to psychiatrist Donald Winnicott in *Playing & Reality*, play is also key to our emotional and psychological fulfillment.[13] I believe it was key in the success of the binary learning systems I created. It opens the attention of the mind and invites collaboration.

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[12] Brian Sutton-Smith, *The Ambiguity of Play*, (Cambridge, MA: Harvard University Press, 2001), 202.

[13] Donald Woods Winnicott, *Playing & Reality*, (London: Tavistock Publications, 1971), 105.

Stuart Brown, M.D, founder of the National Institute for Play, tells of a growing need for play at NASA's Jet Propulsion Laboratory (JPL). Arguably the premier aerospace research facility in the United States, JPL is responsible for some of the world's greatest achievements in space. Nearing the end of the twentieth century, many of the scientists and engineers who had ushered in the Space Age were retiring, and JPL was having a hard time replacing them. They had recruited the best engineers from the best schools in the country like MIT, Stanford and Cal Tech—qualified candidates who could handle heavy theoretical problems. But the new recruits seemed to lack the ability to put theory to practice. The head of JPL at the time, Nate Jones, analyzed the problem and discovered a key generational difference: "...those who had worked and played with their hands as they were growing up were able to 'see solutions' that those who hadn't worked with their hands could not." Further research substantiated these findings and resulted in changes to the recruiting process. JPL added questions about youthful projects and play as a standard part of the interview process.[14] Common educational criteria aren't always the best measure of a creative mind, and the way we educate our children may be lacking in ways that the best and brightest make up for outside of the classroom—down in the dirt.

A toddler looks up to a larger-than-life parent and sees a god: all-powerful, all-knowing. From a child's perspective, the wisdom and ability of an adult is unfathomable, even magical. This creates a natural advantage for parents as teachers. Yet most children develop fine motor control, speech ability and cognitive reasoning at an astonishing rate without direct instruction. They observe, experiment, fail, and try again. Parents don't need to sit a toddler down and teach them how to put one foot in front of the other (though some might try). They act instead as watchful guides, preventing serious falls and nurturing as needed.

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[14] Stuart Brown, M.D., *PLAY: How It Shapes the Brain, Opens the Imagination, and Invigorates the Soul*, (New York: Avery, 2009), 9-11.

Without dictated instruction, children thrive. Buckminster Fuller compares these abilities to those admired by his own profession:

> Children are born true scientists. They spontaneously experiment and experience and re-experience again. They select, combine, and test, seeking to find order in their experiences - "which is the mostest? which is the leastest?" They smell, taste, bite, and touch-test for hardness, softness, springiness, roughness, smoothness, coldness, warmness: they heft, shake, punch, squeeze, push, crush, rub, and try to pull things apart.[15]

In the 1920's Mildren Parten completed a study of children between the ages of 2 and 5 that defined six independent categories of play. The first 4 stages are individual. They involve random, exploratory movements; engrossed self-play; passive observation of others playing; and play mimicry. In the fifth stage children take an active interest in the tools and toys of others, and strong social interactions develop. The final stage introduces organization to play; children adopt rules, and work as a group toward a determined goal.[16] Play is the seed to real problem solving; and we are all born with it.

Despite these innate qualities, we educate our children in sedentary, regimented classrooms where many of the elements of natural exploration are suppressed: laughter, excitement, fun, play, coloring outside the lines. The body is constrained to sit still and focus on instruction, pencil, and paper. To measure individual achievement, group interactions are given a backseat to isolated effort. And year after year, students work on the same problems, answering the same questions. Informed teachers strive to guide their classes along a prescribed path to a potentially alienating end.

Divergent Thinking

As compelling evidence of the innate creative abilities in children, Robinson mentions research from *Breakpoint and Beyond* by George Land and Beth Jarman which measured an essential capacity for

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[15] R. Buckminster Fuller, *R. Buckminster Fuller on Education*, (Cambridge, MA: University of Massachusetts Press, 1979), 149.

