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# Learning Through STEM-Rich Tinkering: Findings From a Jointly Negotiated Research Project Taken Up in Practice

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**ABSTRACT:** The Maker Movement has taken the educational field by storm due to its perceived potential as a driver of creativity, excitement, and innovation (Honey & Kanter, 2013; Martinez & Stager, 2013). Making is promoted as advancing entrepreneurship, developing science, technology, engineering, and mathematics (STEM) workforce, and supporting compelling inquiry-based learning experiences for young people. In this paper, we focus on making as an educative inquiry-based practice, and specifically *tinkering* as a branch of making that emphasizes creative, improvisational problem solving. STEM-rich tinkering activities are designed to support interdisciplinary investigations and creativity using a STEM-rich palette of tools, concepts, and phenomena. To date, the majority of research on making has focused on analysis of makerspaces, maker communities, and design and implementation of maker activities. In this paper, we describe a study that documented dimensions of learning in tinkering programs designed for museum visitors. The study, which was jointly negotiated among a team of researchers and practitioners, led to the development of a Tinkering Learning Dimensions Framework and a publicly available video library of tinkering exemplars, both of which are being actively used by tinkering practitioners in their direct service to the public and professional development work for the field. © 2014 Wiley Periodicals, Inc. *Sci Ed* 1–23, 2014

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## INTRODUCTION

The Maker Movement, a grassroots movement of backyard and kitchen tinkerers, hackers, designers, and inventors, has been dramatically expanding over the past several years. Since the first Maker Faire in 2006, making festivals, spaces, activities, conferences, and studies have multiplied around the globe. In June 2014, the White House hosted its first Maker Faire, and at that meeting numerous agencies, including the U.S. Department of Education, the Mott Afterschool Network, and corporations such as General Electric, Autodesk, and Intel, made commitments to supporting the expansion of making activities into community settings. That same summer, more than 7,000 educators participated in the Exploratorium's *Fundamentals of Tinkering* MOOC (massive open online course) offered via Coursera. Clearly, the maker movement has struck a chord in educational circles—educational leaders see in making the potential to engage young people in personally compelling, creative investigations of the material and social world (Blikstein, 2013; Martin & Dixon, 2013; Martinez & Stager, 2013).

In this paper, we share the results of a study undertaken to identify and articulate how tinkering supports learning in museum settings. This study was designed as a *jointly negotiated research project* among educational researchers and practitioners located in a science museum that has been developing maker/tinkering programs for over a decade. The nature of the jointly negotiated study meant that both researchers and practitioners shaped the study's questions, methods, and interpretation of results. The study produced two tools: (1) A Tinkering Learning Dimensions Framework and (2) A Tinkering Learning Dimensions Video Library, both of which have been actively used to inform the design of professional development programs offered by the practitioners to a broader field of formal and informal educators. We argue that the joint nature of the study design and implementation has been crucial to the later use of its results in practice. Thus, in addition to adding to the research literature on learning and making, this study provides a model for how the intersection of informal science education (ISE) and the learning sciences can advance knowledge and action in both research and practice.

### STEM-Rich Tinkering as Educational Practice

Making is a venerable human practice that has recently taken the educational field by storm due to its perceived potential as a driver of creativity, excitement, and innovation (Honey & Kanter, 2013; Martinez & Stager, 2013). *Tinkering* is a branch of making that emphasizes creative, improvisational problem solving. It centers on the open-ended design and construction of objects or installations, generally using both high- and low-tech tools (e.g., Arduino microprocessors with pipe cleaners, hot glue guns, and feathers). At the heart of tinkering is the generative process of developing a personally meaningful idea, becoming stuck in some aspects of physically realizing the idea, persisting through the process, and experiencing breakthroughs as one finds solutions to problems (Petrich, Wilkinson, & Bevan, 2013; Vossoughi, Escudé, Kong, & Hooper, 2013). Problems or challenges are not assigned but are surfaced and pursued by the learner through initial exploratory engagement with the materials, people, practices, and ideas available in the tinkering setting.

