iLab Research Report No. 2

Topic: Self-Directed Learning in a Makerspace
Focus: Science Literacy
Mode: Curriculum design, Learning spaces design
Teacher Researcher: Christa Flores
Time Frame: Fall 2012 - Spring 2016

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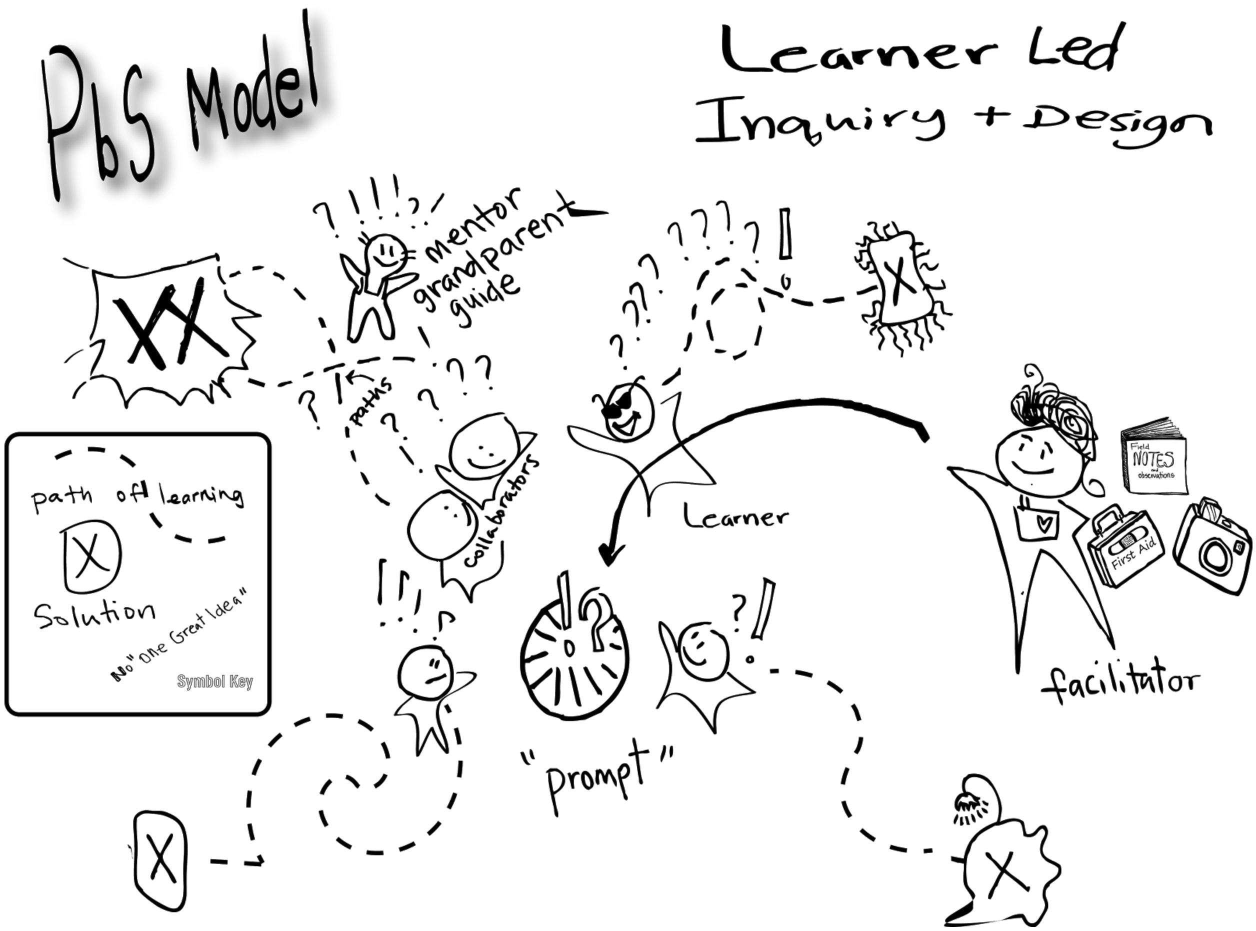
Problem-based Science, a Constructionist Curriculum

The Path(s) of Learning



The Antidisciplinary Units

Materials Patterns Structures Systems Problems

simple <-->complex

Driving Principles of Problem-based Science

1. Deep projects take time. When we spend more than a moment on an observation or task, we make deeper, more rewarding observations. Craftsmanship and mastery are the behavioral embodiment of this concept.

2. Learning to solve problems and to create versus consume, is a fundamental part of living a liberated existence. Exercising creativity and self-directed exploration are just as important as learning facts that were discovered by others. This is the core of constructivism and the true spirit of exploration. Practicing creativity builds creative confidence.

3. Autonomy is not a privilege, but the right of the human child; it is essential to the intellectual and spiritual fulfillment of the individual. Learning self-governance through constructive autonomy is central to self-actualization.

4. Failure is not a measure of a person. It is a natural consequence of trying something new and of learning. Failure teaches us what works and what does not. It is a beloved and essential variable for all learners, engineers and scientists.

Background

Problem-based science is just one model for how to learn science. As a model, problem-based science acts as a practical guide for applying constructivism and constructionism in a science classroom that has access to building tools and materials. Problem-based Science has four driving principles that ideally, speak to the value of the individual learner no matter what their age. The work students due in a problem-based setting is real. Problem-based science is “antidisiplinary” in that to solve real problems, we need to employ the tools and mindsets of any domain. Reading, testing, logic, art, writing, math, communication and self-reliance are all part of a normal day in problem-based science. As such, when using a problem-based model, you will see learners making models, inquiring about prototypes, exploring the inside of discarded objects and designing for the user in a fluid and natural manner. When you begin to recognize the work that learners do as science through the lens of constructionism, the classroom, lab, makerspace, garage, city park, ect., is a brighter more rewarding space for all.

Foundational Research for Problem-based Science

The design of problem-based science is based on a foundation that can be broken up into three parts. The first part comes from my master's thesis, written in 2005 on the underrepresentation of females and minorities in STEM. The second part is based on the educational philosophies of Constructivism and Constructionism. The third part of the foundation for problem-based science comes from a confluence of events that occurred in 2011, the year I began designing problem-based science while working at the Hillbrook school in Los Gatos, California.

Master’s Thesis Recommendations

The process of writing my thesis had been a self-reflective exercise that encouraged me, as a hispanic female, to examine some of the reasons for feeling incompetent or like an outsider in the math classes I hated, as well the science classes that I loved. During this research and reflection process, I reviewed the available literature which discussed barriers keeping women and minorities out of STEM careers that had been published prior to June, 2005. Ten years later, the issues that plagued us at the turn of the millennium sadly remain relevant barriers today. As part of my thesis, I included surveys taken from 7th, 8th and 9th-12th grade female minority students that I had access to while working full time at the Calhoun School, an independent school in New York City. Results of the survey showed that these girls enjoyed subjects with an artistic component (31%) more than math (21%), or science (14%), even if they felt they were best at math and science academically (Flores, 2005). *IMAGE: Data on Surveys Taken in 2005*

Tables 3a-e: Results of Calhoun Student Interest Survey

The results of the following questions are in number of students that made a given response. Total number of middle school students that participated in survey n=29

Table 3a

	Subject						
Question 1-2	Math	Social Studies	Science	English	Gym	Music/Arts	Language
Subject you like best	**6**	**3**	**4**	**6**	**1**	**9**	**0**
Subject you feel you are best at	**9**	**3**	**3**	**8**	**1**	**4**	**1**

NOTE: In the case that students had more than one first choice for the subject they liked best, only their first answer was counted

Table 3b

Question 3	Answered Yes	Answered No
Do you think that boys are better at some subjects than girls?	**4**	**25**

The survey was also designed to investigate the presence of stereotype threat among middle and upper school girls. When I asked students if they thought boys were better than girls at some subjects, I noticed that stereotype threat was less present in the younger grades. Older girl respondents were the only ones to report attitudes that boys might be better at a given subject like math or science. Perhaps by high school they have been introduced to attitudes that support the view that biological differences exist between boys and girls that might affect their strength in certain academic subjects. Ideally, I would have also surveyed boys about their attitudes, as these early attitudes tend to shape the workplace and many of its gender issues in later life.

At the time of writing my thesis I thought my findings, namely that girls prefer art to science or math, presented an obstacle rather than a path to teaching science to a diverse population. Nonetheless, in the conclusion of my thesis, entitled *Suggestions for Science Educators and Administration in Middle School*, I wrote the following passage.

"To maximize student interest in their science curriculum, teachers should focus their curriculum design around the interests of both girls and boys. If studies show that girls are more attracted to life science topics (animals, nature, ecology), curriculum should be designed to be more holistic. Good science is by nature interdisciplinary. That is, weaving in elements of life science with physical science can be done by using essential questions about forces, efficiency, balance, symmetry, etc. Furthermore, if the perceived utility of science influences girls' formation of their attitudes about science, then real life application should be integral to every unit. For instance, incorporating social justice issues into topics such of earth science, using global warming and its effects on animals and habitats as a unit or yearly theme." (Flores, 2005)

IMAGE: 5th grade boy sharing a resume he made with our skill badges in the fall of 2015, here he was asked to pick the badge he was most proud of, he chose Art.

In my thesis I advocated for more authentic approaches to science, approaches that were interdisciplinary and integrated real-world elements and issues. In doing so, science class would provide much needed and appreciated context to learning science. Considering interdisciplinary science and real-world problems gives kids agency as problem-solvers and allows students to be “whole learners” (Perkins, 2010, Agency by Design, 2015).

Ironically, as much as I learned from writing my thesis and reading the philosophies of Dewey in graduate school, I had few concrete solutions or models to address the problems I had described. Nonetheless, I took two working ideas into my own classroom. Number one, I could show up everyday and be a female role model who loved science (a job that I continue to take very seriously every day). Number two, my lessons would incorporate real-world topics like food science, sustainability and epidemiology. I also learned to focus more on hands-on labs and group work, avoiding lectures and whole-class discussions where male students tend to have a dominant voice (Shumow & Schmidt, 2013). Ultimately, however, I lacked training in how to make my own suggestions practical in a middle school science classroom. As a result, from 2005 until 2012, I continued to focus learning outcomes for my students on content, versus process. I continued to give tests and grades based on summative assessments rather than other potentially more interesting or valuable variables. Fortuitously, and without knowing, the research that I had done in 2005 occurred just as the Maker Movement was just beginning, spurring a global re-imagination of education that would become the catalyst for this research.

Constructionism: Using your Head, Heart and Hands in Science

For anyone to learn complex models and abstract ideas in science, there must first be fertile soil in the brain to latch onto these new models. If fertile ground is absent the new idea may be ignored or rejected outright. Science that can not be assimilated would have the effect of being "magic" to a person not ready to assimilate new technologies. Piaget called this fertile ground for new learning a person's schema. If a new idea is incorporated into a learner's schema, this is called cognitive development, or learning. If you are familiar with Plato's model of the cave from his work entitled The Republic (360 B.C.E.), constructivist learning would be like stepping outside of the cave to actively participate in your own understanding of how the universe works, rather than passively accepting handed down knowledge. These ideas would become the foundation for education that is child-centered and ripe for constructionism and the educational philosophy of problem-based science. Let us turn to the work of Johann Heinrich Pestalozzi, to explain more.

Johann Heinrich Pestalozzi (1746-1827) had a saying, "learning by head, hand and heart" which related to his use of hands on learning and manufacturing of real-world objects by children, as a form of education and a pathway out of poverty (Soëtard, 1994). Having read Rousseau's Émile (1800), a book about education which looked at Christianity critically and was later burned publicly, Pestalozzi affirmed "that teachers and parents never should teach children anything they could learn or experience naturally" (Null, 2004). Pestalozzi was a constructivist. Albert Einstein, one of the world's most celebrated scientists, would attend a Pestalozzi inspired secondary school in Switzerland. "Based on Johann Pestalozzi's philosophy of education, the school [Einstein attended] encouraged individual differences, sense perception, visualization, and modeling, all developed through a student's self-directed activity," state authors Robert and Michele Root-Bernstein in an article entitled "The Art & Craft of Science" for the Association for Supervision and Curriculum Development (ASCD) journal Educational Leadership (Root-Bernstein, 2013).

One of the first scientists to focus studies on how children develop cognitively was Swiss psychologist Jean Piaget (1896-1980). Piaget studied young children, beginning with his own, and noticed that children constructed an understanding of their world via sensorimotor interactions with their environment. Piaget attested that both physical and cognitive development in humans used the same sensorimotor pathways into and out of the brain (Pulaski, 1971). Piaget used the terms assimilation and accommodation to explain these twin processes of constructing new knowledge or understanding (Pulaski, 1971). Assimilation happens when the input children take in from their environment becomes part of their schema, or tool box of knowledge. If new information is assimilated, this will show in how the child accommodates his or her behavior. A classic example of this happens during language acquisition. Imagine a child that says "baba" and the father in turn corrects her and says, "bottle." The child will assimilate the new pronunciation and accommodate by saying perhaps “bata,” until she gets it correct. Like Pestalozzi, Piaget was about more than just direct instruction from adult to learner, he also believed in the power and importance of constructivism, or allowing children to discover what they can on their own through direct experience.

The idea that each individual should learn through direct experience rather than direct instruction is one so obvious to real scientists that the Latin phrase Nullius in Verba, which translates to 'take nobody's word for it' was adopted as the official motto of The Royal Society of London (Holmes, 2009, The Royal Society, 2015). The Royal Society was established in 1660 as a Fellowship of “many of the world's most eminent scientists” and it remains “the oldest scientific academy in continuous existence” (The Royal Society, 2015). According to The Royal Society's website, the motto Nullius in Verba, was adopted as “an expression of the determination of Fellows to withstand the domination of authority and to verify all statements by an appeal to facts determined by experiment” (The Royal Society, 2015). Plato’s allegory of the cave remains a compelling allegory in the world of science, to this day.

Interesting side note, women were first elected into the Royal Society in 1945. The first British women to receive a salary for doing scientific work were Caroline Herschel (16 March 1750 – 9 January 1848), a telescope maker and astronomer, and Mary Somerville (26 December 1780 – 29 November 1872), science writer/communicator. The earliest known women to receive a wage for her scientific work was Jeanne Baret (sometimes spelled Baré or Barret) (July 27, 1740 – August 5, 1807). Baret was a French botanist, herbalist and medicine maker who would receive a wage for her work discovering such new species as bougainvillea while also the first woman to make a transcontinental exploration around the world aboard the Etoile, disguised as a male.

Allowing children to construct their own understanding of the world is not only critical to fostering a deeper understanding and appreciation of knowledge, Piaget argued, like Plato, that constructivism was the only pathway to true democracy and self-actualization. In a documentary entitled *Piaget’s Developmental Theory: an Overview With David Elkind, Ph.D.* by Davidson Films, Inc. Piaget asks the following question regarding the role of education, “Are we forming children who are only capable of learning what is already known, or should we try to develop creative and innovative minds capable of discovery from preschool on, throughout life?” (Davidson Films, Piaget & Elkind, 1989). In line with Plato’s concerns for the danger of passive education, Piaget was concerned with the education of children and how they form and develop theories of the world through their own experiences. Piaget advocated that learners be allowed to employ a bottom up, or user generated learning model called constructivism, versus passively receiving canonized ideas from adults and teachers. In reality constructivism is easy to foster. For instance, rather than lecture to learners that objects accelerate faster the longer they fall, let learners drop objects from different heights and measure the effects on the force of the object hitting the ground. Water balloons with food coloring work well.

While Piaget worked at the University of Geneva (1958 to 1963), Piaget would inspire the work of protoget Seymour Papert. Papert would go on to form the Massachusetts Institute of

Technology (MIT) Media Lab and then invent the first programming language for children called LOGO (Papert, 1980). Come full circle, we reach Seymour Papert's seminal work entitled *Mind-storms; Children Computers, and Powerful Ideas* (1980), a book "about how computers can be carriers of powerful ideas and of the seeds of cultural change, how they help people form new relationships with knowledge that cut across the traditional lines separating humanities from sciences and knowledge of the self from both of these" (Papert, 1980). In this work, Papert advocates teaching children to use computers in order to create their own educational experience. Papert, like Ada Lovelace, saw the computer as a tool to empower the learner, not as a consumer prop to passively take in standardized curriculum or to consume entertainment. Lovelace and Papert saw the power of the computer as a transformational tool that can help learners reach further into the yet unexplored.

Problem-based science is deeply rooted in the belief that learners should construct their own scientific understanding and knowledge through making and doing. Through these first hand and real life experiences, students gain a deeper exposure to scientific literacy. When students make models, tools for inquiry, or invent to learn science, this is constructionism in science, or making in science. As a facilitator of constructivism in science, I witness the processes of accommodation and assimilation in the act of the making, fixing, building and deconstruction of artifacts. Constructivism is difficult to measure or make visible. Constructionism, alternatively is based on children making artifacts that are talking points to make thinking visible and physical evidence of learning. Stepping back - to allow children to explore and expand their own umwelt while problem solving - is not only the goal of constructivism and constructionism, it is a source of great joy and inspiration to witness.