[16] Mildred Parten, "Social play among preschool children," *Journal of Abnormal and Social Psychology* 28 (1933): 136-147.

creativity. They called this capacity divergent thinking, or the ability to envision many possible solutions to a given problem instead of just one. In the study, subjects are be asked to list as many uses for a simple object like a paperclip as they can. On average, 98% of adults arrive at 10-15 possibilities. Only 2% are capable of conceiving many times more—at a genius level for divergent thinking. The study used the same test on 1500 kindergarteners and found that 98% scored at the genius level. The same group was retested as they continued through grade school. By ages 8-10, only 32% scored high enough, and by ages 13-15, only 10% remained genius-level. Robinson blames an out-dated, single-answer education for the rapid decline.[17] We don't allow for playful exploration of potential outcomes. The findings are summarized well by Buddhist monk and teacher, Shunryu Suzuki: "In the beginners mind there are many possibilities, in the experts mind there are few."[18]

In late 2010, Victoria Hart, now more widely known as Vi Hart, posted a stop-motion video on youtube of math-based divergent thinking in a notebook. The fast-paced, witty narration of the clip follows a common theme: a general distaste for the way math is taught in school and a fascination with the endless permutations of math in the world around us. Hart calls herself a recreational mathemusician.[19] Her pencils, markers and pens cover page after page of notebook with playful sketches that change parabolas and spirals to worms and snakes and event slug-cats (**Fig. 14**). As she draws she describes the many ways that mathematics can be explored through the patterns and shapes in everyday objects. The process she follows is non-linear; she embraces distraction and happenstance, allowing it to lead to new ideas and conclusions. And her videos are widely popular, with over 17 million views and over 200,000 subscribers.[20]

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[17] Sir Ken Robinson, "Ken Robinson: Changing education paradigms."

[18] Shunryu Suzuki, *Zen Mind, Beginner's Mind*, (NewYork: Weatherhill, 1970), 2.

[19] Kenneth Chang, "Bending and Stretching Classroom Lessons to Make Math Inspire," *The New York Times*, January 17, 2011, accessed September 12, 2012, http://www.nytimes.com/2011/01/18/science/18prof.html.

[20] "Vi Hart – YouTube," YouTube Channel, accessed September 12, 2012, http://www.youtube.com/user/Vihart.

Figure 14 Vi Hart animation stills

The margins of a grade school notebook are a refuge for creative children when they have nowhere else to play. Confined to chairs and desks the mind can wander on paper beyond the walls of the classroom. Hart expresses visual empathy with students who yearn for more from their math classes. As she connects dots to form cones and cylinders, she's also unafraid to directly critique the system:

> Teaching how to think is an individualized process that gives power and responsibility to individuals while teaching what to think can be done with one-size-fits-all bullet points and checkboxes. And our culture of excuses demands that we do the latter, keeping ourselves placated in the comforting structure of tautology and clear expectations. Algebra has become a checkbox subject, and mathematics weeps alone in the top of the ivory tower prison to which he has been condemned.[21]

Significantly, her videos often jump the pages of her notebook. While describing fibonacci sequences and Sierpinski triangles, Hart pulls common props onto her paper stage: pine cones, leaves, flowers and even a live snail. Her argument is clear: Math is fun; It's a tool for play and exploration; And it's all around us. I was not surprised to discover that she also created a binary hand dance using the same framework as the Binary Glove. Her hand pulls hip-hop-like dance moves across a tabletop to music; friends and

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[21] "Doodling in Math Class: Connecting Dots," YouTube video, 7:46, posted by "Vihart," August 21, 2012, http://www.youtube.com/watch?v=v-pyuaThp-c.

grandparents join in; and she even uses the binary steps to finger paint gestural patterns on a canvas.[22] Anyone watching can dance along; they need only lift a finger.

I share Hart's appreciation for mundane objects. You can't avoid math; it's always there. We need only look at our environment with pattern in mind. This was the reason I spent significant time with the students at Nora Sterry talking about the common textures and patterns from their neighborhood. Even the most routine and familiar experiences can trigger unique ideas and open new avenues for creative exploration.

