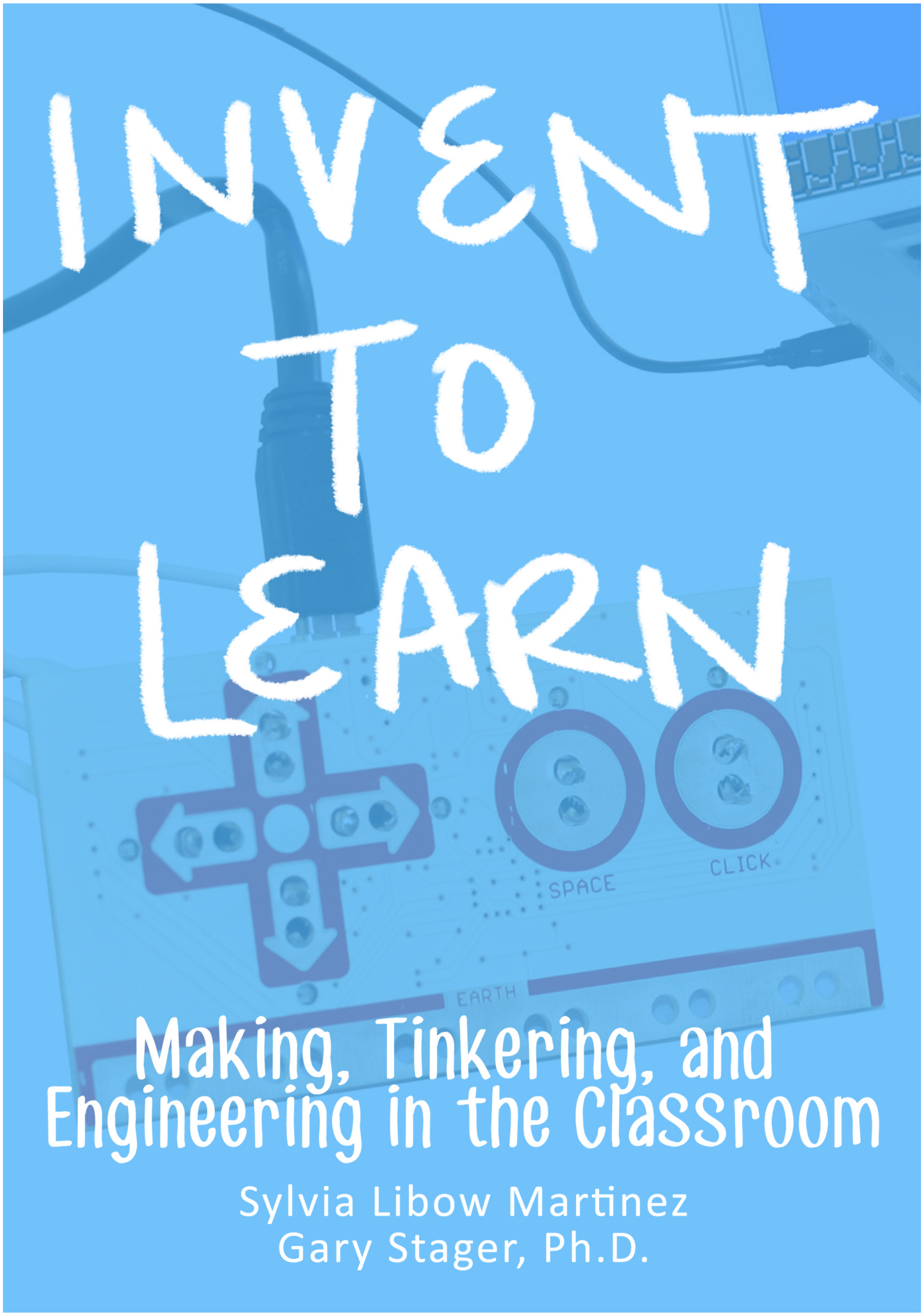
Chapter 2 - Excerpt from

Invent To Learn: Making, Tinkering, and Engineering in the Classroom



Invent To Learn:
Making, Tinkering, and Engineering in the Classroom

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Some of the most crucial steps in mental growth are based not simply on acquiring new skills, but on acquiring new administrative ways to use what one already knows. — "Papert's principle" described in Marvin Minsky's Society of the Mind

CONSTRUCTIVISM AND CONSTRUCTIONISM

Constructivism is a well-established theory of learning indicating that people actively construct new knowledge by combining their experiences with what they already know. Constructivism suggests that knowledge is not delivered to the learner, but constructed inside the learner's head. New knowledge results from the process of making sense of new situations by reconciling new experiences or information with what the learner already knows or has experienced. This profoundly personal process underlies all learning. In this sense, the new buzzword of "personalized learning" is redundant. All learning is personal. Always.