Science, technology, engineering, and mathematics (STEM)-rich tinkering engages learners in activities centered on the use of scientific and technical tools, processes, and phenomena. Physical phenomena or concepts such as balance, forces and motion, light, electricity and magnetism, resonance, symmetry, and others (depending on the activity design) are core-building blocks for the development and construction of the learner's idea. These concepts and phenomena are experienced through the practice of exploration, questioning, iterative designing and testing, and problem solving. Aesthetic dimensions of tinkering play an important role not only in allowing learners creative self-expression and personal investment but in providing constraints, of the learner's own choosing, that structure and also complexify investigations. For example, a desire to place large metallic wing-like structures on a battery-operated mobile object constructed of natural materials such as twigs and leaves may affect the object's rotational motion, stability, or speed of motion. The learner must negotiate between her ideas and goals, her self-imposed aesthetic concerns, the available materials, and the physical phenomena and constraints at the heart of the activity. In the end, learners can come to recognize and understand that particular physical phenomena may force aesthetic compromises or redesigns (e.g., to speed up rotational motion, the wings must be shorter).

Tinkering and making reflect a history of pedagogical theory and design steeped in practical, physical, and learner-driven inquiries advanced by educators such as Dewey (1938/2007), Froebel (1887), Papert (1980), and others. In the context of tinkering settings, novices, journeymen, and experts work side by side, assist one another, and continually shift roles depending on the task, goals, or tools at hand, throughout processes of investigation and invention. These interactions support learning and identity development in ways that resonate with theories of learning and pedagogy in the work of Vygotsky (1978), Friere (1970), and Lave and Wenger (1991).

Yet despite these deep pedagogical roots, and despite the enthusiasm of many for expanding access to tinkering opportunities, the informal science field has been challenged to articulate the learning that is possible or that has been realized through tinkering programs. This may be due in part to the narrow definitions of learning that have historically characterized schooling and that have become more pronounced during the past two decades of accountability-based school improvement efforts (see Stager & Martinez, 2013). The recent emphasis of the *Framework for K-12 Science Education* (National Research Council [NRC], 2011) on the *practices* of science and engineering as the most productive context for the development of conceptual understanding and skills provides a new opportunity to conceptualize and recognize how expansive forms of pedagogy and learning activities can create deep insights, identification, and understanding for the learner.

To date, studies of making in the context of computational thinking (Eisenberg & Buechley, 2008; Resnick, 2012), engineering (Blikstein, 2013), and media literacy (Kafai, Peppler, & Chapman, 2009) largely focus on the design, enactment, and experience of young people engaging in acts of making. Sheridan et al. (in press) have presented an analysis of features of three different tinkering settings (makeshop, museum, and afterschool setting), finding a strong ethos of community and shared practice cutting across these different spaces. Vossoughi et al. (2013) study tinkering as a rich pedagogical context for supporting the learning and development of young people from economically marginalized communities.

Together, these studies create a strong foundation for thinking about key dimensions of maker activities, communities of practice, and settings (Vossoughi & Bevan, 2014), which in turn can begin to help the field address the question: "It looks like fun, but what are they learning?" Indeed, the need to articulate learning outcomes has been felt keenly by practitioners seeking support to continue and expand the maker movement in educational contexts. The purpose of our study, therefore, was to (1) articulate and document what learning looks like in a museum-based tinkering program and (2) create theoretically-grounded and practically-oriented tools that could support ISE educators in the design and conduct of their work, including in professional development activities and in conversations with stakeholders.

### Jointly Negotiated Research

There is a long history of collaborative relationships between researchers and practitioners working in the ISE field. Decades of work by a host of committed researchers have helped to build an important knowledge base about the nature and design of science learning in informal settings (e.g., Allen, 2004; Barton & Tan, 2010; Falk & Dierking, 2000; Zimmerman, Reeve & Bell, 2010). A synthesis of these efforts makes a strong case for the importance of learning science in informal environments (see NRC, 2009).