When using a constructivist approach to learning, students are in a constant state of 'it reminds me of' while they make sense of the world (Piaget, 2013). When students work to solve a problem, they will naturally apply prior knowledge and eagerly learn new knowledge. It's not about learning facts and moving on, rather it is about students setting goals (student: "I want to have the LED's turn off and on") and an adult co-creating the learning experience (facilitator: "Have you looked for tutorials for using the blink function on an Arduino?"). The facilitator doesn't offer a solution. Instead, she provides the student with the materials and time to find a solution. In the process, the student will learn not just about circuitry, programming variables, resistors, polarity, etc., but also about how to use available knowledge and apply this new knowledge to solve a specific problem, giving learning true context and a much needed visceral reward.

The skills children employ when actively creating their education from experience and natural inquiry are necessary for the enlightenment of the whole person and thus the health of society at large. In a constructionist setting, co-creating education with young learners is a privilege not a job.

The Maker Movement meets Progressive Education

When the fall of 2011 came, I was fortunate to find myself teaching 5th and 6th grade science at a school that had been founded by a progressive female headmistress in the 1930's on the basis of constructivism and world peace. The former 14 acre farm had been converted into a boarding school for wards of the state during WWII, then faced economic strife in the 1980's, shifting its constructivist culture to a more traditional one. When I arrived in 2011, the school had several well-developed maker spaces run by the art department including rooms for ceramics, visual arts, music and woodworking, but little remained of the original campus' architecture besides a cluster of small fairytale-like houses in the center of campus. The cluster of houses, I would learn, was part of a curriculum called the Village of Friendly Relations (VOFR) designed by Mary Orem, then head of school, and was a set of child-scaled houses, designed and built by children. The small village was part of a curriculum to teach self-reliance, real-world skills and authentic problem-solving in a world torn by war.

IMAGE: VOFR The Gift Shop, with double door design as it still stands in 2016, Build 1937.

In the 1930's, Hillbrook, then called The Children's Country School, was the site of several progressive curriculum practices which caught the attention of the whole world. One of these school wide programs was the construction of the VOFR, built and maintained by children using money they earned from chores and from applying for a loan from a local bank. In the September 1939 Issue of Sunset Magazine, the Village of Friendly Relations was featured as a testament to the innovative and human-centered approach to education, then head of school Mary Orem was passionate about. According to detailed documents stating the purpose of the project, Ms. Orem designed the Village Building curriculum for children to accomplish three things; 1) Allow children not normally celebrated in a traditional school setting to be leaders, 2) Empower students with real-world problem solving and building skills 3) Give children a space to practice being "good citizens" in a mistake friendly environment. The Village was not just a cluster of play houses, it was a scale model society with real-world problems for children to learn from.

Like Pestalozzi, Orem believed in the power of teaching children self-sufficiency. In a sense, it was Hillbrook's first attempt at adopting the Maker Movement both in practice and philosophy. Orem's model village was a place where children could practice real-world skills like banking and accounting, brick making, carpentry, democracy, newspaper writing, running a tea shop, and conflict resolution. The tiny village was a child-centered lesson in real life experiential learning that would serve to inspire work in constructionism, or Maker Education at Hillbrook 75 years later.

2011 would turn out to be a very influential year in regards to shifting my teaching practices. The science department at the Hillbrook school was auditing our science programs at the same time that the Next Generation Science Standards came out emphasising more engineering and problem solving. Through a strange turn of events, my hairdresser would introduce me to the book *50 Dangerous Things* by Gever Tulley. This in turn would cause me to volunteer to paint and lay down flooring along with many other volunteers, including David Petrich of The Tinkering Studio, at the San Francisco Brightworks school on Labor day weekend. While volunteering, I would learn of Tulley's curriculum design model called the Arc, this would highly influence my "paths of learning" model which uses antidisciplinary units and scales of complexity, such as the level 1-2-3 system.

Simultaneously, I would also be introduced to the book *Creating Innovators* by Tony Wagner while visiting the Castilleja School (Ca) and hear David Kelley and Kim Sax speak at the Innovative Learning Conference held at the Nueva School (Ca).

Due to my experience with design thinking and my new passion for hands on learning, the curriculum I would begin to use starting the fall of 2012 would use making and newly available child-friendly technologies to teach science through the lens of design and engineering. There would be no textbook (unless we made them), no standardized tests (except for tool safety) and no 100% teacher-directed content, ever. To learn how to do what I had proposed, I consulted with experts, such as Ed Carryer of Stanford's Smart Product Design Lab (learn more about SPDL in *Creating Innovators*), to learn more about the use of prompts for semester-long engineering projects. I was designing a constructivist and constructionist curriculum, despite lacking a deep understanding of these terms at the time. My Stanford FabLearn fellowship beginning in 2014 would bring this connection to light.

In the Spring of 2012 I was given the green light to take a risk to test a new kind of curriculum, despite being unsure of what to expect from this seemingly major shift. By the Fall of the 2012 school year, I was ready to prototype the new 5th and 6th grade science curriculum, now renamed Problem-based Science. Problem-based because it would be all experiential, open-ended and hands-on where children would be learning new skills and reinforcing content as they worked towards goals.

The Hillbrook iLab

Beginning in 2011, Hillbrook's former director of technology Don Orth helped the school adopt a 1:1 iPad program. As a result, learning became more mobile. The school needed to examine their old computer lab, which felt obsolete with its desktop computers and static furniture. As a school we wanted to reimagine a learning space from the ground up, so we ditched the old computer lab setup and the Hillbrook iLab project was launched. Thanks to a generous furniture donation, the iLab was outfitted with mobile chairs, stacking whiteboard tables and rolling white boards, but no giant teacher desk. The lack of a teacher desk would send the signal that no one adult owned the space. The agility of the furniture led to the room having a “reset” mode, where all tables and chairs moved to the perimeter and the room was a wide open canvas after each use. The school was also learning about Maker Education and in the process of purchasing an Epilog mini laser cutter which would need a home. The iLab seemed like a great place to put such a machine.

The science department was auditing their program, remember, as a consequence Hillbrook increased the hours of science per week that our 5th graders would get, despite the fact that the school had limited science lab space. Starting the Fall of 2012, 5th graders would go from three hours of science every six days, to five hours every six days. As the 5th grade science teacher, that added classes to my schedule and left me without a science lab to teach in. Marcus Aurelius taught me to use the phrase, “the obstacle is the way,” and I began teaching all of my science classes in the only room available, the iLab. As a school, we also wanted different teachers to use the iLab with their classes, regardless of what discipline they taught, when 5th grade science was not meeting. We were curious how teachers and students would interact with the room and its agile design.

To study the effects of these new conditions, resident teacher Ilsa Dohmen, now Hillbrook’s 6th grade science teacher and research designer, and I designed a focal study to measure the different behaviors in the iLab compared to the traditional science lab which had bolted tables and much less agility with its structures. To test the validity of our observations, we collaborated with Tim Springer of HERO Inc, a research consulting group in Chicago, to analyze any interesting patterns. In a nutshell, we noticed that more choice was better for collaboration, creativity and confidence. More student choice leads to a healthier learning environment, no matter what. These ideas would highly influence the amount of self-directed learning that would happen in the iLab. So much so, that a Learner’s Bill of Rights began to be posted on the iLab door announcing its new philosophy on self-directed learning. The idea Lab became a safe place to share, create and test ideas.

To add to the study of the furniture in the iLab, I was teaching all of my 5th, and sometimes 6th grade science, in the iLab. As a result of the ongoing iLab study, from 2012-2014, the closet was the only space designated to store the materials I needed to teach the engineering and design course I had designed. We did have a laser cutter that was allowed to live in one corner of the room, however, seeding the iLab as the future makerspace it would become.

By the fall of 2014, the official iLab study ended and the formerly neutral space would become more like the school’s first prototype makerspace dedicated specifically to STEAM on campus. When it became clear that I was teaching science full time in a makerspace, I needed to ask how my learning outcomes would shift from traditional science content and teacher-led labs to a messier, richer and more engaging use of the mindsets and habits employed by real scientists, engineers, inventors and designers.

The iLab study and all of the obstacles it served me my first years teaching making in science, gave me permission to take risks and try a new kind of teaching and learning. I experimented with more teacher directed approaches and more student led approaches. The more student led the messier, and more diverse and often most rigorous. The more teacher directed, the more predictable and the more standardized assessment could be. Finding a good balance should be the focus of our work as facilitators of constructionism or making in science. In this report I describe the structure of how I taught science in the iLab, a prototype makerspace, between the Fall of 2012 and the Spring of 2016.

The iLab Learners Bill of Rights

When I designed the iLab to function as a constructionist learning space, I wanted to inform students of the risks and responsibilities of working and playing in a self-directed or (democratic) learning space. To facilitate this shift I created norms that would help students feel safe to learn in the iLab. I wrote a Bill of Rights, stained it with tea and burned the edges and posted it on the front door of the iLab. I was going for stirring up curiosity mostly, while suggesting that following these rules will come with effort. Here is an image of that promise to students who work or play in the iLab.

Dear Students,

The MakerSpace is a self-directed Learning Space, as such, you have the right and responsibility to...

- be passionate about your work (vote on what you are learning and why).
- assess your growth and growth of others as part of your learning process.
- know how the work you do and the topics you learn are important in the real world (solve real problems).
- make lots of mistakes, fail trying, get up and start again.
- be an expert even, if you are not an adult, and to share that expertise.
- be a "geek" (passionate about stuff most people are not).
- to be respected by your peers for being curious or taking risks to share an idea.
- be responsible for yourself (heart and body), your stuff and the self (heart and body) and stuff of others.
- assertively question something that you do not understand or agree with.

Take a tour of the iLab

The iLab is a prototype makerspace or classroom design for constructionist learning with a focus on science. Use this link to take a tour of the iLab from the spring of 2016.

[“Welcome to the iLab”](#).

[IMAGE] Agility features of the Hillbrook iLab. Photo made by Don Orth (2014).

The Problem-Based Science Model

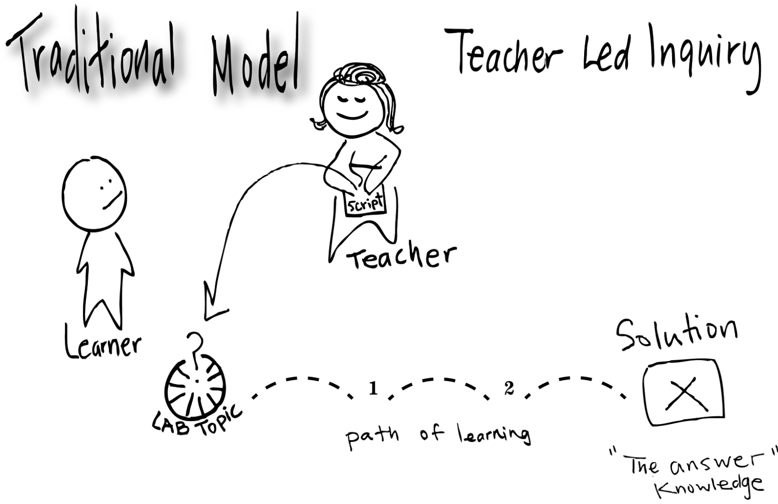
The problem-based science (PbS) model is simple on the surface. Students address real problems, small and large, using real tools, real materials, and real time. Addressing problems small and large is a form of applied technology, engineering, art, math, and science (t.e.a.m.s.). The sequence t.e.a.m.s. is used to suggest that all of the disciplines must work together in an antidisciplinary fashion, as in the real world. It is also a reminder of the real work that students do. In one scenario as facilitator, you may present students with open-ended problems, called prompts. Once given the prompts you would give students the time and space to solve that problem using their knowledge of the t.e.a.m.s. fields. In another scenario, students may be charged with observing their local environment for possible problems to address. This can come in the shape of slow looking (observation and inquiry) or interviewing others to hear their needs (design).

How is PbS Different from the Science Classes We Took in School?

Most likely the science classes you experienced in school were loosely based on an approach to science called the scientific method. In science class, you were tasked with “rediscovering” well-established phenomena, such as density or double replacement reactions, via carefully scripted demonstrations or lab experiments. Although you were going through the steps of the scientific process, you were arriving at a predetermined outcome created by your teacher, far in advance of you existing in her classroom. You may have had a textbook to explain concepts, and tests that measured your knowledge on those concepts. For deeper evaluation of your work, you were expected to follow a rigid lab report format, mirroring those found in academic journals, that did little to assess your personal level of problem-solving, resilience, creativity or long term understanding of the concepts involved. In short, you most likely consumed your science education, rather than constructed it. *[IMAGE] There is not one solution diagram*

In comparison to a one-size-fits all curriculum, PbS reunites students with the complexity, richness and fun of science by putting them in the drivers seat. Learning through inventing and problem solving - while using the latest in fabrication technology, like 3D printers and laser cutters, as well as more traditional making skills, like electronics, robotics, sewing and carpentry

- immerses students in the messy and iterative nature of real science and engineering. **PbS encourages students to gain, or rather retain, a love of scientific thinking, applied math, and the creative use of technology,** while learning through the lenses of invention, design, fixing and tinkering.



Tinkering, making and solving problems is a rigorous form of learning. It is a kind of learning style that requires time. It is a luxury to give students time, but this modern luxury is one every young person deserves in order to reach their full potential. In essence, PbS allows students to construct scientific literacy, by behaving like a real scientist or engineer. David Perkins, author of the book *Make Learning Whole: How Seven Principles of Teaching Can Transform Education,* says this gives students "threshold experiences, that stimulate curiosity, discovery, imagination, camaraderie and creativity."

In PbS, students will make mistakes, encounter obstacles, and experience failure. If a student cannot solve a problem due to a lack of knowledge or skill, that student must choose between constructing new literacy, or choosing a more accessible solution. Rather than shy away from failure **in PbS, we embrace and redefine it as a crucial, and deeply personal step in the learning and design process.**

Problem-based science generates a learning community where leaders and experts can be of any age and where the values and needs of the individual are heard and protected. Schools are not democratic spaces, historically. In a 100% teacher directed classroom students are trained to please and consume their education. A problem-based classroom allows for greater shared ownership. In this model, the teacher stops telling students what they should know and facilitates the learning process by asking challenging questions. Removing the "one adult expert" from the room frees students to explore, which in turn increases their enthusiasm for learning and their engagement. Once students know that their ideas and questions are as important as others, they also feel empowered as leaders and start to develop essential cues to their identities.

All students benefit from this process, but the students who stand to benefit most are those who historically have been underrepresented in STEM fields or those seen as struggling in a traditional classroom. Attitudes about who pursues math and science, as well as images of the life of a solitary researcher, don't resonate as much with certain students as with others. Showing them how science and math can be applied to any problem — social, economic, or aesthetic — and reinforcing this with role models, is a step toward bridging the gap of historically underrepresented populations in the STEM fields. Furthermore, the antidisciplinary nature of making engages multiple forms of intelligence, which allows for a greater number of students to thrive. **Problem-based science promotes a diversity of ideas, talents and voices.**

Playing the Whole Game of Science

In Problem-based Science lessons are best likened to a game. Like most games, there are goals and rules. The goals offer the big picture, like "get the ball over the goal line," while the rules make the game purposeful, safe and fun. We call the goals of the PbS game "prompts." Using prompts, rather than a fixed set of instructions, is an open-ended approach to learning that affords students choice and voice, and promotes confidence, engagement and self-esteem (Deci & Ryan, 2000). An example of a prompt might be to make something that can move a 75 gram steel ball from point A to B, that uses two or more forms of energy, aka a marble run. Once given the prompt, students are given weeks, or months (Driving Principle 1) to brainstorm, form teams based on passion and/or skill sets, then test and iterate on various solutions. No solution will look the same, allowing for a highly differentiated learning experience for each student. The open-endedness of prompts provides students with control over the "why, how and what" of their learning journey (Driving Principle 3).

The rules of the game are simple – everyone must be doing something, this is constructivism's one rule. Being "on task," however, can look different for different students at different times. Some students need to have their hands busy every class, others are content to put on headphones and learn about something online for hours, still others may need time to daydream on a walk in the sunlight, others just need to move their body to get past an obstacle. As in any game, too many highly specific rules take the fun out of it. Imagine watching a great sporting event. For maximum enjoyment you want some rules to understand the nature of the work, as much as you want surprises, anomalies, and adventurous twists and turns.

This is not to say that the teacher just steps back and lets students do anything they want. The teacher's role is to support the students in their inquiry, and keep them working towards their own goals. This part of the role is about observation and communication. Ask for drawings, blueprints, explanations, long lists of brainstorming exercises to get them thinking about thinking. Checking in with learners can be done through a series of mini-lessons, clues to research and daily agenda feedback to see and hear the progress of a learner or team. As students work, the teacher looks for evidence of their understanding, encourages different types of thinking, and supplies collegial support by working as a co-learner. Learning to an outsider looks messy, but fear not. As a facilitator and true scientist in a constructivist or constructionist classroom you learn to see learning in the mess, just as a dedicated astronomer, learns to read the messiness of the night sky.