Constructivism is often misunderstood as meaning that learning only occurs alone. This is not the case. Learning is often socially constructed. Talking and working with others is one of the best ways to cement new knowledge.

We believe that "constructionism," a similar-sounding term coined by Seymour Papert, is the learning theory that most strongly resonates within the maker movement and should be taken seriously by anyone investigating classroom making.

Papert defined constructionism as:

> From constructivist theories of psychology we take a view of learning as a reconstruction rather than as a transmission of knowledge. Then we extend the idea of manipulative materials to the idea that learning is most effective when part of an activity the learner experiences as constructing a meaningful product. (Papert, 1986)

Papert's constructionism takes constructivist theory a step further towards action. Although the learning happens inside the learner's head, this happens most reliably when the learner is engaged in a ***personally meaningful activity outside of their head*** that makes the learning real and shareable. This shareable construction may take the form of a robot, musical composition, paper mâché volcano, poem, conversation, or new hypothesis.

This is much more than "hands-on" learning. The "meaningful" part of constructionism is not just touchy-feely new age language. It acknowledges that the power of making something comes from a question or impulse that the learner has, and is not imposed from the outside. Questions like "How can my car go faster?" or "I like the way this looks, can I make it prettier?" are treated as valid, and in fact, potentially more valid than criteria imposed by anyone else, including a teacher. Learners are empowered to connect with everything they know, feel, and wonder to stretch themselves into learning new things. We seek to liberate learners from their dependency on being taught.

The maker movement is terribly exciting in the ways it celebrates the virtues of constructionism, even if the advocates of learning by making have no formal knowledge of the theory underlying their passions.

Constructionism is a learning theory – a stance about how you believe learning occurs. It is not a curriculum or set of rules. This book explores the strategies for teaching and classroom organization with modern materials and processes to support constructionism.

MAKING, TINKERING, AND ENGINEERING

Making, tinkering, and engineering are ways of knowing that should be visible in every classroom, regardless of the subject or age of the students. In a makerspace these processes may be defined loosely:

- **Making** is about the active role construction plays in learning. The maker has a product in mind when working with tools and materials.
- **Tinkering** is a mindset – a playful way to approach and solve problems through direct experience, experimentation, and discovery.
- **Engineering** extracts principles from direct experience. It builds a bridge between intuition and the formal aspects of science by being able to better explain, measure, and predict the world around us.

Making – Messing About With Transformative Materials

Making is about the act of creation with new and familiar materials. Children have always made things, but their tool palette and canvas have expanded remarkably in recent years.

Making something is a powerful, personal expression of intellect. It creates ownership even when what you make isn't perfect. Researchers have identified "The IKEA Effect" in which people who make things value their creations, even flawed creations, more than the same things created perfectly by experts. (Norton, Mochon, & Ariely, 2011)

The modern maker movement also embraces the ability to share not only the products, but the joyful process of making with videos, blogs, and pictures. Mark Frauenfelder, editor-in-chief of *Make* magazine, wrote about this "virtuous circle" of DIY enthusiasts who enjoy documenting their projects online and inspiring others:

> I've joined this virtuous circle myself. Whenever I build a new guitar or a new gadget for my chicken coop, I post a description or a video about it on my blog. Many people have emailed me to let me know that my projects have spurred them to do their own projects. They've told me that making things has changed the way they look at the world around them, opening new doors and presenting new opportunities to get deeply involved in processes that require knowledge, skill building, creativity, critical thinking, decision making, risk taking, social interaction, and resourcefulness. They understand that when you do something yourself, the thing that changes most profoundly is you. (Frauenfelder, 2011)

Maria Montessori said, "The hands are the instruments of man's intelligence." But intelligence is not only in the act of making, it's in extending ones own intelligence with interesting materials and tools. When used enough, the materials and tools of the maker become part of the intellectual laboratory that can be used to solve problems.