In this paper, we distinguish between "jointly negotiated research" and "collaborative research." The two types of research differ in degree, rather than kind. In collaborative research, practitioners may have real interest in the research question, may support the collection of data, may review and provide input on analysis, but ultimately may have less power than researchers to make final decisions. They may not necessarily be involved in the formalized dissemination of knowledge in terms of theorizing, positioning, and presenting in academic forums: The researcher is seen as the lead driver and, perhaps, owner of the process. In jointly negotiated research, practitioners are fully equal partners in the process of setting research questions, determining analytic lenses, interpreting findings, and sharing results (see Coburn, Penuel, & Geil, 2013). In some cases, peer-reviewed studies in informal learning have been jointly authored by researchers and practitioners, a formal recognition perhaps of the shared investment of time and negotiated meaning making of the joint endeavor (e.g., Callanan, Esterly, Martin, Frazier, & Gorchoff, 2002; Humphrey & Gutwill, 2005; Vossoughi et al., 2013). Because the research questions are more likely to be developed and framed by the researcher, we suggest that the outcomes of collaborative research may have more immediate salience to the development of theory and research (which in turn may have long-term impact on practice) but potentially less immediate impact on and uptake in practice.

The study reported here was undertaken with the idea that jointly negotiated research could produce results that practitioners would use and find useful in their own work. Drawing on work of William Penuel and colleagues (Coburn et al., 2013; Penuel & Fishman 2012; Penuel, Fishman, Sabelli, & Cheng, 2011), we defined jointly negotiated research along the following principles:

1. *Negotiate problems of practice* that are of equal interest and importance to both researchers and practitioners.
2. *Engage in collaborative design work* to explore and test new practices.
3. *Advance both theory and practice*.
4. *Build capacity to sustain change* beyond the immediate term of the research project.

After describing and reporting the results of the tinkering study, we will reflect on the ways in which the jointly negotiated nature of the work shaped the study's outcomes as well as the uses of those outcomes in practice.

## STUDY DESIGN

The study was conducted by a research and practice team that consisted of seven ISE practitioners who designed and implemented Tinkering Studio activities and three ISE researchers who were steeped in museum-based learning but were relatively new to the tinkering program. Although all of the participants were employees at the same institution, the team had not previously worked together.

The work began by examining two draft tools produced through a prior professional development inquiry led by the first author of this paper in collaboration with 28

**TABLE 1**
**Design Principles Framework: Abbreviated Version (Petrich et al., 2013)**

| | | |
|---|---|---|
| Activity | • Goals/tasks relate to and *build on prior interests* and knowledge<br>• *Materials* invite inquiry (demand to be touched, explored, etc.)<br>• STEM is *a means* not *an end* to engagement | • Multiple *pathways* in and through the activity<br>• Ability to *complexify* choices, directions, and tools |
| Facilitation | • Spark interest through *modeling*, inviting, welcoming<br>• Sustain engagement with questions and *what-ifs* | • Deepen understanding and purpose through *complexification* and *reflection* |
| Environment | • Organized to present models, prior work, and related activities seeding *ideas and inspiration*<br>• Organized to support initiative and *autonomy* | • Organized to allow for *cross-pollination* of ideas<br>• Organized to enable and allow *collaboration* |

**TABLE 2**
**Initial List of Learning Dimensions (Petrich et al., 2013)**

| Learning Dimension | Indicator |
|---|---|
| Engagement | • Duration of participation<br>• Frequency of participation<br>• Work inspired by prior examples<br>• Expressions of joy, wonder, frustration, curiosity |
| Intentionality | • Variation of efforts, paths, work<br>• Personalization of projects or products<br>• Evidence of self-direction |
| Innovation | • Increasing efficiency/fluency with scientific concepts, tools, processes<br>• Evidence of repurposing ideas/tools and redirecting efforts<br>• Complexification of processes and products |
| Solidarity | • Borrowing and adapting ideas, tools, approaches<br>• Sharing tools and strategies; helping one another to achieve one's goals<br>• Contributing to the work of others |

expert afterschool STEM practitioners, including two from the Tinkering Studio (see Bevan & Dillon, 2010). Over 2 years, this project had collected and coded 56 videos from 14 afterschool STEM programs and ultimately had produced a set of design principles for afterschool STEM programs (see Table 1). The principles were intended to support professional conversations and design choices for afterschool STEM program leaders.

