

CHAPTER 5

IT LOOKS LIKE FUN,
BUT ARE THEY LEARNING?

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When Marcos first arrives in the Tinkering Studio he spends 10 minutes watching as others construct descending sets of ramps on the Marble Machine pegboard. After a while he walks over to a marble run left behind by a previous learner, picks up some ramps and dowels from the floor, and sets to work—spending about an hour changing lengths, angles, and many elements that allow the marble to hit a chime, spin in a funnel, or turn a corner. Each time he makes a change, he drops a marble into the run, and it all goes perfectly until it shoots off the track at one of the two or three tricky spots where alignments aren't quite right. He tries different ways to slow down or redirect the marble so it will make its way past these treacherous turns. He tinkers with the angles of the ramps, creates “guard rails” out of dowels, and adds wooden “backsplashes” to the sharp turns. Finally he has successful test runs that work from top to bottom. He steps back to survey his work. He tells us that it was “a hard activity.” He takes out his mobile phone and uses its camera to document what he has accomplished before leaving to find his family.

Marcos, Tinkering Studio, summer 2011

Scenes such as this are common in the Tinkering Studio, a dedicated “making” space in the San Francisco Exploratorium. The studio is thematically organized around sets of materials or phenomena that change regularly. Activities might focus, for example, on work with cardboard, electronic circuits, rotational motion, or squishy things. The space and activities are designed to appeal to people of all ages, and learners in the Tinkering Studio are as equally likely to be adults as they are children. Activity stations and display cabinets are distributed around the studio, so that people can

encounter and engage in different ways with the materials or phenomena. Visitors to the Tinkering Studio interact with artists and community tinkerers specializing in these items, and are supported by specially trained Tinkering Studio facilitators to begin to experiment with the materials themselves. In an electricity-themed Tinkering Studio station, people might play with simple circuits, getting bells to ring or strobe fans to whirr, adding a switch and parallel circuits over time. At another station, they might sit in a sewing circle and work with conductive thread to sew belts, scarves, and bags designed to incorporate LEDs, button-cell batteries, and electric circuits. They might interact with a long-standing Exploratorium exhibit called Resistor or with an electrical artwork from a local artist, who might even be in the Studio that day experimenting with circuits made from Play-Doh or other materials. Visitors to the Tinkering Studio are invited to slow down, sink in, and spend time working with phenomena and materials to begin to conceive of, design, and make things themselves. Ideas, models, tools, and facilitators in the studio are carefully curated, but there is no set of instructions, and no prescribed endpoint.

Part exhibition space, part science laboratory, and part atelier, the Tinkering Studio is a new kind of public learning experience. Every day, we see amazing focus, creativity, persistence, and pride developing in people of all ages as they draw on their understanding and imagination to develop



Figure 5.1 Focused work at a marble machine.

Source: © Exploratorium.

52 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

and pursue an idea and to make something concrete (even if ephemeral) that represents their ideas and understanding. We are struck by the amount of time people spend working on their ideas—typically an hour, sometimes half a day—and many return regularly as the themes change. This profusion of delight and dedication energizes us and keeps us going—but periodically we are arrested by questions from people who come to observe the studio in action, usually educational policymakers and researchers whose job it is to identify learning in action, who say to us: “*Well, it looks like fun . . . [pause] . . . but are they learning?*”

This question stymied us for many years, mostly because we did not see an inherent contradiction in the notion of people visibly enjoying themselves (engrossed, committed, joyful) and engaging in processes of learning. We were struck by how the visual amalgamation of “fun” and “learning” disrupted so many people’s foundational assumptions about what counts as learning, even those who were long-time supporters of learning in out-of-school settings.

In this chapter, we describe what learning looks like in the Tinkering Studio. We begin with how we conceptualize learning in the context of science and engineering, when we see people actively engaged, developing intentionality, generating new ideas, and building solidarity and shared commitment to a practice of design, experimentation, and tinkering. We can point to such characteristics of learning in the Tinkering Studio. The specifics of learning depend on what learners know coming into the experience and how they choose to pursue their interests and ideas through the tinkering activities.

Most of this chapter describes how we design for the conditions that afford such learning. We close with reflections on how our conceptualization of learning and design relates to and supports the vision of science learning advocated by the National Research Council’s *Framework for K-12 Science Education* (National Research Council, 2011). We contend that tinkering activities designed to support engagement, intentionality, innovation, and solidarity provide singularly accessible opportunities for learners to engage in scientific and engineering practices that are both epistemologically and ontologically meaningful.