In the 1960s, computers were massive machines used only by the military and large corporations. Papert's genius was in seeing the computer as a rich, playful material that could be used by children as they learned about the world.

In their paper *Computer as Material: Messing About with Time*, Papert and Franz write:

> We mention one other closely related point of interest. The phrase "messing about" in our title is, of course, taken from a well-known paper by David Hawkins. (Hawkins, 1965) Marvelously entitled "Messing About in Science," it describes how he and Eleanor Duckworth introduced children to the study of pendulums by encouraging the students to "mess about" with them. This would have horrified teachers or administrators who measure the efficiency of education by how quickly students get to "know" the "right" answers. Hawkins, however, was interested in more than right answers. He had realized that the pendulum is a brilliant choice

> of an "object to think with," to use the language of Papert's Mindstorms, one that can build a sense of science as inquiry, exploration, and investigation rather than as answers.
>
> Just as pendulums, paints, clay, and so forth, can be "messed around with," so can computers. Many people associate computers with a rigid style of work, but this need not be the case. Just as a pencil drawing reflects each artist's individual intellectual style, so too does work on the computer. (Papert & Franz, 1987)

The idea of computers as "material" stands in contrast to the typical uses of computers in schools, then and now. Three categories of usage were outlined in Robert Taylor's seminal book on the subject, *The Computer in School: Tutor, Tool, Tutee* (Taylor, 1980). Taylor framed potential uses of the computer as either:

1. **A tutor.** The computer displays instruction and conducts assessment.
2. **A tool.** The computer allows the student to perform academic tasks easier or more efficiently.
3. **A tutee.** The student learns by programming (tutoring) the computer.

Despite being published in 1980, Taylor's classification of computer use in schools remains accurate today. The computer as tool and tutor remain dominant.

To Papert, the strength of the computer lies in none of these categories. It is a material to be "messed about with." The act of messing about, which we might call tinkering, is where the learning happens. The computer provides a flexible material that the child can weave into their own ideas and master for their own purposes.

It might seem that what we are talking about here is the "tutee" use, or children learning to program computers. However, there is a subtle difference. In the *Computers as Material: Messing about with Time* article, Papert and Franz describe students investigating the concept of time. The teacher showed her students how a candle would gradually extinguish when covered with a bell jar. How, she asked, can we measure how long it will take for the candle to go out?

This simple prompt created a wealth of challenges and learning opportunities for these students on their journey to solve this problem. They invented multiple ways to measure time, from counting heartbeats to constructing sand-filled homemade hourglasses. The quest to build these timers and clocks was driven by the need for accurate measurement of time, not the teacher's directions. In fact, there were very few teacher directions aside from the challenge to answer the question.

The classroom was "well stocked with materials," even "junk," which gave the children a rich source of material when they brainstormed about measuring time in new ways. Eventually the students used computers to help measure time. They programmed timers and counters on the computer, alongside the ones they built from the other materials on hand. In building these devices, they naturally came across problems that needed to be solved – engineering obstacles, inconsistencies, and mathematical concepts like precision. They built, tested, and re-built their clocks and timers to solve these problems and get better results.

The object of the lesson was not to build a timer or to program a computer. The object was to empower children to use their brains and anything they could put their hands on to solve a problem.

Could the lesson have been learned without the computer? Perhaps, but including the computer as part of the materials used to solve the problem gave the students a richer and more relevant experience. In the modern technological age we live in, there is simply no way to mess around with mathematical and scientific ideas without the computer.

The conclusion of the article recommends how best to use computers in schools. Remember, this is from 1987!