New Interfaces

Bret Victor leads his own crusade to revitalize math education. In a blog post titled *Kill Math* he describes his motivation:

> This mechanism of math evolved for a reason: it was the most efficient means of modeling quantitative systems given the constraints of pencil and paper. Unfortunately, most people are not comfortable with bundling up meaning into abstract symbols and making them dance. Thus, the power of math beyond arithmetic is generally reserved for a clergy of scientists and engineers (many of whom struggle with symbolic abstractions more than they'll actually admit).[23]

Victor calls for a new interface for math and utilizes touch-based technologies as his medium for change. Rather than using static graphs and equations, participants can use simple gestures to modify inputs, drag sliders, and play out animations that show visual representations of otherwise abstract principles (**Fig. 15**). My critique of Victor's models is that each is still controlled within set parameters of a controlled digital environment. The advantage of real world experimentation and play lies in the potential for exceeding expected boundaries to arrive at completely unexpected results. An iPad app can't show what happens when

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[22] "Binary Hand Dance," YouTube video, 2:27, posted by "Vihart," March 31, 2011, http://www.youtube.com/watch?v=OCYZTg3jahU

[23] Bret Victor, "Kill Math," *Worry Dream*, April 11, 2011, http://worrydream.com/KillMath/.

one experiment explodes and collides serendipitously with another. As physicist Frank Oppenheimer observed, "The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny...'"[24]

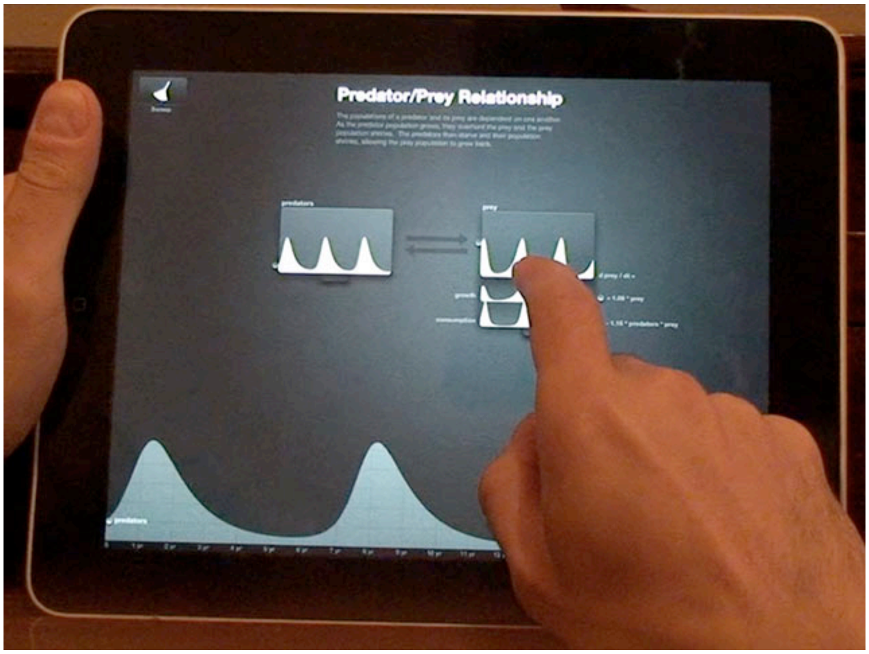

Figure 15 Kill Math. Bret Victor

One digital endeavor that embraces a more open-ended approach is Scratch, a visual programming language developed by the Lifelong Kindergarten Group at MIT (**Fig. 16**).[25] In this digital creative environment, programming syntax is reduced to functional building blocks that fit together like puzzle pieces. Physical metaphors based an familiar play objects are key to the process of creating with Scratch. A photo module fits with a mouse click module that fits with a sound. Though parameterized, the framework remains open in its building-block, sandbox approach. Users can add their own images and use modules

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[24] K.C. Kole, *Something Incredibly Wonderful Happens: Frank Oppenheimer and the World He Made Up*, (Boston: Houghton Mifflin Harcort, 2009), 142.

[25] “Scratch: imagine, program, share,” accessed September 12, 2012, http://scratch.mit.edu.

that feed random numbers into their creations to create games, animations and art. Lessons in logic occur naturally as users experiment in a visually intuitive system. Accidentally connecting two modules can create surprising results. Scratch is used by children, hobbyists and teachers in schools, museums and homes around the world. It's even taught in university level computer science classes, including an introductory programming class at Harvard. By the end of 2011, the Scratch community boasted 950,000 registered members and over 2,700,000 submitted projects.[26] The significance of these numbers is in the powerful collaboration that exists within its community. Ideas are shared, retooled, and shared again.