Tinkering manifestly embodies a powerful way to engage learners in science and engineering practices. Through careful design and facilitation, however, we believe that tinkering activities can be made broadly accessible and appealing to even more learners, of widely varying levels of prior interest and experience in science and engineering, including those that do not think of themselves as tinkerers, mechanically minded, or “good” at science.

1.0 HOW WE CONCEPTUALIZE LEARNING THROUGH TINKERING

We often describe what happens in the Tinkering Studio as “thinking with your hands” (Sennett, 2009). Learners work for a long time, constructing, testing, and tinkering with their projects until they reach that point of “just so.” While cries of delight regularly punctuate the whirring, buzzing, clanging atmosphere of the space, people often work silently and intently with their hands, even when sitting next to friends and families. They ask for tools, for help holding something as they use a hot glue gun; they point to and comment on things that are working or not working. But mostly they are exploring phenomena, testing ideas, and responding to feedback with their hands. We can see, embedded in the things they build, what they are asking and their theories of the properties of the materials or phenomena. We see their thinking especially in how the artifacts change over time, as the learners come to understand, through iterative design and testing, the ways in which light reflects and refracts, the speed and direction of the turning objects based on the ratio of cams and pulleys, the geometric features of shadow makers relative to the light source, or the material properties of cardboard, Plexiglas, and aluminum grids.

Our work draws on constructionist theories of pedagogy (Papert & Harel, 1991) and is based on an expansive view of learning, conceptualized as a process of being, doing, knowing, and becoming. In this way, we move beyond traditional school-like conceptions (knowing), beyond traditional constructivist conceptions (doing), and include conceptions of the socially situated developing self (being and becoming) as central to activities and processes of learning. Our thinking draws on the work of many scholars who have investigated the dynamic relationship of self, setting, activity, and how it supports learning (Herrenkohl & Mertl, 2010; Holland, Lachicotte, Skinner, & Cain, 1998; Stetsenko, 2010). In this view, learning is signaled by ever-expanding participation in social activities that make possible, and that are made possible by, the learner’s growing repertoire of knowledge, skills, interests, ideas, and sense of purpose (Vygotsky, 2004).

Critical to learning in the Tinkering Studio are opportunities to engage with the work and ideas of others; to be supported with tools and assistance to develop and pursue one’s own ideas; and to develop and evolve these ideas as direct engagement with materials and phenomena provides feedback, creates constraints, and inspires new thinking and solutions.

As designers and students of the space, we see evidence of learning in people’s deepening:

- *Engagement:* Active participation, which might include silent or still observation and reflection.

54 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

- *Intentionality*: Purposeful and evolving pursuit of an idea or plan.
- *Innovation*: New tinkering strategies that emerge through growing understanding of tools, materials, and phenomena.
- *Solidarity*: Sharing, supporting, and pursuing shared purposes with other learners in the Tinkering Studio, or with the artifacts they have left behind.

When we see these qualities developing in the space or the learners, we know that people are on a trajectory of learning. They are drawing on their resources; they are taking risks with their ideas; they are operating on the edge of their understanding. They are engaging in the different investigative practices of designers, scientists, artists, makers, and engineers. This, to us, is what learning “looks like,” and this is what we strive to support in the Tinkering Studio. The specific concepts being learned vary according to the individual’s prior experiences and also to the particular activities in the Tinkering Studio. The particular practices learners pursue vary according to their interests and goals—whether more or less evidence-driven, more or less idea-driven, more or less aesthetics-driven. Our goal is to design the experience so that learners can find and pursue a purpose, exercise their creativity and imagination, and confront and solve conceptual challenges, within a STEM-rich tinkering context.

2.0 HOW WE DESIGN FOR LEARNING

Exploration in the Tinkering Studio is driven by the learner, but it is inspired and informed by the setting: by the materials made available in the studio and by the architecture of how it is made available; by the active work of others in the space; by the archaeological residue of projects left by earlier visitors; and by the modeling and participation of tinkering facilitators, as well as community makers and artists who work in residence for changing periods of time. The environment and activities are surprising, whimsical, and aesthetically compelling—they draw people in, get them going, and keep them engaged through their open-ended and continually complexifying nature.