> Seek out open-ended projects that foster students' involvement with a variety of materials, treating computers as just one more material, alongside rulers, wire, paper, sand, and so forth.
>
> Encourage activities in which students use computers to solve real problems.
>
> Connect the work done on the computer with what goes on during the rest of the school day, and also with the students' interests outside of school.
>
> Recognize the unique qualities of computers, taking advantage of their precision, adaptability, extensibility, and ability to mirror individual students' ideas and constructions of reality.
>
> Take advantage of such new, low-cost technological advances as temperature and light sensors, which promote integration of the computer with aspects of the students' physical environment.
>
> While the theme of this article has been the role of the computer in the educational process, let us clearly state that the ideas underlying our teaching strategies were formulated by educators and philosophers whose lives long predated the invention of the computer, and whose ideas can be applied to any learning situation and to any material. Our emphasis, as was that of Piaget, Dewey, Susan and Nathan Isaacs, and others, is clearly on the inquiry and the learner, not on the specific curriculum or facts to be learned. In this undertaking, all materials are created equal, although admittedly the computer did add unique and powerful aspects to the learning process. (Papert & Franz, 1987)

"Computer as material" may be the most powerful idea we will explore in this book as we further develop the concepts of making, tinkering, and engineering in the classroom. In future chapters we will support these ideas with more practical suggestions for teachers, such as how to develop good prompts and select the best kinds of materials, both digital and physical, to promote intellectually empowering experiences.

Tinkering – A Mindset For Learning

Tinkering is a uniquely human activity, combining social and creative forces that encompass play and learning.

In most school activities, structure is valued over serendipity. Understanding is often "designed" by an adult committee prior to even meeting the students. Play is something you do at recess, not in class where students need to "settle down" and "be serious." Schedules and bells tell students where to be and what they are to learn. Textbooks set the pace of learning, and teachers tend to follow the pattern of chapter assignments and tests. Too often, kids are hooked on teachers and teachers have a faith-based relationship with the textbook.

This is evident when you ask students what they are doing in math and they answer, "Chapter 12." The reason for all this structure is not that it benefits the learner. In reality, it benefits the teacher-as-manager and the administrators in the system. The structure makes it easier for one teacher to teach a one-size-fits-all curriculum to large numbers of same age students. None of the constraints of school are for the benefit of learning – they create a more manageable, homogeneous, efficient platform for teaching a predetermined bit of content.

Creating a learning environment that deliberately breaks this teacher-as-manager focus is difficult, yet necessary. It requires a new teacher mindset and also requires giving students explicit permission to do things differently.

When we allow children to experiment, take risks, and play with their own ideas, we give them permission to trust themselves. They begin to see themselves as learners who have good ideas and can transform their own ideas into reality. When we acknowledge that there may be many right answers to a question, it gives children permission to feel safe while thinking and problem solving, not just when they answer correctly. When we honor different kinds of learning styles it becomes acceptable to solve problems without fear.

In *Epistemological Pluralism and the Revaluation of the Concrete,* Sherry Turkle and Seymour Papert argue that equal access to mathematics and science (including computer science) for women is not just a matter of historical gender inequity, but a basic imbalance in valuing only "abstract, formal, and logical" ways to think about science.

> The concerns that fuel the discussion of women and computers are best served by talking about more than women and more than computers. Women's access to science and engineering has historically been blocked by prejudice and discrimination. Here we address sources of exclusion determined not by rules that keep women out, but by ways of thinking that make them reluctant to join in. Our central thesis is that equal access to even the most basic elements of computation requires

> an epistemological pluralism, accepting the validity of multiple ways of knowing and thinking. (Turkle & Papert, 1991)

They go on to describe other ways of knowing and learning, contrasting the planner with checklist in hand to the *bricoleur* (tinkerer in French) who, "… resembles the painter who stands back between brushstrokes, looks at the canvas, and only after this contemplation, decides what to do next." (Turkle & Papert, 1991)

The message is clear in many classrooms that there is only one way to approach learning. It's taken on face value that science is analytical, math is logical, art is creative, and so on. Contemplation is time wasted and there is only one way to solve problems. Children hear these messages loud and clear – "This subject isn't for me," or worse, "School isn't for me."

In her book *The Second Self*, Sherry Turkle describes tinkering as an alternate, but equally valuable approach to science, calling it "soft mastery" in contrast to the "hard mastery" of linear, step-by-step problem solving, flowcharting, and analytical approaches. (Turkle, 1984)

School, especially in science and math classes, typically only honors one type of learning and problem-solving approach, the traditional analytical step-by-step model. Other more non-linear, more collaborative, or more artistic problem-solving styles are often dismissed as "messy" or "intuitive" with the implication that they are not reliable.