The next few sections describe all of the patterns that I used testing the problem-based science approach in a makerspace, beginning with how to establish emotional and physical safety. Emotional safety comes with rules that establish language for talking about problems and solutions. Physical safety comes from categorizing tools and materials according to their potential to harm or challenge a learner.

The Structure of PbS

The Level 1 - 2 - 3 System

Another really important topic in science, math, technology, art and engineering is scale. The thematic units as well as the problems they generate are all a demonstration of how to use scale when focusing in on fields of knowledge in science. Problems, as well, are discussed according to a scale of difficulty. This scale is something that adapts and evolves depending on the learner themselves, their age, aptitude, passions and experience. For instance, what might be a level 1 problem to one student, may be a tricky level 2 problem for another student with less experience. Lastly, materials can be looked at with a level of scalable detail and discussed on a scale of how hard they are to build with. Below is a synopsis of the model I used in the iLab to denote the scale of the above topics.

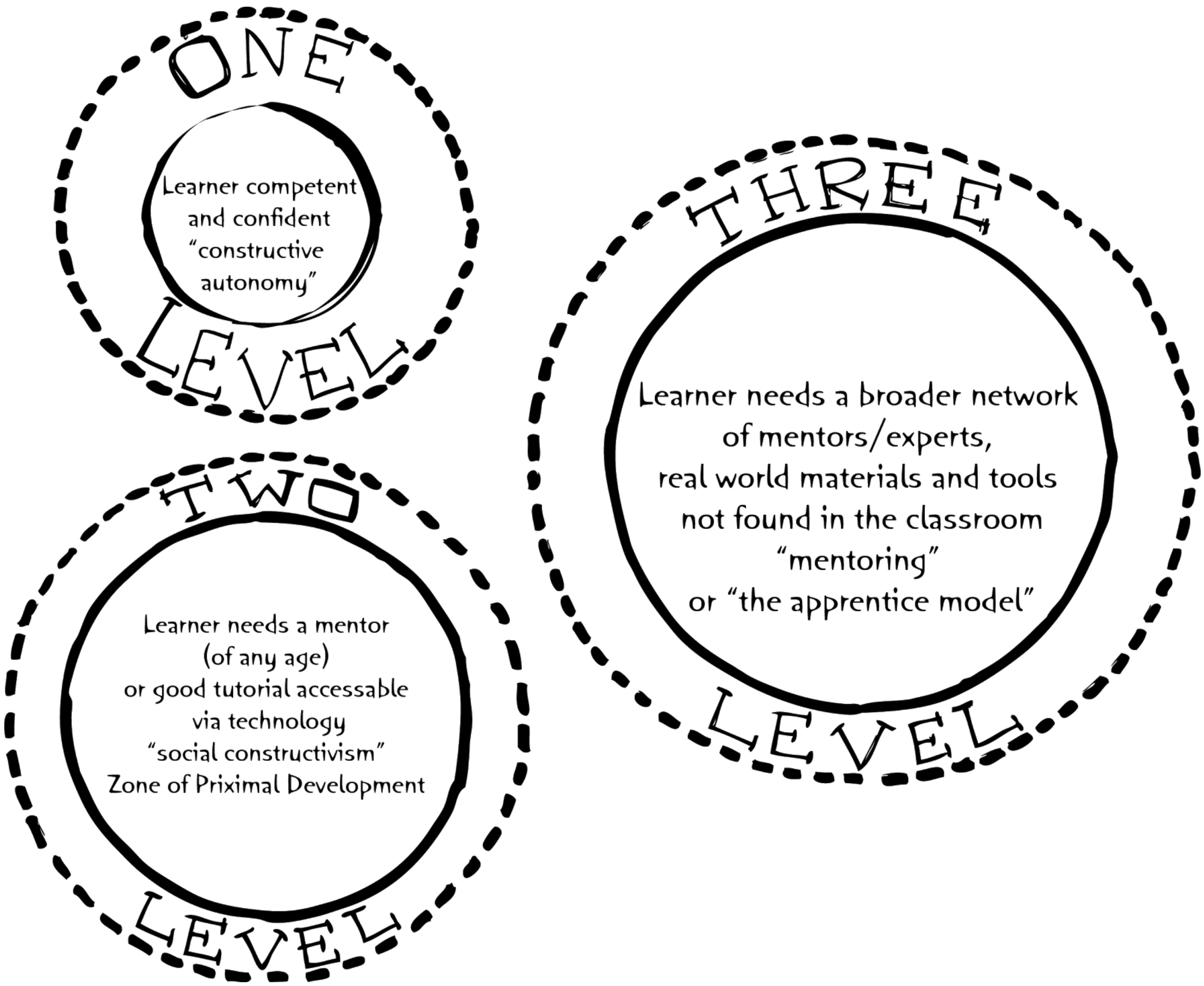
Level 1 - 2 - 3 Problems or “Prompts”

When children face problems they want to solve, these problems may be within their skill set and imagination to solve, or far outside of their abilities to solve alone. At times they will run into problems that they can solve quickly, with simple tools and in relative isolation. At other times a student will face something novel that causes her to be stuck and she will need a mentor (peer or teacher) to get her to the next step. Still at other times, students will face problems that far outreach the skill set of her immediate learning group. This is when the tools of the internet, outside experts and real collaboration are required.

In Problem-based Science, the curriculum is structured in such a way that students encounter a range of problems in each unit. Materials and patterns are designed to be open-ended enough to allow choice and early and safe exposure to different kinds of problems. When a student decides what she wants to make in science, this is the self-directed and student choice aspect of the work we do, she may chose a task that is fraught with problems and dead ends or she may chose to stay in a safe zone. We use levels, from one to three, to describe the problems students encounter and chose.

This leveling of problems pairs well with the concept of the Zone of Proximal Development, or Z.P.D. model, invented by Lev Vygotsky. Vygotsky defines the ZPD as "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers" (Vygotsky, 1987).

IMAGE: ZPD model



In problem-based science, Level 1 problems should have a relatively clear solution. Students may have solved a similar problem before and have a known technique, and they should be able to solve the problem by themselves. In Level 1, a solution is known, the supplies needed are close at hand and the problem-solver is able to work independently in a state of constructive autonomy.

Level 2 problems are larger puzzles that require community. At Level 2, it is not uncommon for a learner to feel stuck and to need help to solve a problem. Here is where social learning theory takes center stage. Constructivist learning experts Savery and Duffy list three elements which are key to learning: the environment, “puzzlement” and socializing. Socializing is key, argue the authors because “other individuals are a primary mechanism for testing our understanding,” (Savery, J. R., & Duffy, T. M. 1995).

Students can choose to solve a problem alone or engage in collaborative work with others, whether this is a YouTube video, or communication with real peers and adults. Learners can move seamlessly between supported, mentored learning and autonomy – similar to practicing piano between scheduled lessons with a coach. Level 2 problems lie squarely in the zone of proximal development as learners acquire new knowledge or skills via the support of a learning community. Learners feel stretched in this zone, all the while having a safe network to lean on.

“Hard Problems”

Level 3 problems far outreach the ability of a single group of co-learners to solve. Level 3 problems demand the use of tools that might be dangerous, access to real-world experts, and tons of innovation. As such, Level 3 problems reside in the outer sphere of the Z.P.D. model. At Hillbrook, Level 3 problems were simply called “hard problems” because they require time, collaboration, taking risks to learn new skills, creativity and resilience. Level 3 problems are real-world problems and the solutions require real materials, real tools and real time to allow kids to wrestle with them. For a middle school student a hard problem might be constructing a real artifact from scratch, or without pre-existing blueprints and instructions, aka inventing.

The true sign of a good hard problem is when no one has an immediate or quick solution for a given obstacle, including the adult(s) who may have been the source for a given problem or prompt. Hard problems are best addressed when you have established a safe learning community and give students time to self-identify the skillsets that come in handy in a makerspace. Once presented with a hard problem or prompt, students can take charge, chose teams based on their skills, then work towards a range of solutions using a collective design process. I have used a system of process resumes and badges to identify skills. Hard problems require real mentors and experts at hand to teach a tool or to give advice or feedback. To make this feasible, mentors and experts can be parents, grandparents or working professionals reached using web-based media, such as Skype.

Level three problems or hard problems allow students to practice resilience. Resilience is defined by resilience researchers as a “persevering adaptive capacity” or “the ability to adapt to changed circumstances while fulfilling one’s core purpose” (Zolli & Healy, 2012). Others have called it “grit,” and “failing forward,” because problem solving, making and tinkering presents learners with inevitable dead ends, as well as unexpected discoveries (Duckworth et.al., 2007, Maxwell, 2007). In the more traditional science classroom, or any academic classroom for that matter, a child is encouraged to attempt to learn a concept preselected by the teacher then demonstrate her learning of that concept maybe one or two times before required to move on to a new subject, project, or paper and potentially leave a weak piece of work behind. Worse yet, a teacher may design all of the discovery of dead ends out of her lessons to prevent failure of any kind. By scaffolding the road to success in her classroom, she inadvertently creates dependence on the adult and a fear of failure. In a makerspace, dead ends and failure are a natural part of the process of asking questions and testing ideas. Indeed, deep learning is impossible without it.

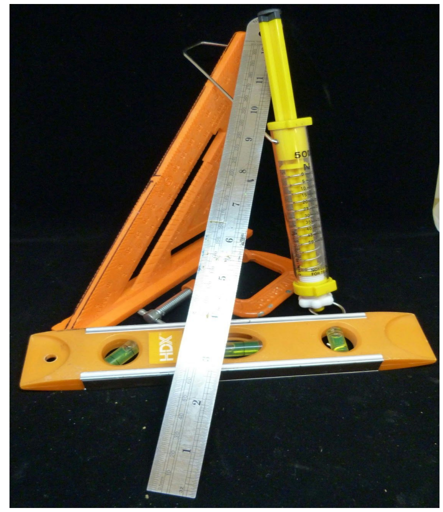
Hard problems demand a re-imagining of education, where learning takes time and is highly social. Allowing learners to engage with hard problems is akin to the "slow food" movement, valuing depth over breadth in content. Hard problems ask teachers to slow down, to allow deeper understanding. Problem-based science offers a chance to make deeper connections instead of the consumption of obsolete facts or preparing for the test. In the end, the real world is full of problems that students can be working on while they gain science literacy, as well as more confidence in math, writing, art, sharing work and solving problems.

The Level 1-2-3 System for Materials and Tools

In the iLab materials and tools also have a rating system. Leveling tools helps establish safety and a mentoring program, where students understand and respect the risks of a tool and are willing to help others learn new tools. At the Hillbrook school, by 5th grade most students are comfortable with all level 1 tools. Level one tools are easy to learn how to use, mostly analog in nature and durable. Level one tools are open for all, including teachers in adjacent rooms to check out and use. Level 2 tools require an introduction into how to use the tool. Level 2 tools require more responsibly on the part of the user and are often expensive to replace. Level three tools require a certification from an adult to use because misuse would result in permanent or serious physical harm to the user or harm to the tool which is very expensive. Level 3 tools that can harm are corded drills, soldering irons, and some toxic chemical based adhesives. Level three may also just indicate intellectual difficulty. For instance, an Arduino and an electronic sewing machine are both level three tools for a middle schooler. Access to level three tools is contingent on a student's willingness to take the certification seriously, apply the tool to a real problem they are experiencing (context) and their willingness to mentor others when they are certified.

Leveling materials helps students to think about the relative ease of cutting, and making attachments and also gets students thinking about cost of acquiring materials, sourcing materials and resource management. Level one materials can be acquired from anywhere for free or for very little cost. Cardboard, paper, styrofoam and miscellaneous crafting materials are all level 1 materials. Materials that might have a cost, require special tools to cut, or that take more effort to connect are level two materials. Wood, plastics and sheet metal are all level 2 materials. I also level Legos, Tinkertoys and NXT bits level 2 because they are not consumable, but they are easy to build with. We love level 2 materials. Level 3 materials require dangerous or difficult tools to work with. Glass, ceramic and metal thicker than 1/16 inch or are all level 3 materials because they require high heat to work with and serious cutting tools. Some tools are also materials if they leave with a student's project. An example of a level 3 tool that can also be a disposable material is an Arduino.

TOOLS

Level 1		

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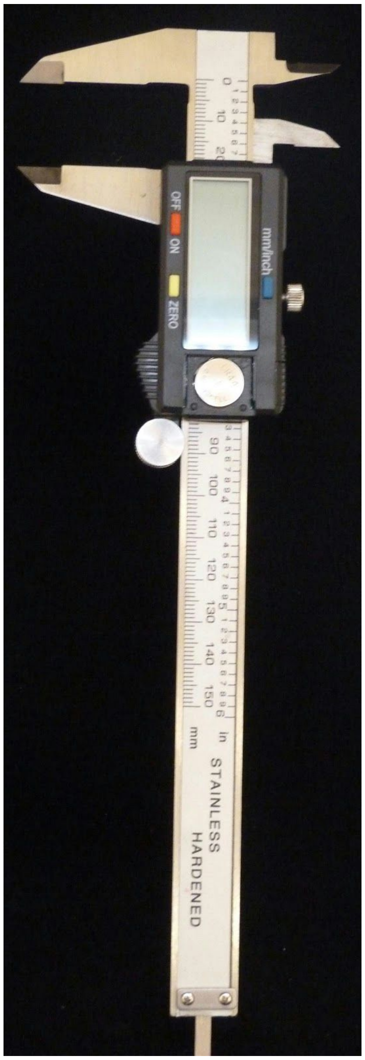
<td>
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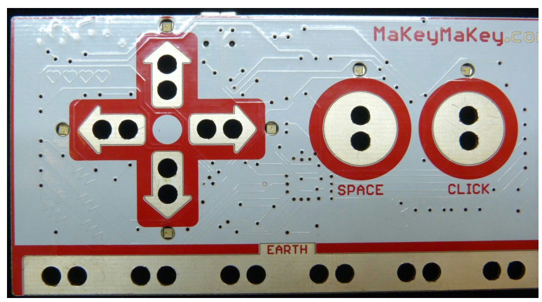
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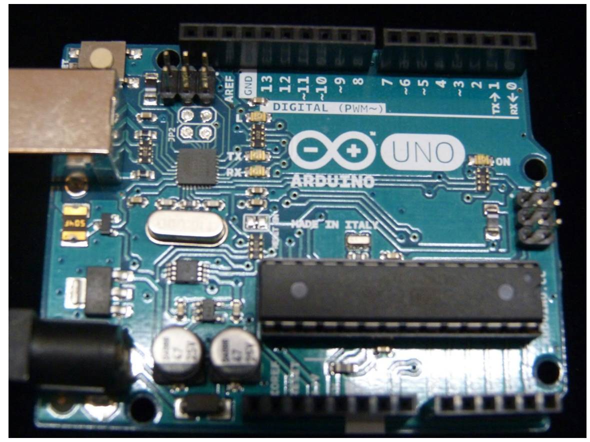
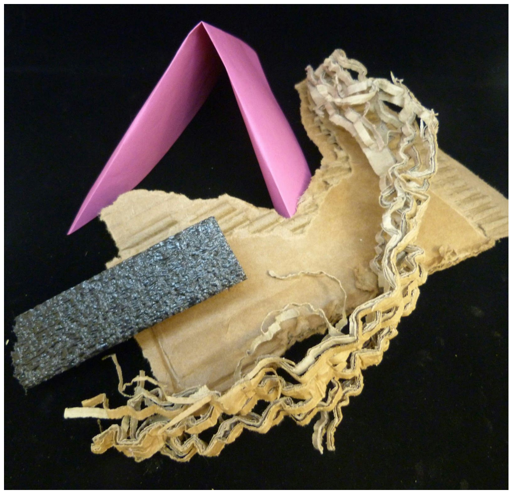
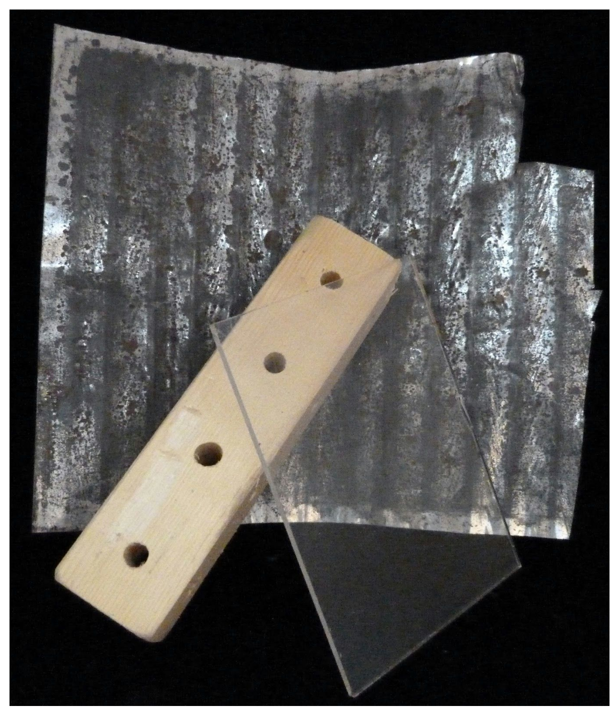
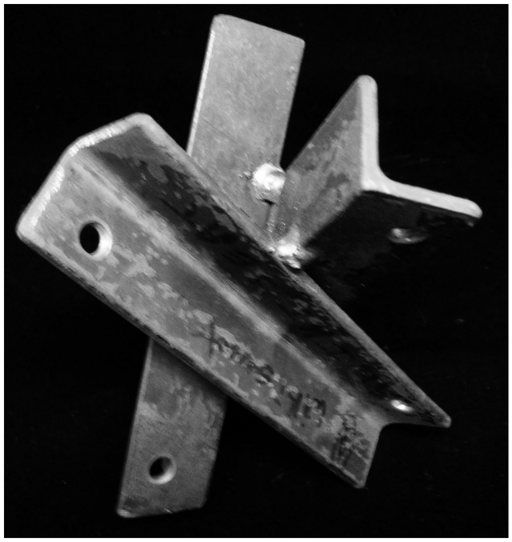
Level 3		 

MATERIALS

Level 1		
Level 2		

Level 3		

The Four Year Timeline of Problem-based Science

Problem-based science was taught in both 5th and 6th grade the fall of 2012 until the spring of 2014. While projects and prompts will depend on who is in the class any given year, the thematic units focused on were decided upon before the school year begins. Over the four years I experimented with focusing on different units with 5th grade and 6th grade. Often I layered units together into single projects. For instance, the Tiny Green House project, done the fall of 2012 in 6th grade science was a design thinking and architecture project that used the tools and habits of Patterns, Structures, and Problems. Spring hard problems for 5th graders began as a combination of Structures and Systems from 2012-2014, then shifted in 2015 to a culminating projects that asked students to apply knowledge, the mindsets and habits from our Materials, Patterns, Structures, and Systems units, to real-world (Level 3 - 4) Problems. Problem units consisted of deep projects which required the help of more adult mentors, volunteers (I.E. parents and grandparents) with skills we needed in the iLab. For instance in 2014 and 2015 we had help with electrical engineering, Arduinos and power tools. In 2016 a resident teacher assisted with laser cutting, and observing and measuring student growth.