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repeat 10
    move 10 steps
    play drum 48 for 0.2 beats
    move -10 steps
    play drum 39 for 0.2 beats
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Figure 16 Scratch interface

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[26] "Scratch (programming language) - Wikipedia, the free encyclopedia," accessed September 12, 2012, http://en.wikipedia.org/wiki/Scratch_(programming_language).

Collaborative play offers advantages that were clear at Nora Sterry. Consider the stark difference between the two math classes at Nora Sterry. The first, where students experimented with the Binary Pad in isolation, failed. In the second, students shared knowledge and discovered quickly how to use a new interface. Before long they were considering new ideas primarily because they were engaged together in the learning process. Interface designer, Reto Wettach, spoke of the importance of visibility in interface at TEDxBerlin in 2009. According to Wettach, screen-based interactions are anti-social and inhibit group learning. He points to research by Vittorio Gallasse who discovered mirror neurons. Gallasse recorded the brain activity of an ape while it ate a nut; he then learned that same areas of the brain became active when the ape observed him eating a nut. Further research found that the human body can even increase muscle mass (if only by a very tiny amount) by simply watching sports.[27] Consequently, Wettach argues that we should make computer interfaces more visible.

Jay Silver and Eric Rosenbaum of MIT are doing exactly that with a project called MaKey MaKey (**Fig. 17**).[28] Their educational product ships with a bundle of colorful alligator clamps and a low-cost circuit board that connects to a personal computer. The circuit board is designed with a familiar interface in mind—the original Nintendo controller. A generation of gamers was defined by simple handheld input devices like these. Many online games and other digital experiences use a similar configuration because of its broad familiarity. The exciting components of MaKey MaKey are the alligator clamps. The board doesn't come with any buttons. Instead, the clamps can be attached to just about anything in place of a button. The board senses subtle changes in conductive materials: fruit, most foods, Play-Doh, buckets of water, graphite on paper, and even other people. The first MaKey MaKey device I played with was a piano keyboard that used four bananas and one pear for keys. Instead of presenting users with a fixed interface,

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[27] Reto Wetach, "Bodies and Secrets: Towards a Democratization of Hardware," filmed November 30, 2009, TEDxBerlin video, 16:45, posted December 2009. http://www.tedxberlin.de/tedxberlin-2009-reto-wettach-bodies-secrets.

[28] "MaKey MaKey: An Invention Kit for Everyone (Official Site)," accessed September 12, 2012, http://makeymakey.com.

the most important part of the interaction is building the interface. You can take bites from the bananas to play; toss them to friends; squash them with force; sketch a custom interface on paper and even play Dance Dance Revolution by stomping in buckets of water. The interface itself encourages participants to come up with new ideas that activate more than the nerves in the end of your fingers, but potentially your sense of taste, smell, and the whole range of bodily motion.