There is also a clear implication of gender roles in these adjectives – soft mastery skills are most often attributed to women, while hard mastery skills are more often attributed to men. When school favors hard mastery over soft mastery, we implicitly ask some children to ignore their own best instincts. We figuratively tie one hand behind their backs.

The point is not that tinkering is good for one type of student and not others. Tinkering is not what you do with the students who "can't do regular work" or just something to make girls feel comfortable. Adopting a tinkering mindset in your classroom allows all students to learn in their own style.

> A lot of the best experiences come when you are making use of the materials in the world around you, tinkering with the things around you, and coming up with a prototype, getting feedback, and iteratively changing it, and making new ideas, over and over, and adapting to the current situation and the new situations that arise.
>
> I think there are lessons for schools from the ways that kids learn outside of schools, and we want to be able to support that type of learning both inside and outside of schools. Over time, I do think we need to rethink educational institutions as a place that embraces playful experimentation." — Mitchel Resnick (Rheingold, 2011)

Tinkering, when presented as a way to approach problems in an iterative, contemplative fashion, can take its rightful place in schools next to analytical approaches to problem solving.

Tinkering as Play

> Tinkering is what happens when you try something you don't quite know how to do, guided by whim, imagination, and curiosity. When you tinker, there are no instructions – but there are also no failures, no right or wrong ways of doing things. It's about figuring out how things work and reworking them. Contraptions, machines, wildly mismatched objects working in harmony – this is the stuff of tinkering. Tinkering is, at its most basic, a process that marries play and inquiry. (Banzi, 2008)

"Play is the work of the child" is an oft quoted maxim from Maria Montessori, echoed by Jean Piaget, "Play is a child's work," and even Fred Rogers, "Play gives children a chance to practice what they are learning." But play is not a chore, nor is it the opposite of work; Stuart Brown in the book *Play: How it Shapes the Brain, Opens the Imagination, and Invigorates the Soul*, says the opposite of play is depression.

> Play is called recreation because it makes us new again, it re-creates us and our world. (Brown & Vaughan, 2010)

Both Abraham Maslow, "Almost all creativity involves purposeful play," and Dr. Benjamin Spock, "A child loves his play, not because it's easy, but because it's hard," understood that play can be fun, creative, purposeful, and mindful at the same time. Play is not a frivolous waste of time. When children are deeply involved in play, they are learning. Their passion, flow, and sense of timelessness mirror the actions of the tinkerer. (Csikszentmihalyi, 1991) It is through these activities that children stretch to become the people they are meant to be.

> Play creates a zone of proximal development of the child. In play a child always behaves beyond his average age, above his daily behavior; in play it is as though he were a head taller than himself. As in the focus of a magnifying glass, play contains all the developmental tendencies in a condensed form and is itself a major source of development. (Vygotsky, 1978)

Edith Ackermann, a colleague of both Jean Piaget and Seymour Papert, has spent her career investigating the intersections of learning, teaching, design, and digital technologies. She says that play and design are similar:

> Both design and play involve breaking loose from habitual ways of thinking, and making dreams come true! This, in turn, requires 1. an ability to imagine how things could be beyond merely describing or representing how things are (ask what if, do as if, inventing alternative ways); and 2. a desire to give form or expression to things imagined, by projecting them outward (thus making otherwise hidden ideas tangible and shareable). Both are about building and iterating. Messing around with materials, or giving the head a hand often sparks a maker's imagination and sustains

> her interest and engagement: you get started and the ideas will come. You persevere and the ideas will fly. (Ackermann, 2010)

Engineering as Inventing

> We tried all the systems that had been tried before, then we tried our own systems and we tried some combinations that no one had ever thought of. Eventually, we flew. — Orville Wright

The origin of the word "engineer" is a maker of an "engine," which is from the Latin word *ingenium*, meaning a clever invention. Engineering is the application of scientific principles to design, build, and invent.