I recommend, at the middle school level, that Problems units are done with students in configurations of teams. My students form teams based on their badges and any social emotional concerns they can predict coming up. Usually a small set of trusted students is put in charge of making the teams and this works out 75% of the time. The other 25% of the time we make new accommodations for students, even to work “alone” as a consultant with a highly desired skill that every team can benefit from such as documentation, laser cutting or programming. This makes what would be a difficult student or one unable to collaborate, a super collaborator. Everyone having a job and role is the most important thing to reinforce. This helps students feel safer in a self-directed environment.

[TABLE] Timeline of Problem-based science units and projects

2012-2013 school year					
Grade	Fall		Grade	Spring	
	Unit	Project Name		Unit	Project Name
5	Materials Patterns	*Self-portraits* *Egg drop*	5	Structures/Systems	*RubeGoldBridge*
6	Materials Patterns/ Structures/ Problems	*Self-portraits* *Tiny Green Houses*	6	Problems	*Good Food and Toy Design Challenge*

2013-2014 school year					
Grade	Fall		Grade	Spring	
	Unit	Project Name		Unit	Project Name
5	Patterns	*Measure something*	5	Structures/ Systems	*CitY3K pinball machines*
6	Patterns Problems	*Design a survey* *Find a need*	6	Problems	*Good Food and Toy Design Challenge*

2014-2015 school year					
Grade	Fall		Grade	Spring	
	Unit	Project Name		Unit	Project Name
5	Patterns	*Secret Code*	5	Problems	*Design Detectives for the Common Good*
7	Problems	*Entrepreneurs workshop (elective)*			
8	Problems	*Young Engineering Scientists (elective)/ Hillbrook History House*			

2012-2013 school year					
Grade	Fall		Grade	Spring	
	Unit	Project Name		Unit	Project Name
5	Materials Structures/ Systems	*Open exploration* *Cardboard automata*	5	Problems	*The Hillbrook HERstory Museum*
7	Patterns/ Structures/ Systems	*Introduction to robotics with Arduino*			
8	Materials/ Patterns/ Structures	*Open iLab Making (elective)*	8	Problems	*LearnSTEM capstone project*

Assessment and Grading Practices in Problem-based Science

Science is an academic subject at most schools, including the Hillbrook School. Most academic courses entail a suite of tests and homework assignments to be assessed for a grade. Given the constraints and expectations of teaching an academic course in middle school, I began using a variety of formative assessments that can be used along with a point system culminating in summative assessments. Each student makes an argument for their final grade using evidence and reasoning. However, there are no paper and pencil tests in Problem-based Science (unless created by the learner for self-assessment). Students assess themselves on the design and engineering process by arguing for a pass or fail grade. They keep detailed logs of skills and project progress, and create design reports. They also learn to participate in peer critiques and in public showcases of their work.

Not every project uses all of these assessment strategies. The most important criteria for a good assessment is that it is useful to the student as they work on their project. If it is not a useful tool to make the project work easier, it becomes an inauthentic exercise in making up things for the teacher. Documentation of the process of invention, using daily logs, blogging, portfolios, etc., on the other hand aids the learner in self-reflection, and later in the ability to avoid the same mistakes and to tell their learning story.

[IMAGE] The Life Cycle of Cotton, Hillbrook 5th grader making thinking visible through drawing. This artifact is now a model for the learner to use as a tool to talk about her own understanding. Lifecycles of materials is an great way to introduce drawing and information design.

Example Assessments for PbS

Badges and Resumes

When students begin the year, they come to the makerspace with lots of pre-existing experience using different tools. Through the course of the year students will also learn new tools to add to their tool belt, so to speak. To mark this growth, I use a paper badge system. When students finish a project they can update their “maker resume” and reflect on what tools they have practiced in science by adding badges. A resume is simply a sheet of paper that has all of the badges they feel they have earned glued in one place. Note, the skills I use are for middle school students. The skills you emphasize in your own makerspace or science lab may be different. Below is an image of just some of the badges my students can earn while learning science in a makerspace.

[IMAGE] Resume Badges Sheet 1

Daily Log or Science Journal

In the Problem-based Science classroom, teachers can assess student progress based on the student's design journal, which keeps track of the student's design notes, ideas, measurements, agenda, etc.. Students learn how to track their iterations through detailed labeling of sketches and captioned photographs of prototypes for reference at any time. For the constructivist scientist and inventor, the journal is your textbook. Cultivating a habit of documenting progress, ideas, observations and questions, is cultivating the first step to being a scientist and inventor.

Younger students can use paper for log entries, but as 1:1 technology advances, this process may be better suited to electronic portfolios. Googledocs, sites and blogging tool are free digital platforms that adapt to the classroom and allow learners to share work, keep logs and curate an online presence. Using digital platforms may be less charming or romantic than the paper journal, but it makes learning four dimensional and more easily sharable.

[IMAGE] Daily Log, Screenshot 1
[IMAGE] Daily Log, Screenshot 2

It is made of chalk,water, and cardboard. I feel like this went well, finding how to use chalk/shell to make a usable material was a collaborative effort in between me and Zoe. I can't wait to present because this project uses my passions for art, science, and video games.

October 22 2015

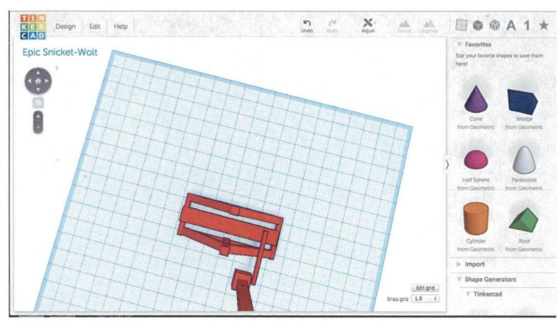
My agenda is:

1. Fix my pac-man's eyes with glue

2. Make a big ball of yellow chalk powder

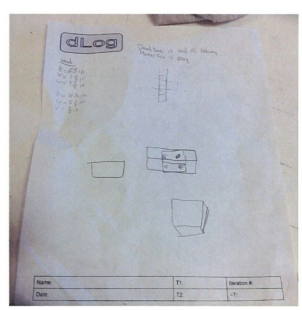
3. Mold it into a ball

That should take long enough.



1/29/15

Today we tried to finalize our plans. It was decided that we would cut down on the size seeing as the wood on our trebuchet was partially reusable. Tomorrow we will begin to deconstruct the old trebuchet and collect wood. We couldn't decide what wood we should use. However oak would work well. We have decided to use our old arm seeing as it is fully equipped to be launched and is by far the least manipulated wood on our weapon.



Peer Critiques, or The “Crit”

Many professionals rely on peer review to improve their work with feedback from the people who know it best. In the design disciplines, for example, there is a process referred to as the “crit,” short for critique or critical review. This involves showcasing of projects for peer review while the projects are in development. This “crit” has become an essential part of student assessment in Problem-based Science. It allows students to not only demonstrate their understanding of their topic, but also their pride in their work. When students know they need to present their work to peers, they instinctively want to put their best foot forward. Furthermore, peers who have approached the same problem or prompt are typically the most stringent critics, offering authentic feedback that can lead to a better solution.

Teams get points for sharing their work during peer critique sessions as they get vital feedback about how to improve their designs and share arguments for their use of materials or a design. In a paper entitled “Arguing to learn in science: The role of collaborative, critical discourse” by J. Osborne a review of the importance of critique and critical dialog in general are needed when learning science. “Argument and debate are common in science,” states Osborne, “yet they are virtually absent from science education. Recent research shows, however, that opportunities for students to engage in collaborative discourse and argumentation offer a means of enhancing student conceptual understanding and students’ skills and capabilities with scientific reasoning. As one of the hallmarks of the scientist is critical, rational skepticism, the lack of opportunities to develop the ability to reason and argue scientifically would appear to be a significant weakness in contemporary educational practice. In short, knowing what is wrong matters as much as knowing what is right,” (Osborne, 2010).

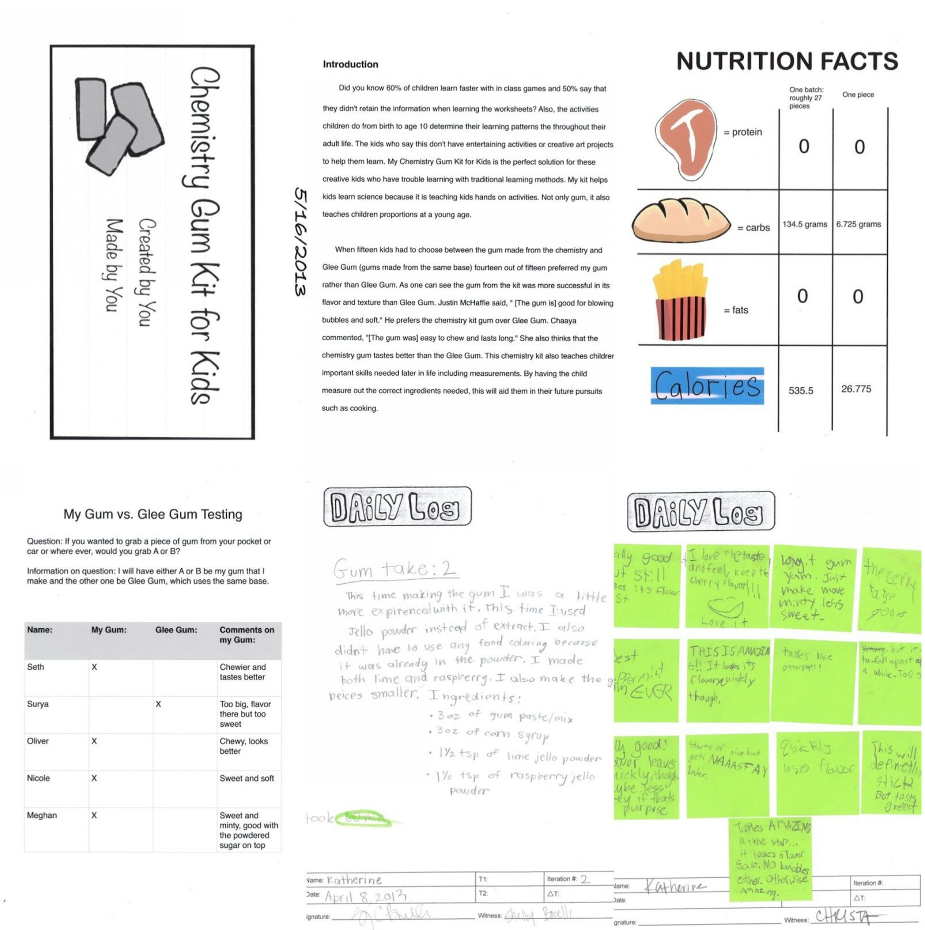
[IMAGE] Our first love notes.[IMAGE 5.5B] Love Notes.

Product Design Reports

A Product Design Report (PDR) is like a lab report in that it captures student learning while making and testing something. Students practice argumentative writing, scientific testing, data visualization and note taking. Unlike a lab report, students also use concepts in graphic design and narrative writing to detail original student designs in one visually appealing, and empathy building package. When students use PDR's to curate all their work on a single product/project. they typically include the following elements;

- Title page with original art (can be a photo of the project) and name of product and its designer(s).
- A document that argues for a passing or failing grade using claims supported by evidence and reasoning.
- An infographic or data table of some kind further showing a student's conceptual learning of content and data collection.
- All of the daily logs recording the day to day process of a project.

In the weeks leading up to PDR completion, I provide a checklist of what should be included. Time is allowed in class for this self-reflective process and curation. It not only makes learning visible for the teacher, learners also get to visuals and make tangible models of their learning journey in science.



[IMAGE] Sample PDR 1 The following example shows the PDR made for the end of the Good Food/Toy Design Challenge of 2014.

Self-Assessment

In making and design activities, the student will have many opportunities to diagnose their own work (with or without the aid of an expert). Self-assessment is the Trojan horse for more authentic and humane forms of assessment, and it turns out to be an inevitable tool for learning in a makerspace. In a self-directed learning environment, students gain knowledge as it becomes relevant to a solution for a problem at hand. Not every student learns the same concepts or acquires the same skills. This presents a challenge for assessing students on a standardized scale, but it also presents an opportunity to apply self-assessment and practice assessment literacy (Smith, et.al., 2013). Because every learner has a unique learning path, documenting process in PbS becomes, by necessity, the right and responsibility of the learner. While using self-assessment students gain the ability to:

Define and Critique "Quality" of Work (self and others)

- Based on principles of known design, science, engineering and research.
- Based on a rubric of pre-selected standards created by students or teacher.
- Based on peer-feedback and classroom mentoring.

Communicate Competence and Reasoning

- Using verbal or written statements of pass or fail for a given goal based on evidence and reasoning.
- Arguing for the use of specific materials and design ideas.
- Telling compelling stories about success and failure.

Children understand the objectivity of a pass/fail system when it comes to learning a new skill or solving a problem. Failure and success are objective outcomes that they can independently measure by answering the following question: Did you solve the problem or not? Students may fail to achieve a goal or develop a product, but in PbS, this teaches them to search for another path. Students learn that every failure teaches something new and should be embraced as an opportunity for growth and improvement. The goal is not to feel weighed down by failure, but to continue working toward success and to learn how to tell the story of that journey.

EXAMPLE 1: This example comes from a student in a fifth grade Problem-based Science class. In this self-assessment, the student makes an argument for a grade of passing or failing, based on evidence and reasoning. We ask students to think like scientists and speak like storytellers. All problems are graded on a Pass/Fail system with an opportunity for passing with honors or failing with honors. Below is a sample draft of a student's argument for passing the four rules of the spring hard problem. We use Google docs, as they offer students easily accessible tools for self-publishing, as well as a quick and permanent means for me to give students feedback about their argument.

Collaborator's Name: Ms. Neilson
Title: Spring Hard Problem
Date: May 21

The rules for the challenge were:
1. Find a need with your adult collaborator
2. Addresses the need you found
3. Uses some kind waste from on the campus
4. Make a solution that is beautiful or creates connections at Hillbrook

Originally, I was working with the Wild Wolves, but I had nothing to do. Twenty classes before Maker Faire, I switched to a new project, a math game for first graders. My collaborator was Ms. Neilson.

Making my game for the first graders was actually pretty easy. For someone new to programming, it would be really hard, or even impossible. I have been programming for four years, so making a game was a simple, but enjoyable task.

I got it finished, but I knew I would eventually add new features. I got tons of help from my adult collaborator Ms. Neilson, my friends Jacob and Halle, and from all of the Hillbrook first graders.

I decided my game would be very short, but the first graders would aim for a higher score each time. Though I knew that I would expand a ton.

Currently there is a crab that asks for an addition problem, a monster you slay with a subtraction problem, dolphins that you count with multiplication, and a penguin that asks for the fraction of a pumpkin.