The Tinkering Studio is located on the Exploratorium’s public floor, amid a sea of exhibits, surrounded by a low wall. Museum visitors first see it from a distance; it looks like one more part of the museum’s open exhibit space, though visitors might notice that people in the studio seem to be more stationary and focused than elsewhere in the Exploratorium. A low wall and swinging gate serve as a threshold between the open exhibit floor and the Tinkering Studio. Once through the gate, visitors encounter exhibits or art pieces that involve phenomena or materials being explored in the studio

that day. While playing with the exhibits or viewing the installations, learners may begin to develop questions or ideas, or they may become curious about the range of activities they see others pursuing at one of the activity stations distributed throughout the space. Drawn to a particular activity, learners begin to interact with the tools, materials, and themes. They might begin to build a contraption that they think will hover in the wind tube. Through working with a collection of materials that includes, among other things, strawberry baskets, pipe cleaners, Mylar, and drinking straws, they might try to build something that is parachute-like, or that has wings. Others might design specifically with thoughts of thrust, lift, weight, and drag already in mind. After testing their contraptions in the wind tube, they might see their object unexpectedly sink or perhaps shoot out of the tube. *Why did it not float as they had intended? What do they need to do to get it to float? Or perhaps: Could they make it shoot out of the tube even higher and faster the next time?* As they begin to develop their own questions, construct their own ideas, and “build out” their understanding, they often confront the limits of their knowledge or fluency with the phenomena as they become stuck.

The process of becoming stuck and then “unstuck” is the heart of tinkering. It is in this process that authorship, purpose, and deep understanding of the materials and phenomena are developed.



Figure 5.2 A Wiffle ball with spidery pipe-cleaner legs hovers in a wind tube.

Source: © Exploratorium.

56 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

We find that as learners become comfortable with moments when their understanding is challenged by the results of their own designs, they become more engaged, spend more time investigating and/or constructing, and take ownership for and build confidence in their abilities to learn and understand. Indeed, in interviews, when we ask them to describe the history of their artifacts, learners often dwell on these moments of frustration and, most importantly, their solutions to the unexpected challenges to their understanding. These seem to be the most meaningful parts of the process of tinkering. The interviews reveal how important the sense of self is in the interplay of objects and activities in the Tinkering Studio. In an educational context, particularly one that is not mandatory, as in a museum, what helps people persist in their investigations is both the intriguing nature of the materials themselves and the personal investment learners have in their own ideas and understanding. It is the personal accomplishment of becoming unstuck, plus having an artifact to point to—an artifact that may be rickety or lopsided, but yet has resolved the problem that so puzzled the learner—that makes tinkering activities so compelling to the learners. They surprise themselves with their accomplishments. Their ideas, creativity, thinking, and resilience are validated in their own eyes.

In the sections following, a brief discussion of the development of the Tinkering Studio, we explain how we design to support this process of inspiration, creativity, frustration, and breakthrough, which we contend is at the heart of generative *making* activities.

2.1 Origins of the Tinkering Studio

The roots of the Tinkering Studio come from an MIT Media Lab project called PIE (Playful Invention and Exploration), funded in 2000 by the National Science Foundation. PIE supported a small group of museums to experiment with meaningful ways to engage children with small programmable computational devices called “Cricket,” developed by the Media Lab’s Lifelong Kindergarten Group led by Mitchell Resnick (author of “Tinkerability,” another chapter in this book). Crickets are small computers about the size of a nine-volt battery that can be connected to sensors and motors as well as programmed to collect data, activate a kinetic sculpture as a way to “display” the data, or do other things envisioned by the learner. In testing Cricket-based activities, we noticed that to effectively engage learners’ interests and support their creativity and risk-taking, activity designs needed to provide an array of loose parts, support thematic explorations with a variety of possible outcomes, utilize technology and tools as a part (not the focus) of the activities, and provide time to support learners’ initiatives. More than a dozen different PIE activities were developed through this project.

In 2003, the Exploratorium received an NSF grant to launch the PIE Institute (led by the first two authors of this chapter, Petrich and Wilkinson) to support a network of museums interested in providing PIE activities for children attending museum-classroom-based workshops. In these museum workshops, it was typically known who was attending, how much time we could give to each activity, how the environment supported the workshop in general, and how to manage loose parts and (sometimes dangerous) tools.



Figure 5.3 Constructing with cardboard in a cardboard Tinkering Studio.

Source: © Exploratorium.

58 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

At the Exploratorium, over time we began to move the PIE activities out of the controlled museum workshop and onto the museum's exhibit floor. Tinkering activities in the open floor space needed to accommodate a changing flow of visitors, who came with varying prior experiences and who stayed for self-determined amounts of time. Therefore, we had to think carefully about ways in which to structure the environment and activities so that learners could find their own starting points, tinker at their own pace, be inspired and informed by others, and be free to come and go as their interest and time allowed.