> In the K–12 context, "science" is generally taken to mean the traditional natural sciences: physics, chemistry, biology, and (more recently) earth, space, and environmental sciences. . . . We use the term "engineering" in a very broad sense to mean any engagement in a systematic practice of design to achieve solutions to particular human problems. Likewise, we broadly use the term "technology" to include all types of human-made systems and processes – not in the limited sense often used in schools that equates technology with modern computational and communications devices. Technologies result when engineers apply their understanding of the natural world and of human behavior to design ways to satisfy human needs and wants. (National Research Council, 2012)

We teach children science and math so they can make the world a better place, not so they can pass tests. Edith Ackermann says:

> In the practice of design, the purpose is not to represent what is out there (or model how things are) but to imagine what is not (or envision how things could be) and to bring into existence what is imagined. Creators are fabricators of possibilities embodied: They both make and make-up things! (Ackermann, 2007)

Unfortunately, we think of engineering as being something very serious that one studies in college. In fact, engineering is something that is perfectly compatible with young children. When we encourage children to build with sand, blocks, paint, and glue, we are simply asking them to take what they know about science and apply it to the real world. In the truest sense, children are natural engineers and we can create classrooms that celebrate this fact.

Engineering is concrete. Engineers make things that work in the real world, within constraints of time, budget, and materials. Constraints make life interesting, and dealing with constraints creates opportunities for ingenuity and creativity. Engineers plan, but they also experiment and tinker. Yet, most kids are deprived of engineering experiences until they endure 12 years of abstractions. Knowledge construction follows a progression from concrete to the abstract, but the abstract is not "better." It's just a different way of knowing. If the playful, creative inclinations of young children were nurtured in an engineering context, their understanding of the increasingly elusive math and science facts would be developed in a meaningful natural context.

The just-released Next Generation Science Standards state that each citizen should learn engineering practices that include "defining problems in terms of criteria and constraints, generating and evaluating multiple solutions, building and testing prototypes, and optimizing – which have not been explicitly included in science standards until now." ("Next Generation Science Standards," 2013) Let's hope that these standards are interpreted to mean real engineering that is playful and creative.

In his paper *How Kids Learn Engineering: The Cognitive Science Perspective*, researcher Christian Schunn explores how to support early engineering learners (Schunn, 2009). His research points to several contradictions in the way students are taught science and math. In many classrooms, students are presented with endless "basic skill" lessons on scientific vocabulary, lab safety, theory, or even history lessons about famous scientists before actually engaging in hands-on activities. Sometimes, there are no activities at all – just the facts.

Such front-loading techniques do not work. They bore students and by the time the activity is presented, many will have lost interest. Engaging children as quickly as possible in real projects creates an authentic context for learning a specific science formula or math equation since students realize they need that skill or information to continue *their* projects. Good projects create the need for learning more. This is much more powerful than a checklist or threat of a bad grade.

In this book, we will use making, tinkering, and engineering as lenses through which to explore ways to enhance children's learning.

Tinkering, Engineering, and "Real Work" — Sylvia

It seems that to many people, tinkering connotes a messiness and unprofessionalism that doesn't apply to "real" jobs in scientific fields.

I believe just the opposite is true – tinkering is exactly how real science and engineering are done.

I like to think I have a unique perspective on this. After graduating from UCLA with an electrical engineering degree I went to work at an aerospace company on a research project to create the world's first GPS satellite navigation system. It was fun, exciting work because we were building something that we knew would change the world. The task was literally theoretically impossible, which made it even better. The hardware was too slow, the software didn't exist, the math was only a theory, and existing navigation systems weren't built to handle what we needed. I was thrown together with an assortment of mathematicians, scientists, hardware gurus, engineers, and programmers who weren't used to working together. The military pilots we collaborated with didn't trust any of us or our new-fangled ideas, which created even more interesting team dynamics. There were many days when we just sat around and talked through the problems, went to try to them out in the lab, and watched our great ideas go up in smoke. Then we did it again...and again…and again… until it worked.

It was the essence of tinkering. We tinkered with ideas, methods, with hardware and software, always collaborating, always trying new things. There was no "right answer," no "scientific method," and sometimes the answers came from the unlikeliest sources or even mistakes. There were flashes of insight, fighting, battle lines drawn, crazy midnight revelations, and the occasional six-hour lunch at the local pool hall.

My flash of insight, 20 years later, is that perhaps we should avoid squeezing all serendipity out of STEM subjects in a quest to teach students about a "real world" that exists only in the feeble imagination of textbook publishers. Tinkering is the way that real science happens in all its messy glory.

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