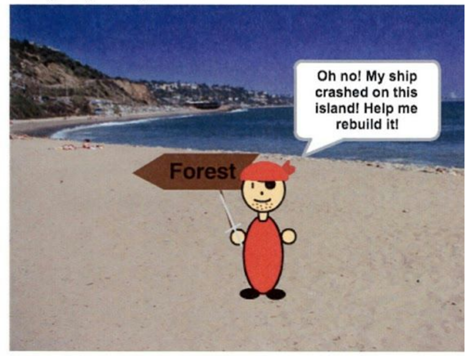
I passed rule one because I asked my adult collaborator and the first graders many things and found the need that they needed to learn math. For example...

I passed rule two because I created a game that reviews all the math that they know. I passed rule three because it didn't apply to me. I passed rule four because I worked a lot on the graphics by spending a lot of time drawing the characters and only used one sprite(the Crab) from the sprite library.

If I could add more to my game(which I can), I would add it so that the pumpkin was randomized. I also might add more math. I think I deserve honors because I finished my project with very little time.

Screenshots:

the beginning of the game



the Island

the beginning of the game

the beginning of the game

the Island

[IMAGE] EXAMPLE 1: End of year argument for grade after the spring hard problem in, 5th grade problem based science at Hillbrook. Learner used Scratch to code a math game for 1stgraders. Here a 5th graders was empathizing with 1st graders to inform his game design.

EXAMPLE 3: This example comes from an activity to help facilitate working in teams for long term projects during our spring hard problem. This rubric was a tool for learners and team members to see the "work" needed to solve their problem and the range of engagement that one might take in this work. Having the ability to see a spectrum of engagement for hard work, such as research and blogging, empowered students to discuss where they want to be as learners and as teammates.

Work	0-5 Points	6-10 points	11-15 points	
Researching requires taking notes, includes copying and pasting quotes and images	I have trouble focusing on my team's topic if I am on my iPad. I don't always tell anyone what I am learning. I never record my sources.	I can find reliable sources but I don't always take notes or I have a hard time taking notes in my own words. I forget to record my sources after I learn something.	I share what I learn, take notes in my own words, not just copy paste, and use a range of sources including reliable EBSCO links. I record my sources.	13
Blog Writing 200 + words	I can read and edit others work, but writing in class is not my thing.	I am a great editor, and I can work with one or two other people to write a blog, but it is not my favorite thing to do.	I can sit and write in or out of class productively. I can write 2 to 4 paragraphs an hour	12
Daily Log 50-200 words	I haven't really added much to the daily log except once or twice.	I have switched off writing down my team's drafts and our daily progress. I have done an equal amount of logging as everyone else. Sometimes I forget to put the date, headings and a "by me" line	I always put down my observations and the observations of my team as evidence of our productivity. I use clear headings, dates and images	10
Total Points (add all the points you gave yourself in each category, the max you can get is 45)		Average (total divided by 3) 12		

Name: Joanna Witness Zoe, Logan, Kyle, Tyler

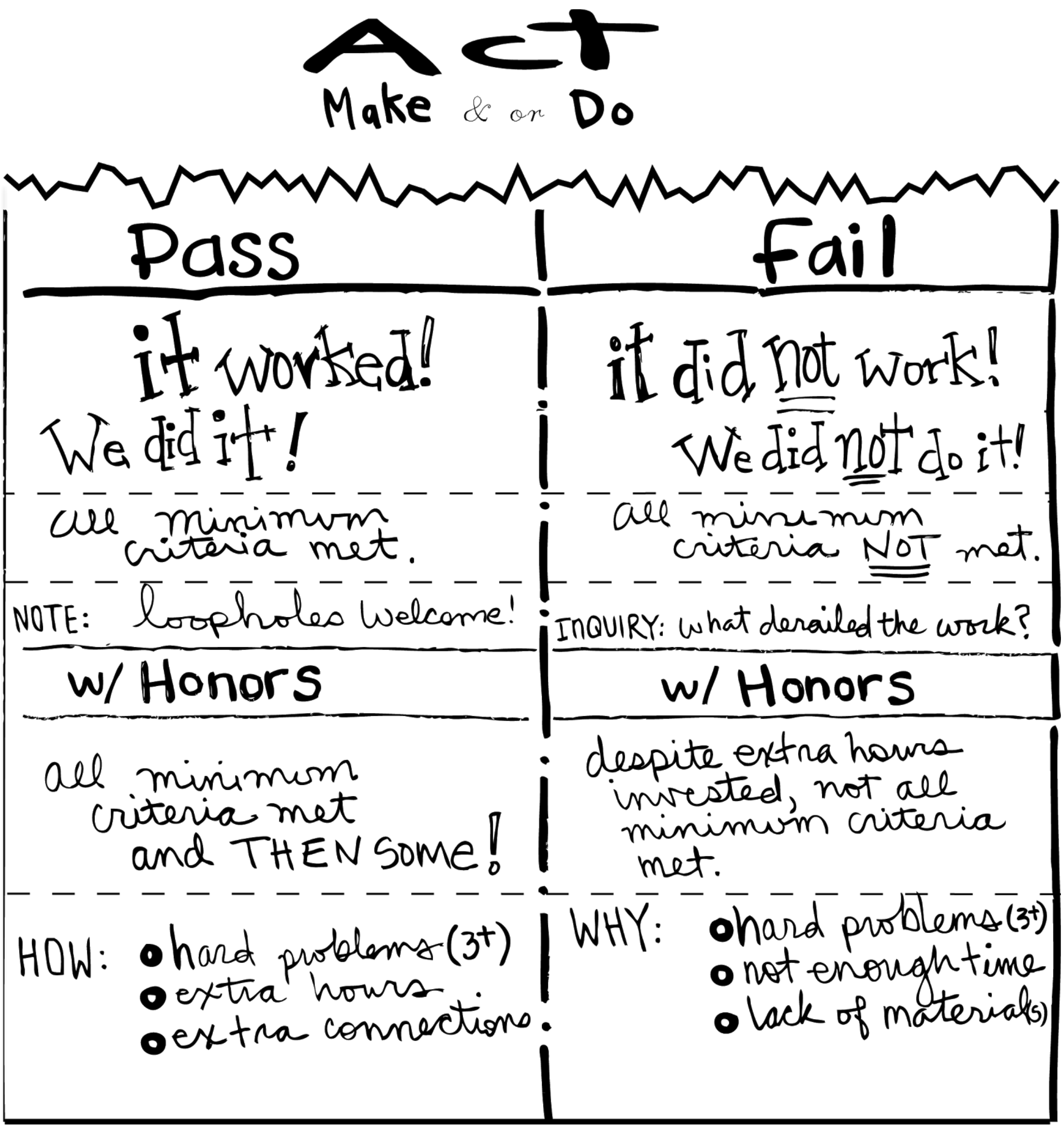
[IMAGE] Example 2: Self-assessment rubric for team membership, phase one of HERstory project, 5th grade PbS at Hillbrook School.

The Pass or Fail Grading System

When a project ends, or we run out of time in the school year, students are required to submit their formal grade for their project. This is shared in the form of an argument outline, written or vocal, in 5th grade and as a formal persuasive essay in 6th. These writing assessments were designed to mimic the work students would eventually due in 6th, 7th and 8th English, as well as a more traditional lab report in 7th and 8th Science. The four designated "grades" that students have to choose from are *Pass, Fail, Passing with Honors or Failing with Honors*. Passing looks like following all of the rules of the game. Getting a ball to move from A to B. Easy enough, depending on the difficulty to build and fix the design of the solution. If a student picks a solution that is a Level 3 problem, or hard problem, they may run out of time, no matter how hard they work, including coming into the iLab at recess or after school.

This amount of effort often warrants the most coveted grades of all, *Passing or Failing with Honors*. Failing is always a good conversation to have with a student. Most often they see the habits or mindsets that resulted in their failure, rather than argue the difficulty of the solution they picked. This kind of failure is just something that happens when learners enter a self-directed learning space for the first time, such as the Fall of the new school year. More importantly, no one ever claimed a grade of Fail in the Spring. Once a “grade” is chosen, a student then describes and submits all the evidence they used to make their decision. This can come in the form of images, email correspondences with mentors, daily logs, and words (on paper or video) explaining why they feel they gave themselves the grade they chose. This assessment is really testing their reasoning skills and their ability to communicate their own learning. If a student can share their learning effectively they get full credit for their argument, no matter what “grade” they gave themselves.

[IMAGE] Pass/Fail grading system



Public Showcase

Showcasing work publically is a healthy form of external reward, allowing others to learn from and get inspired by a student's hard work. Having a real audience can provide powerful motivation for students when doing challenging projects, whether building a robot or writing a short story. When the teacher is the only one assessing work, then the work students do can feel fake. Sharing work publically makes the efforts that students undertake seem more valuable to the maker/scientist. Showcasing student work can be done on a small local scale, in a classroom peer critique or much more publicly, such at events like a Maker Faire. Students also have several online options for sharing their work including blogs, websites, Instagram and similar social media outlets, as well as sites like Instructables and YouTube, where they can publish how-to guides of their projects.

[IMAGE] In class, all school showcase of 3D Selfie Project (Materials-Structures Unit) Fall 2015.

[IMAGE] A student is sharing the design and testing of his team's trebuchet at the Bay Area Maker Faire after the spring hard problem of 2015. His design was based on the need for a prototype "danger playground" on our school's campus. The playground/outdoor classroom taught the joy and respect of self and others that goes along with building dangerous toys/tools.

Bringing Assessment together into a Maker Portfolio

A portfolio is an analog or digital (also known as electronic or e-portfolios) collection of student work, which has been intentionally selected to either represent the learner's capacity for growth or to highlight a student's best work for public showcase. If the portfolio functions primarily to document the learning experience (as formative assessment), this is called a working or "process" portfolio. If the portfolio contains only a selection of best work for public sharing (summative assessment), this is called a final portfolio. Public sharing of a portfolio can range from peer-assessment activities, to student-led conferences, to applications to high schools and colleges. (Lombardi, 2008)

PbS assessment is based on multiple artifacts collected in a personal or team portfolio. Students actively construct their own portfolio, as well as assess their own work for placement into their portfolio. When students are involved in their own assessment, it puts them in control of their own learning goals, and what might need to be learned next. (Valencia, 1990) Portfolios are valuable for a makerspace based program because no other form of assessment can chronicle the process of invention, tinkering, researching, self-assessment and making the way a portfolio can. In PbS, we use portfolios along with peer-assessments and capturing their growth over time. For more on the use of portfolios to assess making in schools, please see the research report called the Open Portfolio Project, put out by the Maker Education Initiative.

[Table] The Power and Limits of Portfolios

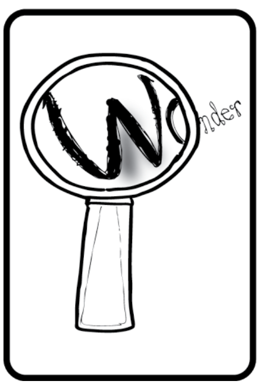
Power	Limits
Merges learning and assessment; making, diagnosis, critiquing and communication	Takes time to teach students how to create high-quality portfolios
Gives a more diverse picture of a student as learner, formative and summative	Quality can be subjective unlike numerical scores
Students work collaboratively through peer critiques, self-marketing or storytelling	Needs an audience (who will validate this form of assessment for students; conferences, admissions)
Can be digital or analog or a hybrid of both	Digital work needs to be in a universal format and owned by students (e-portfolios are technology dependent) and analog portfolios need to be stored with student access in mind

Observations: What do Students Learn in PbS?

Below is a synopsis of the observations that I made of student learning while working in the iLab using a curriculum based on making and engineering and self-direction. These findings are broken into three parts. Part one is the general modes or tools used in a makerspace when students construct their own scientific literacy. Part two lists the mindsets and habits (real work) students employ and practice while inventing, tinkering and learning science in a makerspace. The third part describes the set of antidisciplinary units used to expose learners to certain science and math content through constructivist acts of informal exploration and formal research.

3 Tools for Constructionism in Science

During this iLab study, students were observed applying three tools or modes for gaining science literacy in a makerspace. These tools all allow students to practice their creativity and building skills. The tools were inquiry (including exploration), inventing or innovating, and making models. In the real world, these tools are just paths of learning that are colliding all of the time. When practicing constructionism in science, you will see these tools collide and collaborate naturally, allowing your students to experience a richer, more diverse kind of science literacy.



INQUIRY

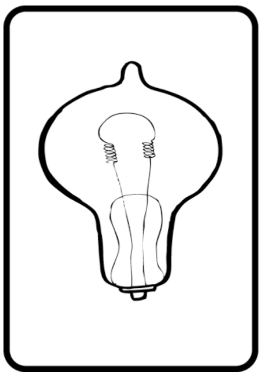
Asking questions or exploring to gain new knowledge or deeper understanding

When students ask questions about what they observe in their environment they are often challenged to design tests that will help them to gain answers to their inquiry. Many real world scientists are also inventors who make their own tools to facilitate inquiry.

Constructing one's own scientific literacy through inquiry follows from asking questions about how to solve problems, fix, make or in many cases break something. Below is a list of a few of the inquiry behaviors that may take place when students learn science this way.

- **Deconstructing -** Inquiry through taking old machines or toys apart just to see inside or to harvest parts for new 'what if' scenarios.
- **Prototyping -** Inquiry as putting prototypes to the test, noticing connections and patterns and developing a sense of observation that can be refined and used in future investigations.
- **Free Exploration** - Inquiry happens when you put out various types of materials, from marshmallows to LEGOs, in the spirit of Reggio Emilia, then step back, give learners the time and space to explore, while you as the adult observe what materials and questions your students engage with.

- **Tool making** – Students who make their own tools, such as microscopes, hand lenses from e-waste, or robots with cheap and easily accessible sensors understand how they work better, and in turn, use them more effectively and with deeper understanding.
- **Testing** - Inquiry in a constructionist setting looks like testing materials by dropping, burning and sending currents of electricity through them, while learning how to test safely. This style of learning sometimes requires goggles, gloves and a nearby burn kit, but it is worth it. Through their questions and testing, learners are able see the inherent beauty of the “unique voices of stuff” (Justice and Riley, 2016), also known as the physical and chemical properties of matter.
- **Measuring, collecting data** and **active research** - Inquiry is seen when students design and give surveys, interview, or simply measure the distance of how far an object of their design moves. Modern tools and sensors can help extend student perception, and allow for more precise analysis of the world than traditional science equipment.
- **Passive research** - Inquiry might also come when a known answer to a question can be found when students use available literature and media sources to discover how to do something. This is basic information literacy such as finding reliable webpages, searching library databases and decoding scientific text.



INVENTION

Designing and making innovative artifacts that meet needs in the real world

Going through the process of design and invention is a form of exercising the scientific process as well as applying concepts in math and science. In the act of inventing new ideas or artifacts, students brainstorm, observe, build and test. Young inventors also gain a sense of how their ideas and actions can make a difference in the world.

Invention and innovation in a science classroom are expressed in all the ways that student exercise their creativity. There are the obvious ways: following a specific design process, or asking students to invent something useful in the world. But beyond these, invention can be woven into the classroom in many different ways. Below is a list of activities or behaviors learners will practice when inventing in a science classroom or makerspace.

- **Playing** - Just playing with materials is a form of creative expression for most children. When the adult rules are left out of the equation, creativity will take over. Taking part in creativity games that force you to devise as many novel purposes for an item in a set amount of time is a way to practice the skills of an inventor. Games and exercises, such as improve games that support creative thought should be employed to set a model of how to share ideas safely.
- **Tinkering** – Tinkering, like play, is an avenue for creativity, but slightly more structured. In the classroom, tinkering should be productive but not directed. The mindset of tinkering is determined and focused, with an attitude that if I don’t know how to do something, I can figure it out using all the tools at my disposal, including my brain, my friends, my teacher, and the world around me.
- **Brainstorming** – Like play, brainstorming should be high energy, and safe. Students brainstorm when they spend time coming up with lists of ideas for their project or for a solution.
- **Hacking, re-using, upcycling** – Seeing opportunity in waste is a form of creativity. Projects sometimes fail, seeing the usable or reusable wood, lights, motors, etc. from old projects, understanding and utilizing e-waste are all forms of creative resource management.

- **Creating** - Whenever a student makes something that did not previously exist such as art, music, stories, code, a game, that learner is using creativity. Even when learners study a model for how to make something when learning, this will aid them on the path of iteration and innovation.
- **Finding loopholes** – When you use a prompt for a project, students will begin to find loopholes in the rules to foster even more creative solutions.
- **Non-conventional acts** - Sometimes invention looks like using a tool or material for something that it is not intended for. Or using tools to make new tools. When this form of novelty poses a danger, discuss the physics behind the danger while still encouraging the act of novelty.

MODELING

Creating effective, compelling representations of scientific content or concepts

The most common form of making in science is the making of models that represent known concepts and content. Creating models that communicate effectively is a form of making thinking visible that allows for the integration of many making skills, including the use of programming and the sensory tools of the artist.