We formalized these experiments in 2008 when we roped off about 400 square feet of space on the Exploratorium's public exhibit floor and called it the Tinkering Studio. The studio was popular from the start. We found that many visitors began making repeat visits to the Exploratorium so they could "do more tinkering." At about this time, we began a research-and-documentation project to understand how our designs and experiments were supporting learning opportunities for museum visitors. We spent the next four years systematically designing, studying, and documenting our work in the Tinkering Studio, incorporating findings into the design and implementation of an expanded, permanent Tinkering Studio at the Exploratorium's new campus at Piers 15/17.

2.2 Activity, Environment, Facilitation

Over the last few years, we have produced a set of design principles that articulate key features of the Tinkering Studio that we believe spark and support people's active engagement and learning—in particular, fostering the process of inspiration, creativity, frustration, and breakthrough described above. The design principles were developed through a three-year participatory research project that also involved the study of learning designs in other informal settings. They are currently being further tested to understand how they relate to the learning indicators discussed above and later in the last section of this chapter. Here, we describe these design principles in ways that reference our underlying cultural-historical theory of learning and our constructionist theory of pedagogy.

We describe the principles for activity, environment, and facilitation one by one; however, we stress that we do not encourage a mix-and-match or pick-and-choose approach to the Tinkering Studio. We design for all of these principles at once, though what they may look like will vary at any given time depending on what the Tinkering Studio is doing that month.

2.2.1 Activity Design

Activity design principles encompass how we establish or suggest broad activity goals and pathways, as well as how we select the palette of tools,

materials, and phenomena that constitute both the context and the support for learners to make progress toward these goals.

- **Activities and investigations build on learners' prior interests and knowledge.**

We generally design activities that involve familiar, everyday materials and phenomena, but often used in unfamiliar, unexpected ways. For example, when we investigated the theme of time in the Tinkering Studio, we used clocks in different ways. Learners could dissect mechanical clocks. At another table, learners were invited to create metaphorical clocks. At other stations, we engaged people in the familiar concept of time-based animation, in one case through the process of creating strobe-light zoetropes, and in another by inviting learners to contribute to a mural using simple Japanese brushes and ink, and to watch an adjacent time-lapse video that showed the creation of the mural including up to the last minutes when the learner made his or her own contribution. We find that using materials in this way expands the possibilities of resonating with people's prior experiences, whether from a point of familiarity or of surprise and intrigue; this resonant response prompts them to pick up the materials and get started.

- **Materials and phenomena are evocative and invite inquiry.**

We select materials or phenomena largely based on two criteria: their inherent potential to be sensually and aesthetically evocative (to be beautiful, complex, surprising, and observable on their own) and their potential to provide immediate feedback to the tinkerer's actions. The possibility for learners to change an object, produce something new, and quickly see results is essential to the trajectory of experimentation. For example, creating spinning tops is a common science activity, and in designing, building, and decorating tops, learners quickly gather a sense of how symmetry affects their behavior. In the Tinkering Studio, this activity is complexified both by the range of materials, sizes, and scales that one can pursue, but also by the inclusion of aesthetic elements to decorate and personalize the tops, which creates new constraints that can challenge the tinkerer's understanding and mastery of the physical phenomena involved in spinning tops. For example, decorating a top with googly eyes to make a crazy face affects the balance and symmetry and therefore the performance of the top. In general, we tend to select materials that are slightly flawed or that do not fit together perfectly, so that they require more thinking, effort, and ingenuity to get them to work as planned.

60 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

- **Tools and concepts of science are a means, not an end.**

Tinkering Studio activities are designed to provide learners with personally creative and inspiring experiences that are accomplished through working with and developing understanding of relevant science and math concepts, phenomena, and tools. Mastery of the phenomena is the means toward achieving one's goals. For example, in light painting—where tinkerers create tabletop tableaux involving light sources, colored filters, and shadow makers, which are then projected onto a screen—tinkerers are immediately confronted with the relationship of the distance between the light source, the shadow maker (the object), and the screen (on which the shadow is projected) as they experiment with configurations to achieve their desired projected image. These relationships are further explored as the learner continues to tinker, becoming more fluent with, and confident about, the placement of these objects in the investigation/construction. Through such trajectories of learning (Bransford & Schwartz, 1999), tinkerers develop intuitive understanding, facility, and comfort with science and scientific concepts and tools, creating the conditions in which they are more likely to continue to engage with these concepts, including in formalized settings where they may re-encounter concepts they now know well.