The earlier project had also synthesized practitioners' video analysis conversations to produce a tentative list of valued indicators of learning (Table 2) that the project participants saw exemplified in the practices captured on video.

The early draft learning dimensions and indicators, which had been generalized to be relevant across the 14 participating organizations, resonated with their values; but the Tinkering Studio educators wanted to specify what the dimensions and indicators looked

**TABLE 3**
**Number of Recordings Made of Each Activity**

| Activity | Groups/Individuals Recorded |
|---|---|
| Marble machines | 20 |
| Wind tubes | 14 |
| Circuit boards | 16 |

like in the tinkering context. The researchers on the team, led by the second author, were interested in refining and testing the validity of the learning dimensions to contribute to the research literature in ways that could inform practice.

The study took place over an 18-month period. To create the data set, the researchers on the research and practice team (hereinafter "r+p team") audio and video recorded 50 groups or individuals as they engaged in one of three activities in the Tinkering Studio—circuit boards, wind tubes, and marble machines (activities are described in the next section, but see tinkering.exploratorium.edu/projects for details). Researchers used hand-held cameras with attached minishotgun microphones to follow learners as they moved around the environment. To study a broad age range of learners, researchers employed purposive, rather than random sampling and selected a "target" person (whether in a group or alone) to follow. If other learners interacted with the target individual, those interactions were recorded as well.

Recordings were made over the course of 3 weeks during the summer of 2011. No recorded participants engaged in more than one activity. Table 3 shows the number of recorded groups or individuals engaging in each of the three documented activities.

After the audio/video data were collected, the r+p team worked together in a multistep process that leveraged each individual's training and expertise: (1) Researchers used Studiocode software to triage the videos, noting any events that might be considered evidence of the draft learning dimensions. (2) Researchers went back through the events and created "callouts," short clips from the longer videos that seemed to illustrate one or more of the learning dimensions. (3) Researchers reviewed the callouts and made tentative changes in the draft learning dimension categories to better align them to the evidence in the videos. (4) Researchers presented the new categories to the practitioner team, illustrating the categories with callouts. (5) Through iterative discussion, the r+p team determined whether the revised dimension categories and associated indicators captured the types of learning valued by the tinkering educators and whether the callouts seemed valid (i.e., whether the callouts adequately illustrated the category description). (6) The process was repeated over the course of many discussions until all participants agreed upon final language for the categories and indicators (see Table 4 for results).

The data analysis process aimed to explicitly recognize and reflect practitioner insights, understanding, and language. Over dozens of hours, the video analysis discussions were characterized by attention to turn-taking, and ultimately to the idea that the practitioners would have the last word: If they were not convinced by or satisfied with the learning dimensions constructs or the video examples, the researchers continued to refine the language and seek new video examples. Finding total agreement was important to the goal of producing knowledge that the practitioners would use in their practice (programs, professional development, and stakeholder conversations). Careful listening, respect, and trust were essential for ensuring that practitioners felt empowered to question or argue with researchers' assertions. At the same time, as we will show, the interests of researchers were also respected in that practitioners came to focus only on constructs supported by the