Making models is a skill of necessity demonstrated by real scientists all throughout history. All too often in a school setting, however, we default to purchasing models to teach concepts rather than create them ourselves. Modeling a maker mindset for your students by creating your own models and having students generate their own models is just good practice.

- **Explain your work** - In science we often ask students to show how something works or the results of their testing using posters and presentations. This is a good skill for students to learn, whether at a science fair or a Maker Faire.
- Make a **diagram, blueprint, sketch or drawing** - All two-dimensional models are a form of art that help students learn the structure of things. Drawing models of organs, the life cycle of rocks or plant and flower parts is a historically scientific act. Add the skills of scale and accuracy, and students will find that the things they make with their hands more resemble what's in their heads, making thinking visible for both students and teachers.
- Make a **prototype to scale** – Testable ideas begin as material prototypes in most makerspaces. Making a small-scale model of your intended project allows learners to get their ideas into the tangible world quickly. This kind of modeling also allows for any obvious problems in the design to come to the surface early on in the design process. Using Computer Aided Design (CAD) software comes with the added benefit of being able to iterate your design.
- **Program a simulation** – Many software tools exist to give students experience with dynamic systems. Using tools as simple as Scratch and Minecraft can give younger learners an appreciation for the power of computer science and communicating science well.
- **Make a conceptual model** – Not all models need to be to scale. Sometimes a physical or digital representation of a concept or plan works best. When learners use creativity and available materials they learn to communicate and think with things more effectively.
- **Mentor someone** – Teaching others how to use a tool or how to solve a problem is role modeling. This behavior is a large part of creating a learning community that is collaborative in a makerspace. This kind of leadership leads to identify formation in learners. I have even seen students make signs for "clinics" they wish to offer their peers in skill building, such as soldering.

- Make an **infographic, or data visual -** Whenever students are asked to collect data they are also challenged to make a visual explaining their data to others. This comes in handy when using survey design to collect data to find needs in a community during design projects or when testing the distance a trebuchet throws its ammunition.
- **Design a scientific test** - By creating a test with a known procedure to answer a question, students are making a model of how to look at their world. This model is called the scientific process.

Mindsets and Habits

Problem-based Science emphasizes practicing the kinds of mindsets and habits that real engineers and scientists use, such as working collaboratively, in a self-directed space, to solve real problems. Problem-based science is not designed to deliver standardized content, but rather to structure the learning environment to encourage self-discovery of concepts that are important to the world of science, engineering and design. Students apply knowledge they already know and gain new knowledge in the context of solving a problem. During this time students are practicing mindsets and habits that feel like doing real science and engineering, scaled down to the middle school level. To better understand what I was noticing during science in a makerspace, I gave student entrance and exit surveys. These surveys were use to gauge attitudes about making, as well as determine some of the benefits of using this curriculum.

The following table is a list of mindsets and habits revealed by the surveys, as well as classroom observations of students making and learning science full time in a makerspace. These mindsets and habits have been further organized (left hand column) by the benefits (agency, creativity and cognitive growth, constructive autonomy, and supportive learning community) they confer upon the constructivist learner in science.

[TABLE] Benefits to Learner - Mindsets and Habits of the Scientist/Inventor

Benefits to Learner and Community	**Mindsets** "I am willing and able to…"	**Habits** "I practice…"
Agency	See complexity in materials, structures and systems	• Slow looking/observation of objects or systems • Inductive reasoning
	See problems and needs that can be fixed	• Slow looking/observation of environment, empathy, listening, diagnosis
	Ask questions and Explore	• Testing ideas and prototypes • Measuring, Calculating formulas • Gaining literacy from various available sources
	Take risks	• Learning new skills, tools, sharing ideas, showing leadership (earning new badges)
Creativity and Cognition	Think creatively about multiple solutions	• Brainstorming • Improving on ideas, designs and solutions based on feedback, research and testing
	Make my thinking visible	• Drawing blueprints, making data visualizations and models to explain an idea
	Connect the dots	• Recognize the relatedness between disparate ideas • Analyzing data for patterns and anomalies • Form claims and conclusions based on evidence
	Think with my hands	• Making prototypes, build, tinker, assemble, disassemble
Constructive Autonomy	Self-direct my learning and work	• Setting learning goals, making agendas, making process maps, exercising resilience and determination
	Use assessment and feedback as part of learning	• Data collection • Documentation of work, self-reflection • Giving and receiving feedback
Community	Be better together	• Mentoring • Partnering with peers, adult mentors, and experts to give and receive feedback on work • Giving credit where credit is due • Sharing work • Sharing diverse perspectives, ideas and criticism

The Antidisciplinary Units

Materials Patterns Structures Systems Problems

simple <-->complex

In addition to the above mindsets and habits, learners are exposed to scientific and mathematical content knowledge, and even ethical issues, using the lens of thematic or antidisciplinary units. The units will be explained in much more detail later and include the following themes: **Materials, Patterns, Structures, Systems and Problems.** The units are based on big ideas in science or essential questions, instead of specific content, such as rocks, the human body, density, etc. The units are open-ended enough to be applied to traditional STEM topics at any age/grade level and in collaboration with the humanities, math and the arts.

When a focus is paid to thematic units, you can hone in on skills and problems that allow students to construct their knowledge in specific fields or domains of science. More importantly perhaps, each student's curriculum will consist of what he or she is passionate about, or what ever inspires their designs. To make a unit more interdisciplinary, I simply added a prompt to encourage historical research, interviewing, art work or writing.

As the facilitator, you can choose the degree of content detail, technology integration, and design challenge difficulty. I used these tables not as a strict textbook or how to, but as a general guide to share with parents and other adults, to aid them in understanding the science behind making, inventing, tinkering and fixing in science class. Writing this longitudinal research report is also an act of sharing what happens in the classroom with parents, as much as with teachers, artists, scientists, or administrators. The most important thing to remember is that **science is a natural consequence of allowing children to explore with materials and problems in the real world**. Having your students design and make their own learning in science is really just a clever and clear prompt away.

Below you will see the specific lens through which I used the units for a 5th and 6th version of Problem-based science. Typical avenues of inquiry and exploration that arise from a focus on these units are written at the top of the chart. Concept knowledge that students were exposed to through their own inquiries and explorations in PbS included; measurement, types of patterns, forces and energy, basic electronics, three dimensional geometry, and more. This constructed knowledge is listed below inquiry. Ethical issues that arise when solving problems are listed as well to look out for. Next in the chart is the list of habits and mindsets practiced, given our focus on making in science. The exact prompts used for each unit from the above timeline are listed in full detail. Below the summary information in the tables is an anecdotal review of what I learned from using these units for four years.

The Materials Unit

Materials	Material Science, Asking Questions & Safe Testing
Inquiry & Exploration	1. What are materials made of? 2. How can we describe materials? 3. How can we categorize materials? 4. Where do materials come from and where do they go? 5. What makes a material good for make something?
Knowledge	• Atomic Theory, Categories of Matter • The Law of Conservation of Mass/Energy • Physical and Chemical Properties of Matter • Decomposition, Biodegradation, Organic and Inorganic
Ethics	• Sustainability and Resource Management • Exploring and testing without causing harm
Habits	Testing (flammability, acid, conductivity, density), Research, Sketching, Building, tinkering and deconstructing, Iteration, Documentation, Peer and Self-Assessment, Observation, Data Collection, Mentoring, Giving credit, Sharing work
Mindsets	Think with your hands, Ask questions and Explore, Take risks, Self-directed learning and work, Assessment and feedback are part of learning, We are better together

Problem Solving Challenge “The Prompt”	A. Answer as many questions about 3 simple materials or one complex object before X date. Teach at least one of your peers everything you have learned about your material investigation. B. Create a self portrait using (X)% or more of your chosen material

How often do you take the time to examine the materials that the world around you is composed of? It is not a practice that we are accustomed to doing consciously. Once we learn the names of things - that stuff is plastic, that is metal, that is wood - the examination of a material tends to stop there. We avoid any deeper dive into the nature (chemical, physical or aesthetic) of materials until we reach high school chemistry class. By then, materials have long since been ignored and materials are examined through the lens of the abstract, such as density, atomic mass and propensity for ionic, covalent or no kind of bonding at all. By removing the aesthetic from materials in science, we lose what can be a precious spark for inquiry, but early childhood education experts and artists have known this all along.

Practitioners of early childhood education and art would argue that introducing children to the world of materials as early as possible through open exploration and art, is key to fostering and valuing a place of inquiry and self-discovery. Since the 1960’s the preschools of the Italian town of Reggio Emilia have mastered the use of materials, light and color to invite children's questions and curiosities (Strong-Wilson & Ellis, 2007). Learning theorist Loris Malaguzzi, developer of the Reggio Emilia approach to education is perhaps best known for championing the benefits of exposing children to the material and aesthetic world. By bringing in elements of the natural world, such as redwood tree bark, shells, pine cones, etc, along with filters for color and light play, Reggio inspired classrooms present us with the best example of how to use materials and art, as a wellspring for inquiry. From Reggio Emilia we learn that inquiry arises quite naturally when children form relationships with natural materials and learn to hear the particular voices of stuff.

By voices we mean properties, from a strictly scientific point of view. In a helpful makers book called Making Things move by Dustin Roberts, a material’s property “is just something about the material that is the same regardless of its size or shape” (Roberts, 2011). Properties that make stuff good or bad for making objects with might include how easily the material breaks under stress or heat. Properties might also include how hydrophobic or flame retardant a material is, or whether it conducts electricity. All of these properties are easily testable by learners of all ages in a controlled setting.

Every year of problem-based science, the 5th grade was introduced to the Materials unit. As this happens at the beginning of the year, it is a good time to allow for a lot of open exploration by students. Placing materials out and giving students time to play with them will result in natural inquiry and making by learners of all ages. This activity can be done in a very structured and facilitated manner such as giving all learners the same bag of materials, say toothpicks and mini marshmallows, and observing what they make and notice about their materials. You can also put out all available materials, level 1 to 3, including parts of circuits and building toys, then observe what child is attracted to what kind of material.

I have also structured the Materials unit by asking students to chose one kind of material and use it to construct a self-portrait. This project allows students to discover the constraint of materials when building. This project also allows you to introduce the power of iteration and peer feedback. Once Materials have been introduced, students will continue to use their knowledge of material science all through out the units.

[IMAGE] acid testing deconstructed electronic parts raises lots of new inquiry. [IMAGE] materials + humans = making, this exploration led to a mixture of materials chosen for their distinct properties.

[IMAGE] Flame testing materials is a popular activity for gaining a sense of the different chemical properties of matter.

The Patterns Unit

Patterns	Logic, Observation, Data Collection/Analysis
Inquiry & Exploration	1. What is a pattern? 2. How do we "see" or detect patterns? 3. What can patterns tell us? 4. What is a break in a pattern and what can it mean?
Knowledge	● Experimental Design ● Quantitative versus Qualitative Data ● Mathematics: Ratios, Tessellations, Percentages, Averages, Rate, Angles, Fractions, Decimals, F=MA, G.P.E. = m x g x h, Symmetry ● Code/Logic/Cyphers
Ethics	● Safe experimental design ● Benefits/costs of using patterns ● Use of code during war
Habits	Slow looking, Sketching, Analyzing data for patterns and anomalies, Forming claims and conclusions based on evidence, Peer and Self-Assessment, Making Blueprints, Making clothing patterns, Making music, Data collection, Testing, Measuring (distance, mass, forces), Calculating formulas (force, averages), Building, tinkering, Making data visualizations, Making floorplans
Mindsets	Ask questions, Take risks, Think Creatively, Think with your hands, Self-direct, Assessment and feedback are part of learning, We are better together, Connect the dots

Problem Solving Challenge "The Prompt"	A. Make something that measures something or represents an known measure ("measurement mascots") B. Create a secret code based on a historical reference, using two or more disciplines (s.t.e.a.m.), then make something that will deliver that secret message C. Make something that can keep an egg safe from gravity ("egg drop")

Patterns exist in the universe with or without humans to perceive them; humans just happen to be especially adept or fond of perceiving, describing and creating them. At its most rudimentary, pattern recognition starts as an innate recognition of and keeping to memory of “if, then” scenarios. Take into consideration how quickly someone learns that if she touches something hot it will cause severe pain to the skin. Pattern recognition can be a survival mechanism, but it can also be as elegant as composing a symphony or crafting an unbreakable military code.

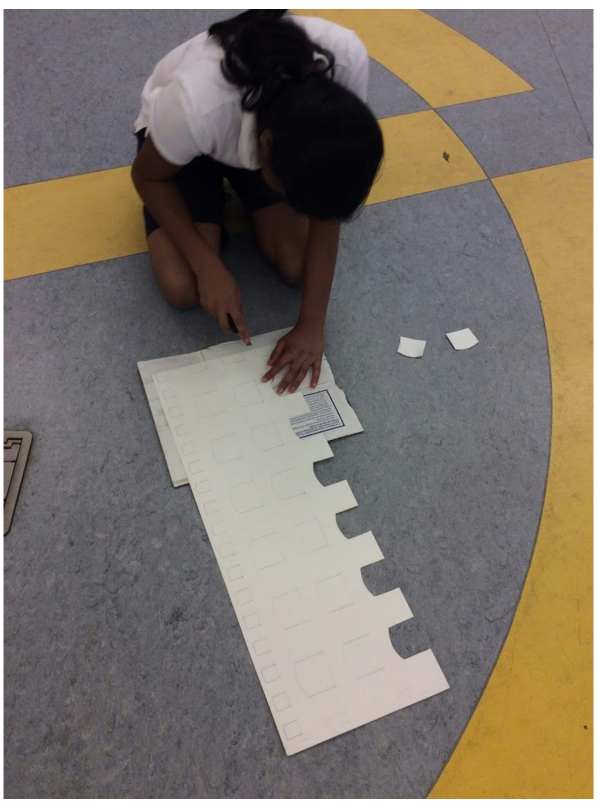
Settlement and human economics created a need by early humans to find a fair model for trade and commerce. This led to the development of weights and scales (Radiolab, 2014, BBC 2015). The concept of land ownership would force us to develop an agreed upon method for measuring the area of land, leading to the development of standardized forms of measuring distance (BBC, 2015). Most early standards of measurements of weight and length would be based on laughably subjective models, such as the length of a king's arm or the mass of a certain number of grains of wheat. It would not be until the Age of Reason, the birth or science and French revolution during the mid-1700’s that the world would adopt a more universal set of standards we now call the Système International or the metric system (Radiolab, 2014, BBC, 2015).

When humans began looking to develop the technologies to explore space, even more precise methods of measuring became eminent. Using the distance of the Earth from the equator to the poles or mechanical clocks, would no longer suffice. We would look at the wavelength of light to establish the most accurate version of a meter ever used. In similar fashion, our method for keeping time evolved from dripping water buckets to the more universally precise oscillations of Cesium atoms. Using the natural patterns of the universe to make our systems of measurement more precise have in turn allowed new advancements in technology and civilization to flourish. Whether this is a good or bad thing, remains a worthy debate to have when teaching measurement in school. Most science classes contain at least one lesson on measurement, why not have students develop their own and use this method to accomplish a goal. In making their own forms of measurement, they will perhaps grow to appreciate the efforts made historically to arrive at the systems we use in science today.

During our Patterns unit we focus on identifying and making patterns. We learn the importance of pattern recognition as well as the significance of an anomaly, or break in a pattern. Why is novelty important? While an anomaly can have a negative connotation, novelty is defined as something new or innovative. Novelty reveals something, well, novel, that we weren't expecting to see. It triggers some ancient part of our brain that should fear or examine novelty for potential use or threat. Like the anomalies in this w**O**rd, novelty tends to catch our eye and create a sense of interest or intrigue. Exposure to novelty can be its own intrinsic reward, as it has been found to help produce dopamine and increase learning potential. Furthermore, novelty illustrates that there is an ever growing frontier to what we can know and understand as individuals. Novelty, therefore, can generate hope that there are solutions to problems, technological or behavioral, that we haven’t yet thought of.