- **Multiple pathways are readily available.**

Activities are designed with multiple pathways for learners to pursue and represent their understanding. First, as discussed above, learners can generally choose from several different (but related) activities at separate activity stations. When exploring circuits, visitors to the Tinkering Studio can sit at one station to connect circuits to make bells ring, move to another station to sew belts or purses with conductive thread, or interact with a small collection of electricity exhibits. Second, activities are designed for multiple possible pathways and outcomes to allow for a greater range of experiments, a more diverse array of starting points, a more varied pattern of tool use, more opportunities for observations, testing, failure, and success. For example, building marble machines could involve creating a precise series of ramps that flawlessly convey marbles from one track to the other, from the top to the bottom of the pegboard wall. Other learners may be interested in more complex ideas such as rolling marbles through a loop-the-loop, or in and out of a series of funnels, or jumping them across gaps in the tracks. The potential for experiments is highly dependent on learners' interests and questions, any of which involve engaging with potential and kinetic energy, trajectory, momentum, conservation of energy, gravity, friction, projectile motion, and more. Thus, there is no one prescribed way through the

activity. But it is not *anything goes*: the materials themselves, as well as the ideas and examples in the space that focus people's activities in productive ways, create and constrain possibilities. Designing for multiple pathways expands potential for learners to work with and test their assumptions and understanding, which will vary from learner to learner depending on their prior experiences. Supporting multiple approaches to exploring the phenomena or materials is both helpful and inspirational to learners and also provides tinkering facilitators with evidence and insight into the way learners are understanding the topic at hand.

- **Activities and investigations encourage learners to complexify their thinking over time.**

It is not enough simply to offer multiple pathways or alternatives in an activity; we need to ensure that activities encourage people to challenge and stretch their comfort level and understanding, no matter what level they begin with. Tinkering activities offer simple, attractive starting points to ensure some initial success, but they are designed with ongoing opportunities for complexification as the learner progresses toward understanding a principle, concept, or function. Connecting a light bulb to a battery pack is an early exploration that confronts many learners at the electricity boards activity. The lit-up bulb is initially satisfying, until the learner decides he or she would like to replace the bulb with a motor, or buzzer, or two light bulbs. He or she may decide to add a switch. The complex artist piece on the wall next to the electricity boards station prompts some learners to work toward a similarly cascading set of colorful blinking electrical events. The possibility for the materials to be used in a variety of ways, and in a variety of complex circumstances, is a hallmark of a designed tinkering experience.

2.2.2 *Environmental Design*

The environmental design of the Tinkering Studio includes the organization of all things (living and human-made) found in the environment. This includes a subdued color palette, natural and warm lighting when available, a collection of approachable materials (as described above), and a human scale to the overall space (something we found essential as we prototyped in the Exploratorium's cavernous exhibit hall at the Palace of Fine Arts). These elements can help learners transition from the free-roaming browsing behaviors of the museum to the more focused activities of a workshop-like setting. The environment should be a comfortable place for learners to experience delight, failure, frustration, and deep engagement over time. The environment should be alive when learners are in the space.

62 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

- **Past project examples and current activities are situated to seed ideas and inspiration.**

We design so that the archeology of the environment is apparent when visitors first enter the space. Often this is accomplished by what learners see others working on, and equally often by how the environment honors the work of those who have worked in the space earlier. Cabinets of curiosities, shelves, and niches full of objects and installations from past engagements inform and inspire incoming learners. We also display images and videos highlighting prior or related work. Opportunities for facilitators and learners to refer to someone else's creation, or compare construction techniques or goals, offer a way to seed new ideas and to help solve a problem that a learner might encounter.

- **Activity station design enables cross-talk and invites collaboration.**

We design workspaces in ways that require people to meet and interact with others, even if just to reach tools or take turns projecting images, or to ask for help in holding something steady. For example, rather than segmenting separate spaces for each learner at the pegboard wall for the marble run activity, the entire wall is available for the learners to negotiate together. Learners become natural facilitators when someone is asking for help about something that another has just figured out. We limit the number of tools or particular materials both to avoid over-stimulation and also to encourage sharing and improvisation. These types of adjacencies and designs lead to natural discussions and conversations between learners, an acknowledgment of what each person is working on, and an opportunity for help and feedback at every point along the way.