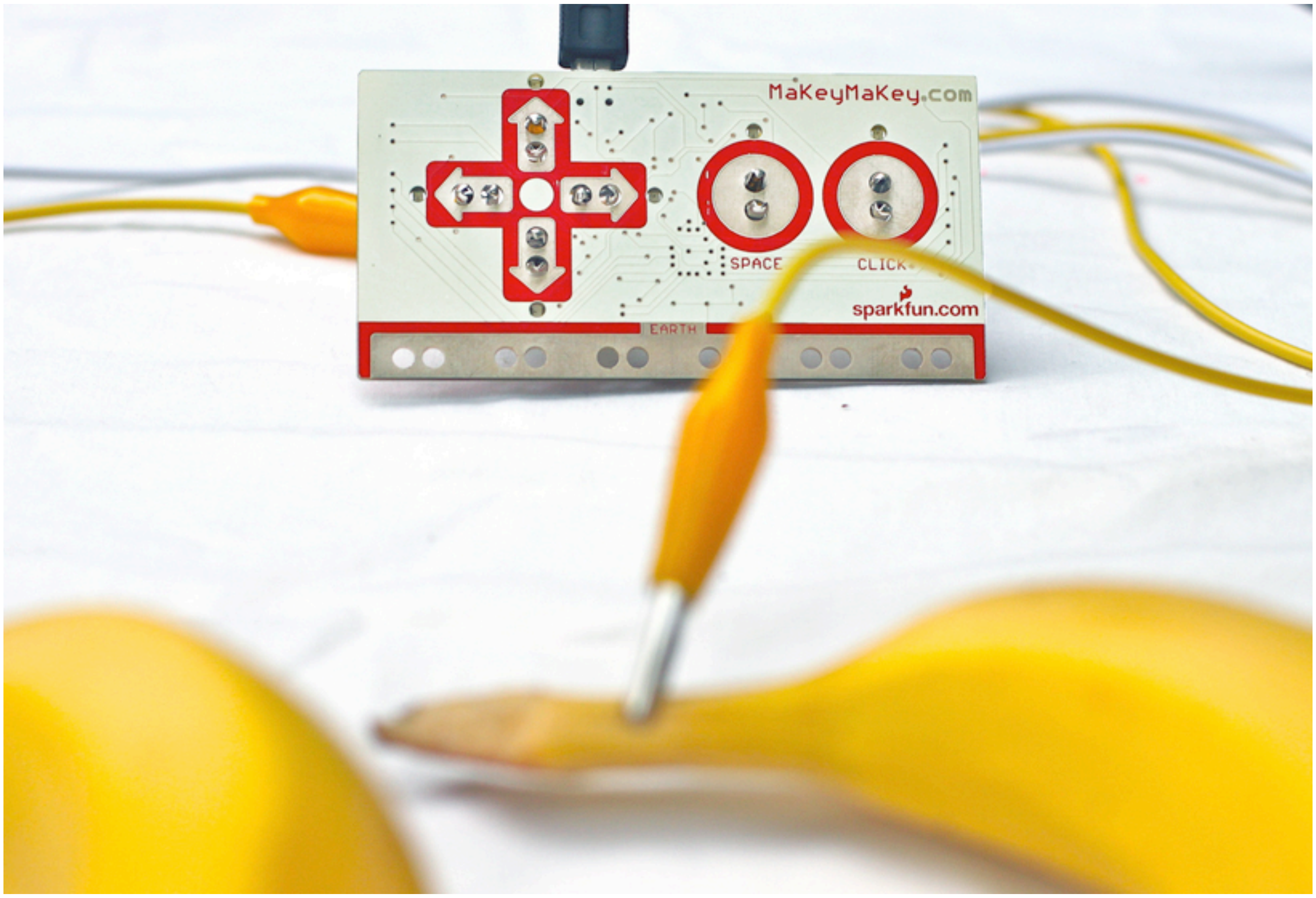

Figure 17 MaKey MaKey

Embodiment

Stuart Brown writes of "a deep human need to interact with the material world: to feel the tug of gravity, to physically move through dimensions."[29] Embodied games are built into childhood experience. My neighborhood used various forms of counting elimination games to select an "it" player for tag or hide-and-seek. These games occur on-the-spot and require only spoken word and gesture. Players place hands or feet together in a circle. One child points to others in sequence while reciting a rhyme or spelling out a word—*eeny, meeny, miny, moe* or *one potato, two potato*. Since the number of letters or words isn't known beforehand, the eventual outcome appears random. Each elimination leads to a newly varied cycle until the last player remaining is "it". Additional complexity can be added by lengthening the rhyme or allowing each player to hold two hands in the circle. The longer the process, the more difficult it becomes to game the system.

Variations of these same elimination algorithms exist around the world[30]. Other algorithmic games are played for simple enjoyment. Non-competitive clapping games typically involve two players and a set of cooperative hand and arm gestures performed in sequence with a rhyme. Beyond the enjoyment of song and dance-like rhythm, this type of play requires coordinated concentration. Players can control the speed of play to accommodate their collective skill level and will invariably increase the pace of the game; once a speed ceiling is reached, new patterns or variations can be introduced. The structure of Binary Face Off was based on these face-to-face games of complementing gestures. Young minds are drawn to pattern recognition—particularly when these patterns are played out physically through dance and gesture. Interfaces that utilize the body capitalize on this attraction.