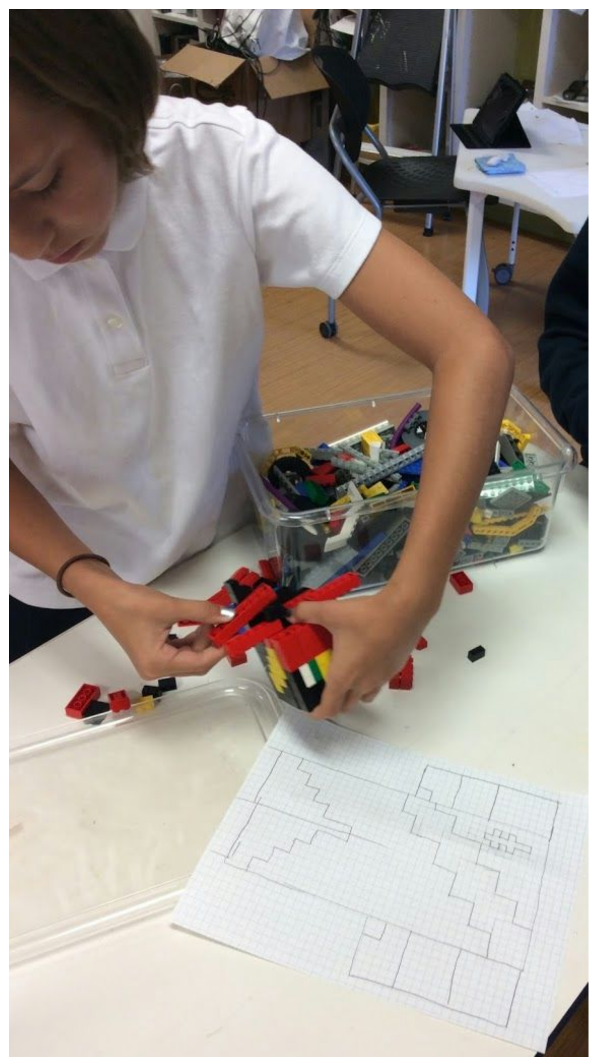
In class we discuss anomalies as being the sign of potential danger, disease or damage. For instance, random genetic anomalies, more often than not, result in a deleterious genes, not the next great evolutionarily advancing trait. We also discuss the importance of death, disease and other seemingly bad anomalies as playing a vital role in overall change that is good, such as social revolutions and adaptation to a changing environment. For the open minded, an anomaly is not a certain threat, but a novelty that spurs inquiry. Interestingly, differences in learner's tolerance for difference may be explained by studies done by Dellu et. al., which suggest that novelty seeking behaviors may be at least partially genetically determined.

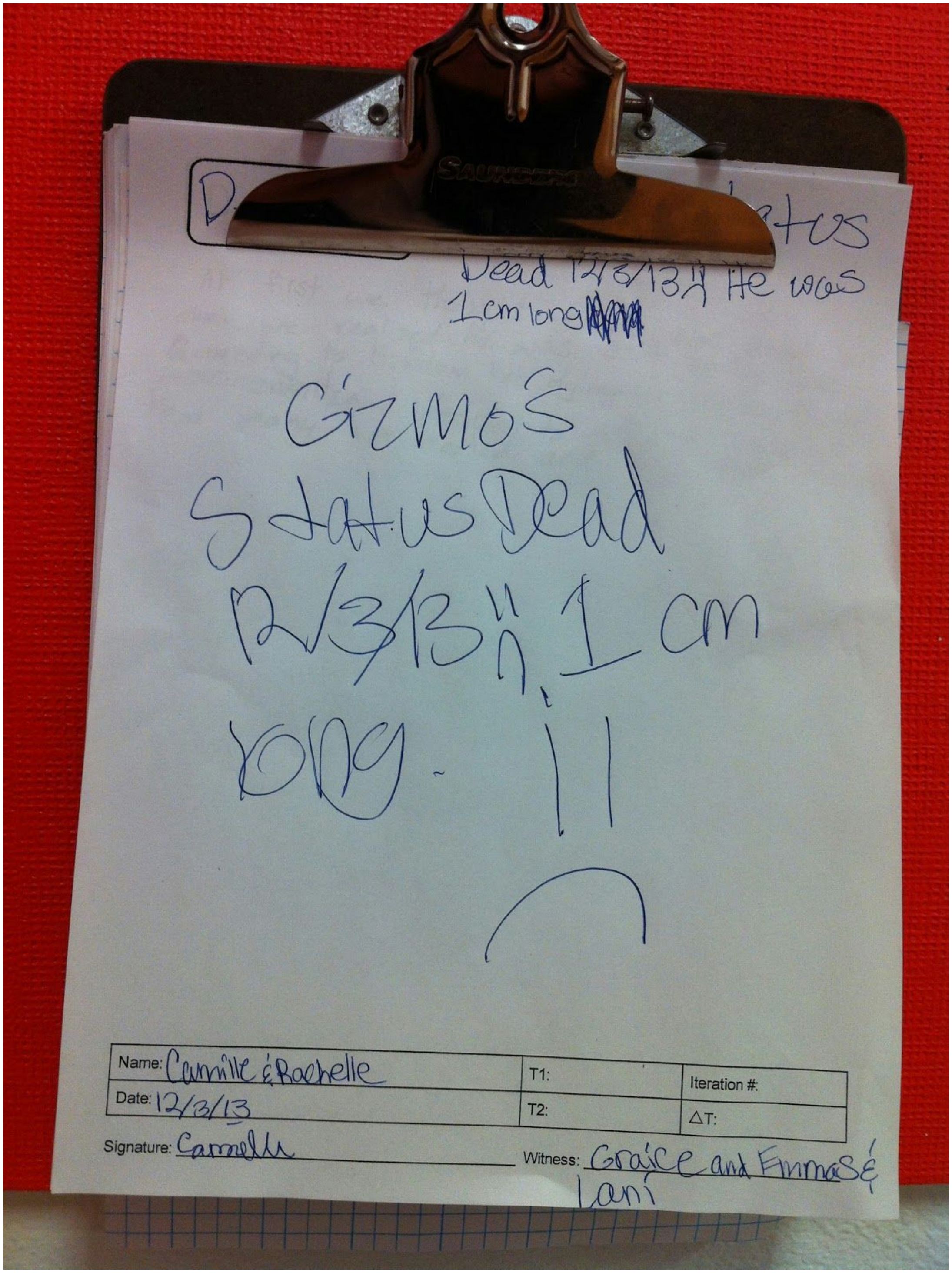
During a focus on the Patterns unit, I experimented with open making and pattern finding the fall of 2013. During this exploration students were asked to measure something through inquiry or making something. To have student recognize patterns, they were asked to record their observations or make scaled blueprints for anything they wanted to make. In the fall of 2012 and 2014 I experimented with giving my students prompt B and C from the above table. These more teacher directed prompts were also really fun and allowed the use of specific equations or historical research. The only significant difference between the patterns that the students generate during free exploration and those that we as teachers provide as prompts, is that the students becomes the designer/owner of their pattern, and that is a powerful initial condition for learning.



[IMAGE] Scale model architectural projects in 6th grade are ideal for blending materials, with structures and patterns.

[IMAGE] Blueprints are patterns, as in this LEGO (plastic) based 3D Selfie project in 5th grade. This project was a bridge between Materials and Structures, but patterns are everywhere. This design is based off of a Minecraft skin.





[IMAGE] The dead results of one open exploration exercise for Patterns in the fall of 2013. Students were studying the growth of butterfly larva.

The Structures Unit

Structures	Physics & Engineering
Inquiry and Exploration	1. What is a structure? 2. What makes a structure sound? 3. What kinds of structures are there? 4. How is structure related to function?
Knowledge	● Parts, Purpose, Complexity ● Balanced Forces, Load ● Basic carpentry ● Bridge Design and Construction ● Mathematics: Mass, Averages, Scale, Angles, 3-Dimensional Geometry
Ethics	● Safe structures for real loads ● Voiding warranties
Habits	Spatial reasoning, Measurement, Making blueprints, Making floorplans, Making scale models, Hand and power tool use, Temperature probes, Data analysis, Budgeting, Prediction, Basic carpentry, Evidence based reasoning, Peer and Self-assessment, Building, tinkering and deconstructing
Mindsets	See the parts, purposes and complexity of structures and systems, See problems and needs, independently or with others, Ask questions and Explore, Think creatively, Think with your hands, Take risks, Self-direct, We are better together

Problem Solving Challenge “The Prompt”	A. Create a 3Dimensional self-portrait using 80% or more of one material. B. Build a bridge with paper that can support the most amount of pennies.

The simplest structure is a three sided figure. A triangle is called a truss in architecture and engineering. A structure considered to be beautiful is the circle, perhaps because of its inherent symmetry and efficiency. These facts are significant because the beauty of thematic units is the ability to deconstruct and then reconstruct bridges between different fields of knowledge. Structures can be the subject for engineering, biomimicry, poetry or the structure and function of cells. Using the Structures unit is a way to discuss physical, earth and life sciences in a manner that connect the dots between what makes a structure sound and how function relates to structure, a major theme in science. The Structures unit is literally about building bridges in math and science class to learn about basic construction, the benefits of materials and forces acting on structures.

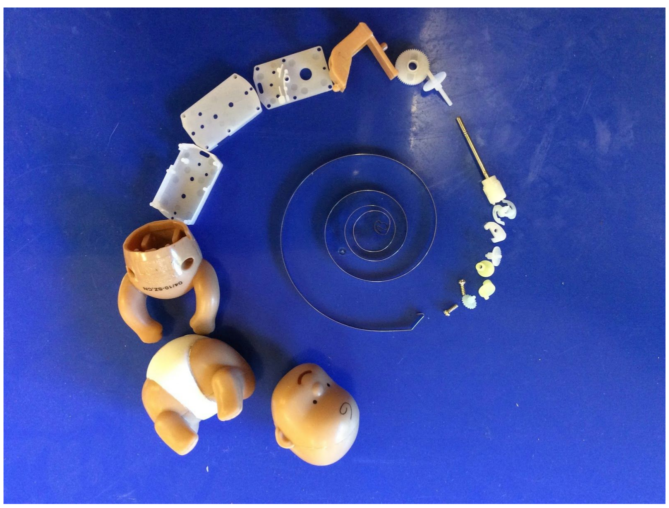
Structures are often more complex than a circle or triangle with can be defined using lines and points. Some structures have built in complexity. Structures are often parts of more complex ideas, such as systems. This makes Structures and Systems natural partners in any project design. Structures also pairs well with Materials, as any structure can also be defined by the materials that make it up. This is where the use of a powerful thinking routine becomes useful.

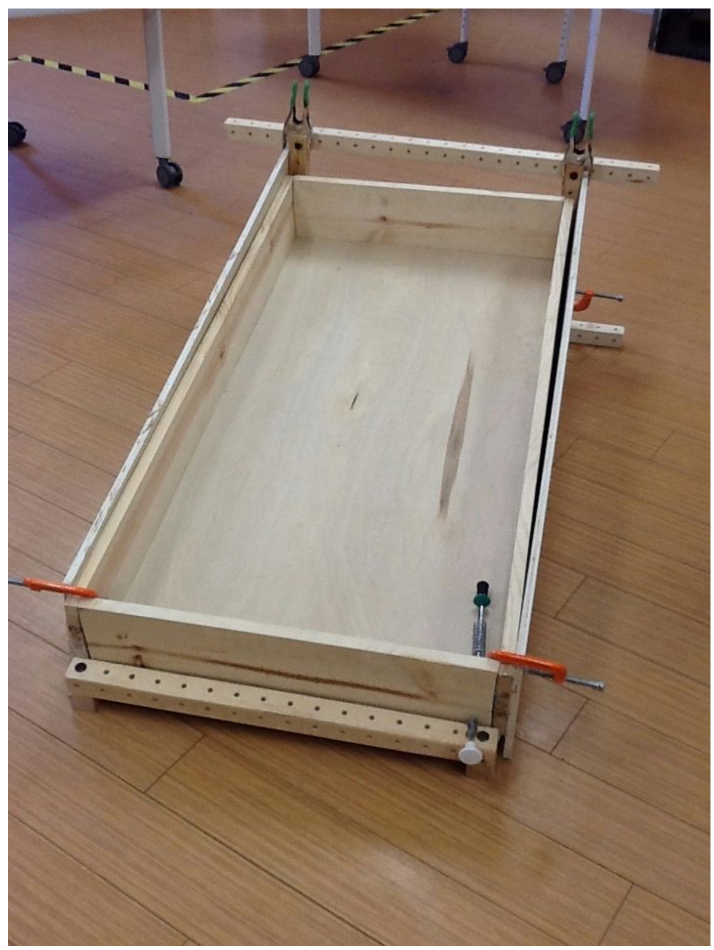
In the 1960's Harvard began an initiative called Project Zero to enrich learning in and through the Arts. Began by philosopher Nelson Goodman, and later led by David Perkins and Howard Gardner, Project Zero has evolved into a system of projects and teaching tools that are proving to revolutionize the way we think about thinking, learning and teaching. Thanks to a division of Harvard's Project Zero called Agency by Design, we have a model for introducing Tinkering into the classroom. This model is called Parts, Purpose, Complexity and has learners go through a series of close looking and take apart activities, then articulate their own understanding of how things are made and how they work. From the free pdf. shared by the Agency by Design team, the Parts, Purpose, Complexity activity encourages learners to think differently about everyday objects, "This thinking routine helps students slow down and make careful, detailed observations by encouraging them to look beyond the obvious features of an object or system. This thinking routine helps stimulate curiosity, raises questions, and surfaces areas for further inquiry. (Agency by Design, 2015).

How does the activity work? A student or group of students are handed an old toy or electronic device of some kind. Before they do anything they are asked to examine all sides of their object and name as many parts as they can. Let's say they have a battery operated stuffed animal, they would identify the outer material or fur, the moving joints if there are any and the place where a battery inserts, just to name a few parts. They would then explain the purpose of each of the parts they identified and what might be complex about each of them. The next step is the the really fun step, where learners get to use scissors, screwdrivers and other hand tools to deconstruct their object. The activity becomes intrinsically rewarding as learners feel as though they are dissecting a foreign thing and exploring its inner parts, with their own purposes and special complexities.

This thinking routine begins to make more sense the more you do it, not only as a first hand learner, but as a facilitator as well. This activity lends itself well to discussing material science and resource allocation for the products we use. To add mathematics to this activity, have students weigh their object and compare the different materials that make up their object (all the plastic, metal, fabric, etc.) to the original weight. At the end of the activity you have a completely deconstructed object which leads to several new exercises. If the objects have harvestable motors, gears or other parts, these parts can then be the inspiration for new inventions. Inspired by the Tinkering Studio and the book *Things Come Apart: A Teardown Manual for Modern Living* by Todd McLellan, another activity that learners can take on that will further engage them with their deconstructed object, is to spread and organize all of the disassembled parts into one photographable piece of art.

To have students gain a deeper understanding of structure as it relates to function they can create working, or dynamic system models. Scale models that seek to illustrate only the structure of something are static models. These kinds of models tend to invest their exactness into the size and shape of the model. Working or dynamic models tend to be interactive or have moving parts that make up a system.





[IMAGE] Sci-Art made from the deconstruction of a wind up toy.

[IMAGE] The wooden frame for the pinball machines from our Systems unit. Materials: plywood, steel nuts and bolts, and pine Grid Beams.

[IMAGE] During our bridge between structures and systems, these 5th graders made cardboard automata, a blend of storytelling, art, mechanical and material science.

The Systems Unit

Systems	Interdisciplinary Science
Inquiry and Exploration	1. What is a system? 2. What do systems do? 3. What kinds of systems are there? 4. What makes a system stable?
Knowledge	● Parts, Purpose, Complexity ● Natural versus Artificial Systems ● Equilibrium, Homeostasis ● Agile versus Static systems ● Embedded Systems, Networks ● Flow, Energy Transformation/Transfer ● Mathematics: Rate, Averages, Ratios, Fractions, Decimals, F = MA ● Mechanics, Gears, Torque ● Electronic circuits ● Basic carpentry
Ethics	· Disrupting systems for change
Habits	Evidence based reasoning, Peer and Self-Assessment, Diagnosis, Building, Blueprint making, Building, tinkering and deconstructing, Iteration
Mindsets	See the parts, purposes and complexity of structures and systems, Ask questions and Explore, Think creatively, Think with your hands, Connect the dots, Take risks, Self-direct, We are better together

Problem Solving Challenge "The Prompt"	A. Keep a 65 gram steel ball in motion for x number of seconds, using 2 or more forms of forces, bridging 3 or more forms of energy. Demonstrate design elements that reflect an understanding of how humans will live in the year 3000. Must use a claim, evidence reasoning format to support the Science behind the ART. Build ONE complete system rather than smaller teams separately B. Make something that can move a 75 gram steel ball from point A to B, that uses two or more forms of energy, Connect your structure to another team's to make a chain of alternating A and B inputs and outputs C. Make a moving automata that uses only level one materials (cardboard, paper) and art.

Before beginning the Systems unit formally, my students and I worked together to define systems using the example of the school system. Together we determined that a system has a purpose or solves a problem, is made up of connected and related structures, and systems have a structure or pattern of their own. According to Andrew Zolli and Ann Marie Healy, authors of Resilience; Why things Bounce Back, a resilient system is characterized by being modular, having a tight feedback or sensory system to detect changes in the environment, and conducive to change or evolution. Compare an agile system to a static system. Static systems are strong, no doubt, look at the pyramids, the two party system and the current educational system as good examples of relatively static systems.

Challenging students to create working models that mimic real life objects and systems is a valuable making opportunity in science. Building parts of the circulatory system or a moving joint in the arm, allows students to work with the real life mechanisms, such as pivots, oppositional forces, and fluid dynamics. To build a working model of a limb, students must use materials and structural designs that mimic the movement of real joints, lending to a deeper appreciation of these systems.