- **Studio layout supports individual initiative and autonomy.**

While we design for collaboration, we also design for learners to exercise autonomy and not be dependent on the studio facilitator for help, tools, or supplies. We put all necessary materials out on an accessible table, which our visitors can approach at any time as their thinking or needs change. When learners enter the space, a facilitator briefly introduces them to the array of materials available. Activities have no fixed end point or end time, so learners can move from activity to activity as they reach their own transition points or are seeking new ideas or inspiration. They can also return to further complexify their work as new ideas come up in the context of new activities and can be incorporated back into work at another station.

- **Activity adjacencies encourage the cross-pollination of ideas.**

Materials stations are often moved to the edges of the space, away from the design and making area. Walking through the making space to get to the materials table generates encounters with ideas and solutions that learners may not have been actively looking for, but may provide new ideas and breakthroughs. Indeed, although each tinkerer may take a different pathway through an activity, we find that similar outcomes are predictably created as an idea spreads, or is shared in the space. These moments of inspiration roll like a wave through the activity when people are ready for them. For example, at a marble machine, when somebody starts to use tape to create “guard rails,” in minutes we will see tape appear across the wall as people pick up on an idea that seems to work. Activity tables are rounded to make it easier for one more learner to join a space at a table. When someone at a shared table invents a new kind of spinning motion on their top, that achievement is immediately experienced by others in close proximity.

2.2.3 Facilitation

Facilitation is key to the operation and impact of the Tinkering Studio. The attitude, support, and outlook of tinkering facilitators create an environment of intellectual safety, creativity, and a genuine interest in supporting the learner’s ideas rather than forcing the acquisition of a particular set of procedures or specific facts. Tinkering facilitators understand that their most important job is to support learners to come to care about and persist in developing their ideas. Through the process of that development, learners will be required to grapple with the scientific concepts and phenomena embedded in the materials and activities.

- **The facilitation is welcoming and intended to spark interest.**

A critical role of a Tinkering Studio facilitator is to set the tone and welcome tentative visitors into a creative and exploratory space. Facilitators’ enthusiasm creates a starting point for learners who may be cautious about opportunities to publicly create and to demonstrate what they know and do not know in the process. Initial facilitation moves include welcoming people and communicating that there is something in the Tinkering Studio for everyone (whether or not you identify as a “tinkerer” or “maker”), and that the facilitator will be available to help and support the learners as needed. Facilitators typically put materials in front of a new learner and show one or two moves with the materials to get the learner started. They may also point to the work of others in the space to generate ideas or models that learners can work toward.

64 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

- **Facilitators try to focus learners' attention, based on individual paths of understanding.**

By observing the moves of the visitor, and by talking to him or her about what he or she is doing, facilitators can identify what ideas or concepts a learner is working with as he or she begins his or her investigation and then make suggestions about tools or ideas accordingly. Many times, facilitators may not need to intervene, once they confirm that the learner is on a fruitful path. Sometimes, the facilitator may find that the learners are on a path that will lead to frustration or getting stuck, but it is important that the learners be allowed to continue until they themselves realize they are stuck. Jumping in to help too early takes authorship away from the learner. Jumping in too late may result in a learner giving up. In the Tinkering Studio, the zone between too early and too late is fairly wide, as the activities and environment tend to maintain people's interest and commitment for a good while. For example, a battery-powered scribbling machine (an activity where an offset motor creates a vibrating-moving-drawing contraption) often completely falls apart when it is first built and set in motion. But rather than providing guidance about how to build and reinforce the design from the start, facilitators let the visitors get feedback first-hand from their own contraption. The scribbling machine's falling apart leads learners to rethink either their designs or the ways in which they have executed them. Facilitators can step in to draw the learner's attention to particular materials (pipe cleaners or wires) or phenomena (symmetry and center of gravity) that are at play in other functioning scribbling machines in the Tinkering Studio. These are facilitation moves that can help learners become unstuck and to recommit to their creative processes.

- **Facilitation should strengthen understanding by helping learners clarify their intentions through reflective conversation.**

An idea that leads to getting stuck is an important learning opportunity, maybe more important than the moments where the learner's idea unfolds flawlessly. A facilitator's role in helping a person come to see and understand why he or she is stuck is as important as their role in helping a person celebrate something that is working. The facilitator's role is not to "quiz" the learner to ascertain whether or what content understanding was achieved, but to continue the investigation by offering subtle challenges, or asking questions that may lead to the complexification of the learner's idea. Learners may feel successful when a construction they create works as anticipated, but it is often important for facilitators to dig a little deeper, to develop a clearer understanding about what the learner knows. Asking

the learner to apply the successful idea to another context, or to a new set of materials, or to a new design, often goes a long way in confirming or challenging the learner's grasp of the ideas. For example, in connecting circuits, a young learner who successfully connected a battery and a bulb was surprised when he was unable to successfully connect the wires and terminals to add a switch and a second light bulb. The facilitator stepped in to reposition the materials on the table, clearing away unnecessary wires and more clearly positioning the battery, switch, and bulbs in a circular arrangement to more concretely frame the question about how to approach the circuitry. This simple repositioning helped the boy re-engage with the activity and begin to complexify it further.