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[29] Brown, *PLAY*, 184.

[30] Henry Carrington Bolton, *The Counting-Out Rhymes of Children: Their Antiquity, Origin, and Wide Distribution*, (New York: D. Appleton & Co, 1888), 9.

The Japanese comedy group Itsumo Kokokara created a dance fad in Japan called the Algorithm March as part of an educational children's television series *PythagoraSwitch* (*Pitagora Suitchi*). In the tradition of Sesame Street, the 15-minute puppet show uses short, entertaining segments to teach various world phenomena and basic scientific principles. Videos of small-scale Rube Goldberg machines are used to draw attention to key ideas and messages. The show aims to encourage an observation of the natural world as inspiration for creative problem solving and often featured familiar, commonly available objects. This allows children to explore the ideas from the show on their own, recreating the same systems or exploring their own varied inventions.

The *Algorithm March* creates an accessible algorithm for children (**Fig. 18**).[31] The choreography is simple and performed with different groups of participants from firefighters to soccer players to ninjas. Participants act out a specific sequence of eight full-body gestures in time with a simple song:

1. Bend knees, reach out straight with hands
2. Lean back with arms akimbo ("big shot")
3. Turn around, bow
4. Face right, right hand horizon sweep
5. Bend knees, breast stroke
6. Bend down and pretend to pick up a chestnut from the ground
7. Shake arms downwards (like you are pumping a bicycle tire)
8. Flap arms as though being inflated by a pump[32]

(repeat)

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[31] "Algorithm March! with Ninja," Magnify video, 2:07, posted by "Pytha," November 5, 2007, http://pythagoraswitch.magnify.net/video/Algorithm-March-with-Ninjas.

[32] "Algorithm March," accessed September 12, 2012, http://en.wikipedia.org/wiki/Algorithm_March.

Figure 18 Algorithm March

The leader begins with the first gesture while the others wait in line. In a round, the participants step forward and perform the gesture that was previously performed by the person directly in front of them. Eventually all gestures can be seen side-by-side in their proper order. When performed by a single person, the dance is entertaining. When performed in a line with others, neighboring gestures complement one another. One player ducks while another swings an arm overhead; or another player creates an opening with their arms that a neighbor can stick their hands through. The simple sequence has great learning potential since each player need only watch the person directly in front of them. Only the leader needs to know the entire sequence. Teachers have taken advantage of this simple method for explaining algorithms and for having fun in the process. A search for “algorithm march” on YouTube reveals thousands of uploaded videos from classrooms around the world.

I never intended to teach the Algorithm March to the students at Nora Sterry, but I included a video of the march in my presentation to explain how a simple set of instructions applied to a series of objects can become something greater. Since the Binary Pad could only be used by a small group, I left the looping video of the Ninja Algorithm March playing on the projector while they waited. Fortunately, I had a video camera running to capture the resulting behavior. Several children moved to the front of the classroom and began acting out the gestures of the march. After a sequence or two, more students joined in. They mirrored the figures in the video and had the sequence down in a matter of minutes. Children learn quickly when motivated by fun—especially when the teacher isn't watching.

Beyond merely moving the body, learning benefits greatly from interacting with real and varied sets of physical objects in space. Environmental interaction is the most natural form of learning. We learn as much walking to school—if not more—than we do sitting in the classroom. The philosopher Hubert Dreyfus defines the body's interaction with real, physical objects in space as embodied learning. Central to this kind of learning is improvisation. Everything does not need to be specified in advance and complex relationships can be present without a formal recognition that they exist. Dreyfus defines three components to embodied learning. First, a prompt that invites physical interaction. This can be a simple set of instructions, the rules to a game, or a physical object that suggests reciprocation. Second, the learning must take place in an environment. An environment is more than a sheet of paper or a computer screen or even a conversation. It contains not just multiple elements, but a variety of types and classifications of elements. And third, the environment must allow for transferability between these elements, so that interactions can reverberate through unexpected and unforeseen connections.[33]

Who understood these components better than Frank Oppenheimer, creator of the Exploratorium in San Francisco. As a young boy exploring New York's museums, Oppenheimer was impressed with the importance of using real objects instead of simulations. In reaction to a an exhibit on knights at the Metropolitan Museum of Art, Oppenheimer commented: "The opportunity to see those beautiful and ornamented steel vestments enabled me to realize their scale, appreciate their articulation, and to imagine how strange it must have felt to be inside one of them."[34] Later, as a high school teacher in rural Colorado,

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[33] N. Katherine Hayles, *How We Became Posthuman*, (Chicago: University of Chicago Press, 1999), 201.