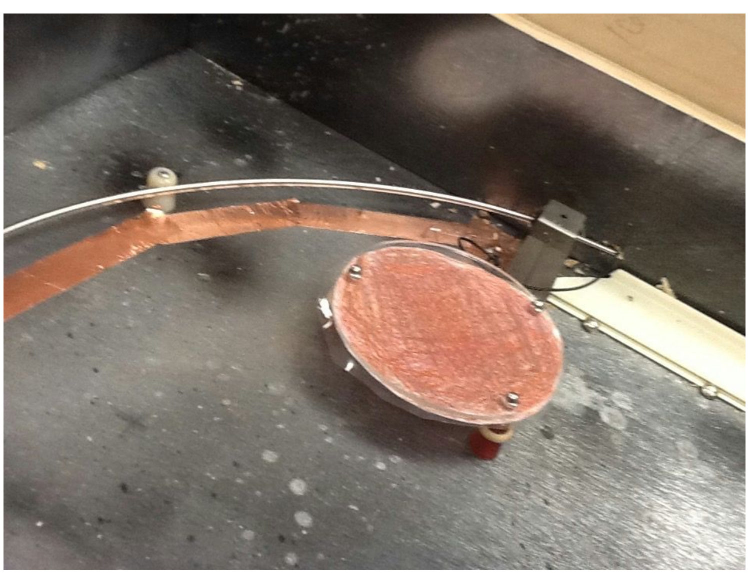
During the Spring of 2013 the 6th grade began studying systems, either food systems or embedded systems in toys. For their final product challenge they need to design a food (edible) or toy (mode of play) that solves a problem. At the same time the 5th grade begun their study of systems by building a "RubeGoldBridge." The **3** rules of this challenge asked students to transfer two or more forms of energy to demonstrate work and model a change in vector. The whimsy built into this project is that students design, entirely what A ---> B looks like. After watching youtube videos of Rube Goldberg projects, they quickly set out brainstorming cool and challenging paths for the steel ball to encounter. The genuine problem of this challenge emerged when students needed to follow the forth or passing with honors rule. There were five teams per 5th grade section and each team's structure had to connect (pass the steel ball) to two other teams, creating a system of systems. Even though the prompt was a Level 2 prompt, it still took hours of debating, iterating, and playing the human knot to get students to work as a teams to pass. Eventually all students became determined to succeed despite the difficulty of the collaborating with a class of twenty, or system of teams.

In the spring of 2014 the Structure and System problem was inspired by science and art of pinball machines. The prompt they were given was letter A from the above table. To solve this problem we began in teams of 4 with a special team of electrical engineers (or the e-team) who had the most experience working with electronics in the first semester. Next we spent a week completing a circuit circus where students mentored and practiced building simple circuits, drawing circuit diagrams, using a multimeter and soldering. Next it was time to get busy building our real pinball machine.

During the 2014 spring hard problem, it felt like the first time that I really took a leap of faith and had no idea what the results would be or if we would all fail. To my surprise, despite what seemed like eminent failure, students were deeply engaged in the process of creating a life size pinball machine. As a special bonus, on March 3rd, pinball mechanic Christopher Kuntz of the Pacific Pinball Museum generously donated one working vintage pinball machine to the iLab for inspiration and research as well as non-functional machine for students to harvest parts from. With a working set of flipper motors and tons of faith, we embarked on our spring hard problem.

After a time of team fluidity, we ended up with seven different teams across each of the two 5th grade class which had coalesced based on passions to solve specific problems for the class game. We had teams of electrical engineers making the score boards using LED's, Arduinos to process triggers, and systems of motors that will interact with the steel ball in the play field. A team of structural engineers built the frame. An art history and research team researched the science behind the games artwork. Mechanical engineers worked on the launcher mechanism and bumpers. Teams of students learning how to use CorelDraw worked on the laser cutter filling orders for all of the teams. There were two sound engineering teams using Makey Makeys and two scoreboard teams using Arduinos working with parent and electrical engineer Mr. Tuckler. We also had a grand parent named Mr. Patterson, a retired electrical engineer working closely with the solenoid motors used by the flipper team. When Mr. Patterson did not know something he Googled the part number for the vintage parts he was trying to help us install. He would show up in class the next day with electrical schematics, demonstrating what real life long learning looks like.

By May, two full sized machines were about 80-90% built. One machine had an art theme of exploring the stars with laser cut stars glued to the sides in patterns of real constellations. The second machine had a global warming theme, where humans in the year 3000 were living under the sea. One machine was up and running for Maker Faire weekend and survived thousands of plays with only a few needed adjustments every now and then. The second machine never got finished and was on display only during Maker Faire. Because the machines were large, they could not be stored on campus if students could not maintain them so they were deconstructed and their materials used for other projects in the iLab. The pinball machine project was the last time I devoted half a year to a Structures and Systems combo unit in 5th grade. In the fall of 2015, structures and systems resurfaced for 5th graders, when we spent a week making cardboard automata.



[IMAGE] Students integrated a Makey Makey with copper tape and structures in this pinball design.

[IMAGE] Real testing of the final systems design, “Exploring the Stars” pinball machine. Bay Area Maker Faire, May 2014.

Problems	Making for Change, Design for the Common Good
Inquiry and Exploration	1. What is a problem? 2. How are needs or problems found? 3. What is empathy and why is it important in design?
Knowledge	● The Design Cycle (Design Science or Scientific Method); Empathize, Document, Ideate, Prototype ● The Scientific Process (Asking Questions, Qualitative Data, Quantitative Data, Data Analysis, Inductive Reasoning, Communication of ideas)
Ethics	What is “good” design? What are “good” goods?
Habits	Observation, Empathy, Interview, Making Blueprints, Building, tinkering, deconstructing, Testing, Measuring, Calculating averages, Data collection, Making data visualizations, Analyzing data, Goal setting, Prototyping, Iteration, Writing a claim and supporting with evidence, Self and peer-assessment
Mindsets	See problems and needs, Ask questions and Explore, Take risks, Think creatively, Think with your hands, Connect the dots, Self-direct, Assessment and feedback are part of learning, We are better together

Problem Solving Challenge	A. Find a need with an adult on campus, design a solution to meet that need, using only up-cycled materials B. Design a food or toy that addresses a need C. Construct a scale model of a tiny “green” house, based on the needs of a given demographic, use one form of renewable energy to heat or light up your house

Problems are considered the most complex kind of prompt in Problem-based science, because they come from working with others and addressing real-world needs. Problems are defined as needs in our environment and often require designing and engineering innovative solutions to address. Problems are rated on a level of 1-2-3-4, where level 3 and 4 problems are real-world problems. Level 3 problems are hard but can usually be solved by a learner's local network of peers, teachers, parents, grandparents and other available mentors. For a more in depth discussion of problems read section “Level 1 - 2 - 3 Problems or “Prompts” of this chapter.

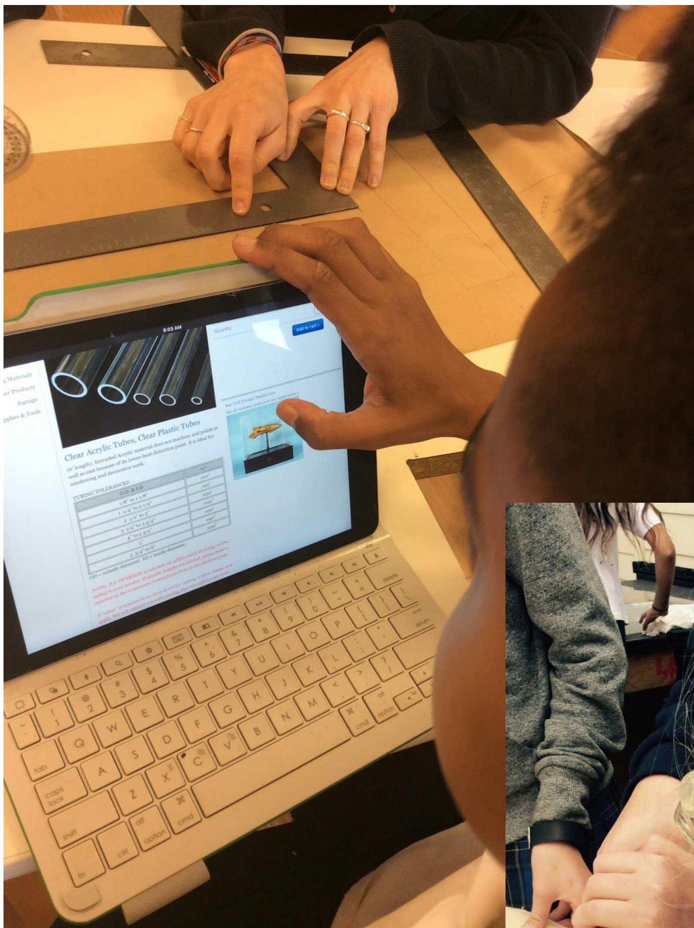
Between the years 2012 and 2014 I kept the Problems unit centered on the 6th grade. This proved to be a rigorous approach to interdisciplinary science beginning with the introductory architecture unit called the “Tiny Green House” project in the fall of 2012 and ending with the “Good Toy and Food Design Challenge” in the spring of 2013. I decided to give the 6th grade the “Good Toy and Food Design” project a second try the 2013-2014 school year. You can read more about this project in the case stories. The 6th grade students kept maker portfolios both in 2013 and 2014. The use of duct tape to make said portfolios was a failure, and we skipped making our own portfolios the next school year. By 2014 I structured the curation of their maker portfolios to hold all of the writing and science knowledge students were making and doing, essentially construct their own textbook for the year. These portfolios included all of the work they did in the fall to interview and determine a need they wanted to address with their design. In the spring the portfolios began to contain prototype designs, peer feedback, self-reflection on sharing their work, and eventually the testing of their prototypes.

When I stopped teaching 6th grade science, I missed the Problems unit, which is really just a design challenge with rigorous documentation. I decided to test using the Problems unit for the spring hard problem the spring of 2015. In the spring students would be asked to apply everything they had learned in Problem-based science during our Materials, Patterns, Structures and Systems units. This was a huge leap of faith once again. Thankfully we had the help of two volunteer mentors and experts visiting part of the week to facilitate some of the projects that required the use of power tools. The volunteers were parent Chris Mackenzie and mechanical engineer Lucas Wilson. This project was called Design Detectives for the Common Good and can be read about in more detail in the case studies.

The spring of 2016 would bring another experiment is using the Problems unit for a culminating project. The 5th graders would be asked to investigate and address a Level 3 and a Level 4 problem. The Level 3 or local problem was to finish the construction of the addition to the Village of Friendly Relations began by the female builders of the class of 2015. The Level 4 problem was a historical and global problem, women's rights and educational equity. The project, named the Hillbrook HERstory Museum, had students in search of a story about a heroine to serve as inspiration for a 10 foot by 12 foot interactive history museum inside the uncompleted structure in the heart of campus.

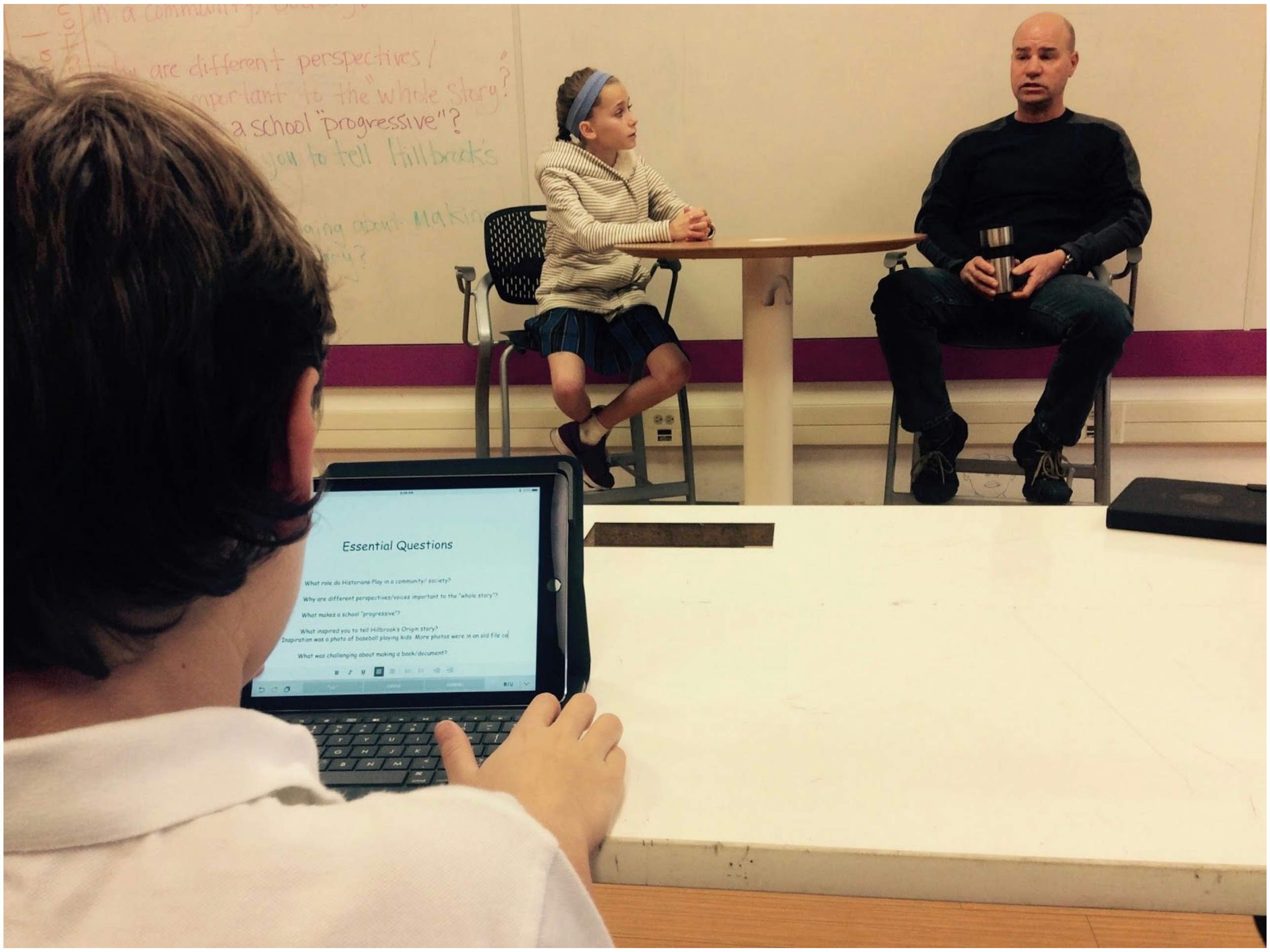
To structure a design and engineering challenge of this magnitude the class of 2019 has been given the following rules to follow. Rule One, work with an adult mentor on campus to research women in history who had a great lesson to teach and form a few essential questions. Rule Two, chose one person who links to Hillbrooks’ history or Hillbrook’s Core Values (Be Kind, Take Risks, Be Your Best, Be Curious) and answer your essential questions to craft a HERstory

that needs to be told. Rule Three, use your HERstory to inform the design of an interactive museum that spans a timeline from 1935-2015, in honor of the school's 80th anniversary. Rule Four, the museum must apply the mechanical arts and renewable energy sources.
Students have arranged themselves into eight teams of 4-5 collaborators to take on one of the eight decades of the school's history. Teams were given all spring semester to complete their research, design and building. To share the journey of this project each team created a website with a blog that could be enjoyed by parents and teachers.



[IMAGE] researching materials from retailers is a form of literacy that often requires applied mathematics.

[IMAGE] Level 3 Tools are a great way to empower young learners. Just the right amount of difficulty or danger is age appropriate in middle school and under very controlled settings, for much younger learners as well.



[IMAGE] Interviewing a historian Paul D’Marco about his journey to document the Hillbrook school’s history in As the Twig is Bent.

Case Studies of Making in Science @ Hillbrook

The following links are a description of curriculum designed and tested by the Hillbrook's science department over the past five years. In some cases, students were asked to make something to learn content or concept knowledge. In other cases, student learning objectives are focused on skills and learning tools or the design process.

- Case 1 Design Detectives for the Common Good by C. Flores
- Case 2 Sound Project by K. Engineer and Jenny Jones
- Case 3 Artificial Limb Project by Brian Ravizza and C. Flores
- Case 4 Good Toy and Food Design by C. Flores
- Case 5 The Cube Project by Lara Blom and C Flores
- Case 6 Tiny Green Houses by C Flores
- Case 7 Modeling Flow by Lara Blom and D. Robinson
- Case 8 Measurement Mascots by Ilsa and Maddy
- Case 9 Circus in Science by Lara Blom and K Engineer
- Case 10 Inventing Light by Jenny Jones and C Flores
- Case 11 Exploring Fluid Dynamics with Air Balloons by Brian Ravizza
- Case 12 Air Rockets by Brian Ravissa
- Case 13 Modeling Timelines by Ilsa Dohmen and Maddy Scheer
- Case 14 Scale Models by Ilsa Dohmen and M. Scheer
- Case 15 DIY Calorimeters for Inquiry by C. Flores

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