3.0 HOW WE RECOGNIZE LEARNING IN TINKERING

We started this chapter with the question perennially heard in the Tinkering Studio: "*It looks like fun, but are they learning?*" We have tried to describe, in response, what learning looks like to us. Moreover, we have tried to illustrate how learning through tinkering is not serendipitous: it comes about through a process of design decisions and principles that create specific types of opportunities for learning.

The design principles described here have resulted from many years of activity development in which Petrich, Wilkinson, and their collaborators experimented equally with activities, environments, and facilitation. Since 2008, under Bevan's (the third author's) direction, the Exploratorium has embarked on a set of research studies to document and understand how our design choices—the interplay of activity, environment, and facilitation—operate to deepen learners' engagement. We have integrated these studies into regular professional development meetings with tinkering facilitators where we review the documentation (video, audio, field notes) and discuss what we see happening, why, and what it felt like in the moment, what we missed, and how to take what we are learning back into our design and staff training programs.

As we undertook these studies, we knew we needed to identify and document learning outcomes and indicators without stopping the tinkering activities or isolating the learners to interview or survey them (i.e., we did not want to "spoil the fun" or disrupt the flow, or decontextualize meaningful personal experiences of accomplishment, both aesthetic and intellectual). We sought naturalistic approaches to documenting learning, which some researchers have argued is critical to supporting creative work in public learning environments (Michalchik & Gallagher, 2010). The primary way we documented our designs for learning was to video people in activity, then review and analyze the video later. We also recorded some

66 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

Tinkering Studio conversations among tinkerers as well as between tinkerers and facilitators. From this work, we list four tentative indicators of learning:

1. Engagement
 - a. Duration of participation
 - b. Frequency of participation
 - c. Work inspired by prior examples
 - d. Expressions of joy, wonder, frustration, curiosity
2. Intentionality
 - a. Variation of efforts, paths, work
 - b. Personalization of projects or products
 - c. Evidence of self-direction
3. Innovation
 - a. Evidence of repurposing ideas/tools
 - b. Evidence of redirecting efforts
 - c. Efficiencies gained through growing fluencies with concepts, tools, and phenomena
 - d. Complexification of processes and products
4. Solidarity
 - a. Borrowing and adapting ideas, tools, approaches
 - b. Sharing tools and strategies; helping others to achieve their goals
 - c. Contributing to the work of others

When people are engaged in the flow of tinkering activities designed to support these practices of engagement, intentionality, innovation, and solidarity, they are on a trajectory of learning that is matched to their particular (and evolving) interests, capacities, and commitments. Though most educators respond positively to these constructs, we recognize that this terminology is not yet part of the commonplace language of learning, which is still dominated by a search for evidence of the learner's ability to reproduce (usually in a new context) a fragment of knowledge or skill. For example, many educators are comfortable with a child's being able to verbally define symmetry as evidence of learning but not convinced by (or secure in the knowledge that it can be reproduced) the child's demonstration of his or her mastery of symmetry in creating a spinning top that achieves his or her aesthetic and engineering ambitions. This is an ongoing tension. We believe that tinkering activities have great potential for expanding thinking about what constitutes evidence of learning.

3.1 Tinkering and Engineering Practices

The specific STEM concepts and phenomena being learned depend, of course, on the activities engaged in and the age, interests, and prior

experiences of the learners doing the engaging. Nonetheless, certain consistent practices in the Tinkering Studio, enabled by the design principles described above, cut across particular conceptual domains, such as electricity or optics. For example, in both domains, learners design, test, respond to feedback (data), and redesign/retest. In our work to identify and articulate learning in the context of tinkering, we turned with interest to the recent *Framework for K-12 Science Education: Practices, Cross-Cutting Concepts, and Core Ideas* (National Research Council, 2011). In particular we examined the document's description of engineering practices, which include:

1. defining problems;
2. developing and using models;
3. planning and carrying out investigations;
4. analyzing and interpreting data;
5. using mathematics, information and computer technology, and computational thinking;
6. designing solutions;
7. engaging in arguments from evidence; and
8. obtaining, evaluating, and communicating information.