[34] Kole, *Something Incredibly Wonderful Happens*, 29.

Oppenheimer developed a hands-on approach to teaching physics. Other teachers in the region "were completely turned around by meeting Frank and seeing the experiments that he made, because he had a way of making them come alive in the hands of the students."[35]

His contraptions are often described as magical, not because they are infused with the latest technologies and effects, but because they demonstrate beauty and wonder through the simplest and most common physical props. Oppenheimer was known for stretching limited funding by using "the most mundane objects imaginable: wooden carts on roller-skate wheels, springs and pulleys and pendulums, Slinkies, sacks containing iron shot, waxed paper, bicycle wheels, toilet floats, piano wire, Polaroid cameras, crochet needles, aluminum foil, and light bulbs." It was important to him to promote a familiarity with physical principles when teaching abstract concepts.[36] This approach has added benefits. By associating learning with familiar objects, students simultaneously develop habits that allow them to see potential experimentation everywhere in the world around them, outside the walls of the classroom. Familiar objects become prompts for new ideas and extended self-learning.

Oppenheimer's teaching experiences at Colorado convinced him of a serious problem with the current educational system. By sitting children in sterile classrooms, removed from the real world, they had become disconnected from their own surroundings, isolated from a world of potential learning. They needed a place to reconnect. He noticed that "strangely incurious" students opened up only after hands-on experimentation. Many had little direct experience with the natural world and had trouble relating to it. "They hadn't climbed trees and sailed boats and collected minerals and taken apart bicycles and fiddled endlessly with electricity and motors...Their experience was so meager, their whole contact with the natural world so restricted, that I thought a place was needed where they could walk through a kind of woods of

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[35] Kole, *Something Incredibly Wonderful Happens*, 118-119.

[36] Kole, *Something Incredibly Wonderful Happens*, 138.

natural phenomena."[37] And so he created the Exploratorium: A Community Museum Dedicated to Awareness. A visit here is truly a treat; not just for your eyes, but for your ears, hands, arms and legs, your sense of smell, touch, and rhythm. He created a playground for mind and body that invites direct, unscripted, bodily interaction. Oppenheimer cared deeply about the *feel* of objects:

> We need to look at children with new eyes. Why do we self-righteously ignore (or even berate) children's intense discrimination among textures and tastes of food, or object to their enjoyment of the feel of food on their hands and faces? Why does a group of adults invariably laugh at children when, as two-year-olds, they begin to move in response to music? Why do we refuse to recognize that knocking down a just built, teetery structure of blocks is a fine example of an order-disorder transition?[38]

Environments that ignore the richness of our body's perceptual capabilities miss important opportunities to capitalize on embodied knowledge.

Computer interfaces are a prime example. Reto Wettach uses an illustration by Tom Igoe to explain how our computers see us[39] (**Fig. 19**). The human body is reduced to a mere finger, eyes and ears. These are truly capable organs and, as this heavily restricted entity, we've learned to do remarkable things. The peak of motor memory learned in a typical computer interface is comprised of a sequence of keystrokes to toggle a view or undo a mistake. Wettach laments that he's "been using Photoshop for enough years and I must still go through the same laborious processes as a beginner." The potential of motor memory, he notes, is more clearly seen in the mastery of musical instruments like the violin or piano—feats that would be impossible through cognitive ability alone; "Imaging riding a bicycle by using drop-down menus and a mouse."[40]

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[37] Kole, *Something Incredibly Wonderful Happens*, 148.

[38] Kole, *Something Incredibly Wonderful Happens*, 188.