The concept of scientific and engineering *practices* is powerful because of its inherent conception of learning as processes of being, doing, knowing, and becoming. The Framework does not define learning solely as the acquisition of facts or mastery of skills, but rather includes engagement with the practices that scientists and engineers use to develop new understandings of materials and phenomena. This more inclusive definition potentially moves the discourse about learning away from memorization of abstract facts to the development of affinity for and fluency in the ways of knowing, doing, and being (the epistemologies and ontologies) of engineers or scientists. Engaging in increasingly complex scientific and engineering practices perforce entails growing mastery of facts, concepts, and skills, but always in the context of pursuing and expanding understanding about questions that matter (for whatever personal reason) to the learner.

What can tinkering offer to the task of implementing the forthcoming Next Generation Science Standards and ideas about engineering practices? We contend that a primary distinction between tinkering activities and other types of engineering activities (such as many robotics programs and design challenges) is that in tinkering the set of constraints that learners are working with and toward are developed in relation to the goals, interests, and capacities of the learner himself or herself. That is, there is no injunction about a building reaching a certain height or a ball rolling down a ramp at a certain speed or a robot travelling a certain distance. Such constraints

68 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

matter a great deal in the real world, to the people who have already committed to a lifelong profession of engineering, and for whom real consequences (e.g., public safety or job security) pertain if they are ignored. But they may matter less to those who have not yet committed to a STEM profession. However, in tinkering, learners create both goals and constraints for themselves, based on their prior experiences, and also evolve these goals and constraints as their understanding and mastery of the phenomena and materials develop. For example, a teenager initially seeks to make a marble roll down a five-foot pegboard at the slowest possible rate. Once he has control over the speed of the marble, he might become intrigued by the sounds the marble makes when bouncing off chimes placed on the pegboard. This might lead him to switch goals to make the marble produce a descending sequence of tones as it travels down the pegboard. The design and engineering practices remain the same. However, the purpose and pathways that drive engagement and persistence are authored by the learner (or by a group of collaborating learners), and are therefore more likely to matter to the learner and support his persistence. Thus, we contend that tinkering makes an important contribution to STEM education and to the adoption of the forthcoming standards because it embeds engineering practices in purposeful and valued activities, just as these practices are embedded are in the real world.

Authentic purpose is essential to the largely unarticulated distinction between STEM skills and STEM practices. Skills can be taught in ways that are disembodied from purpose or meaning. Though a student can come to understand how to conduct an observation through a series of exercises entailing observing and making notes, whether or not the student learns to observe, and what it means to observe, is not a given. Students can be coached to design experiments, but if they have no stake in the experiment or its results, the exercise becomes at best a schooling practice rather than a scientific practice. The practices of STEM are never disembodied from purpose and the social context that gives those practices meaning. Tinkering activities provide a unique opportunity to engage learners in the processes of developing a purpose, pursuing and mastering the STEM concepts, phenomena, and tools essential to realizing that purpose, as well as engaging in that pursuit in the social context of a creative tinkering community.

Moreover, successful tinkering activities emphasize the processes of pursuing ideas, becoming frustrated, and achieving breakthroughs through one's own ingenuity and persistence, which are essential aspects of science practices that rarely emerge in most designed science activities. In this sense, tinkering activities, whether offered in or out-of-school settings, provide learners with unique opportunities to develop affinities, experiences, and identities with practices of science and engineering that can serve as a strong foundation upon which future and lifelong learning can flourish.

4.0 CONCLUSION

It looks like fun, but are they learning? We hope that in this chapter we have shown that if learning is conceptualized as more than the ability to reproduce facts and skills in decontextualized settings, if it is understood as engaging in practices that draw on facts and skills to advance valued and purposeful activity, and if learning activities are designed within a STEM-rich context, such as we have illustrated through examples of the Tinkering Studio, then *yes, they are learning*. But they are not only learning, and learning how to learn, as evidenced by their iterative processes of creation; they are also learning, and learning how to learn, in ways that scientists and engineers learn. That is, they are deeply engaged, in personally meaningful ways, in the evidence-based practices of science and engineering, with the artifacts themselves providing evidence *for* learning as well as evidence *of* learning, in a creative and joyful learning environment that looks like . . . we have to say it . . . a lot of fun.

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70 • Mike Petrich, Karen Wilkinson and Bronwyn Bevan

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