[39] Reto Wetach, "Interface Design Positions – my own," *Interaction Design: News and Inspirations*, June 21, 2011, http://interactiondesign.wordpress.com/2011/06/21/interface-design-positions-my-own/.

[40] Reto Wetach, "Bodies and Secrets: Towards a Democratization of Hardware," http://www.tedxberlin.de/tedxberlin-2009-reto-wettach-bodies-secrets.

Figure 19 How Computers See Us by Tom Igoe

Now imagine doing something as simple as using a pencil without embodied knowledge. As a high school student I was assigned to work one-on-one in the art room with a disabled student named Jeff. Instead of color exercises and still life drawing, we spent the entire school year attempting the most fundamental of drawing skills. Jeff understood instructions and was able to communicate without problem, but he struggled with basic motor skills and hand-eye coordination. Many of the simple tasks most of us take for granted demanded a huge amount of concentration. Simply drawing a straight line required intense focus, and that was a rare achievement. We spent a lot of our time working on how to hold the pencil; how to anchor the base of the hand for control; and how to slow down and think about the progression of a mark on paper. It took months before he successfully drew a recognizable triangle. Shaky as it was, it was a big accomplishment. But strangely, the next day he was unable to repeat the task. Jeff lacked the ability to retain muscle memory. It's easy to take embodied knowledge for granted, because by definition, we don't have to think about it. And yet this alternate mode of learning is fundamental to our existence.

Even in the earliest stages of cognitive ability, infants exercise this alternate mode of learning—using limbs and muscles, touch and force reaction to make sense of their environment. N. Katherine Hayles cites an example given by Hubert Dreyfus to explain this motor-based intelligence in the simple act of learning to grasp an object:

> "The child need not have any analytic understanding of the motor responses and dynamics involved in this action; the child need only flail around until managing to connect. Then, to learn the action to be able to perform it at will, the child only has to repeat what was done before. At no point does the child have to break down the action into analytical components or explicit instructions."[41]

A mode of learning this significant is nevertheless practically absent from our schools. The subjects that embrace its potential—dance, athletics, music, drama, and the arts—are instead relegated or cut entirely in the face of pressure from standardized testing and tight budgets. What do we lose when we take the body out of the equation? Hayles argues that embodied knowledge is more than mere muscle memory, but an essential component of existence: "Thinking and learning does not exist only in the brain, but also in the nerve endings through the entire body. Verbal thinking isn't the only way we exist ... To look at thought in this way is to turn Descartes upside down." She further maintains that the cognitive mind relies on the environmental parameters determined by the body in order to arrive at certainties. This radically changes the way we define knowledge. Conscious thought becomes a byproduct of the framework that embodied learning provides.[42] Can physical dance lay the groundwork for learning abstract math? Ask the students at Nora Sterry.

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[41] Hayles, *How We Became Posthuman*, 201.

[42] Hayles, *How We Became Posthuman*, 202-203.

Conclusion

The ideas for the binary learning systems I created arose from simple observation and the merging and mixing of simple ideas. Playing and exploring the edges of the original system led to further iteration and unexpected discoveries. The process taught me much about how we learn and interact with one another as we approach new challenges. My design approach is heavily influenced by teachers who understand the importance of play and collaboration and who allow divergent thinking in the classroom.

Maurice Merleau-Ponty states that the body is "not a chunk of space or a bundle of functions but ... an intertwining of vision and movement."[43] We are playful, creative creatures. We thrive on curiosity, learn from failure, and bolster one another in the process. Designing physical interfaces that take full advantage of these strengths has shown me that there is invaluable teaching potential in leveraging the body and disrupting the accepted norms of the classroom.

There is growing acceptance for new interfaces—even in our stressed educational systems. What teachers need now more than ever are accessible teaching tools that leverage technology without losing sight of our inherent physical nature. Embodied learning is fundamental to our development and should take a greater role in education. Designers who embrace these ideas and draw inspiration from the familiar will discover more effective ways to flip the switch and inspire children.

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[43] Maurice Merleau-Ponty, *The Primacy of Perception: And Other Essays on Phenomenological Psychology, the Philosophy of Art, History and Politics*, (Evanston, IL: Northwestern University Press, 1964), 8.

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