**TABLE 4**
**Tinkering Learning Dimensions Framework**

| Learning Dimension | Indicator | Description |
|---|---|---|
| Engagement | Spending time in tinkering activities | Learners:<br>• play, envision, make, explore materials, try something over and over, etc. |
| | Displaying motivation or investment through affect or behavior | Learners:<br>• show emotions such as joy, pride, disappointment, frustration<br>• remain after they appear “finished,” and start something new |
| Initiative and intentionality | Setting one’s own goals | Learners:<br>• set goals/pose problems<br>• plan steps for future action<br>• develop unique strategies, tools, objects or outcomes<br>• state intention to continue working outside studio |
| | Seeking and responding to feedback | Learners:<br>• actively seek out feedback or inspiration from materials/environment<br>• anticipate further outcomes<br>• innovate approaches in response to feedback |
| | Persisting to achieve goals in the problem space | Learners:<br>• persist toward their goal in the face of setbacks or frustration within the problem space<br>• persist to optimize strategies or solutions |
| | Taking intellectual risks or showing intellectual courage | Learners:<br>• disagree with each others’ strategies, solutions or rationales<br>• try something while indicating lack of confidence in outcome |

(*Continued*)

video data, even when they felt that, at times, the video technology/method may not have captured some features or developments that they knew or felt to be important.

## DEVELOPING AND VALIDATING THE LEARNING DIMENSIONS FRAMEWORK

In this section of the paper, we describe the research-practice conversations and considerations that were involved in developing the current Tinkering Learning Dimensions

**TABLE 4**
**Continued**

| Learning Dimension | Indicator | Description |
|---|---|---|
| Social scaffolding | Requesting or offering help in solving problems | Learners in the role of novices or experts:<br>• request or offer ideas and approaches<br>• offer tool(s) or materials in service of an idea |
| | Inspiring new ideas or approaches | Learners:<br>• notice, point out, or talk about others' work<br>• innovate and remix by using or modifying others' ideas or strategies<br>• leave something of their work behind to share with others |
| | Physically connecting to others' works | Learners produce work that physically interacts with other learners' work |
| Development of understanding | Expressing a realization through affect or utterances | Learners:<br>• show excitement when expressing a realization<br>• claim to realize or newly make sense of something |
| | Offering explanation(s) for a strategy, tool, or outcome | Learners offer or refine explanation(s) for a strategy, tool or outcome, possibly by testing and retesting |
| | Applying knowledge | Learners:<br>• connect to prior knowledge, including STEM concepts<br>• employ what they have learned during their explorations<br>• complexify by engaging in increasingly complicated and sophisticated work |
| | Striving to understand | Learners indicate not knowing (e. g., through surprise, bewilderment, confusion) and remain in the problem space to explore their confusion and build an understanding |

Framework shown in Table 4. In the sections below, we describe each learning dimension and provide brief excerpts from the r+p team discussions to illustrate the jointly negotiated meaning making that led to the production of the Framework. We seek to show that the process of refining the framework and discussing the video callouts required an ongoing dialectic between values and evidence. This dialectic was constrained by the nature of video data that captured only what was visible to the camera's eye.

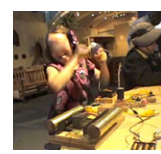
**Figure 1.** Girls tinkering with circuits and sensors.

We began with four draft dimensions of learning: engagement, intentionality, innovation, and solidarity (see Table 2). We ended with four revised dimensions: engagement, initiative and intentionality, social scaffolding, and developing understanding. The indicators associated with each of the dimensions were also revised and elaborated from the draft to the current Framework. We organize this section by discussing each of the final four dimensions, providing descriptions of how the r+p team defined them, and offering excerpts of the r+p team conversations to illustrate how values and evidence were negotiated.

## Learning Dimension 1: Engagement

Engagement has long been identified as an important analytical dimension of learning in both formal and informal settings (Friedman, 2008; Hidi & Renninger, 2006; Humphrey & Gutwill, 2005; NRC, 2009; Sawyer, 2006). It is a primary concern for educators: At a concrete level, if learners are not engaged in terms of being actively involved, educators feel that something is not working. However, engagement can also be abstract (e.g., a feeling of intense focus in the air) or individualized (e.g., evidenced by animated talking for some and contemplative silence for others). As the r+p team reviewed the videos of learners in the Tinkering Studio, a concept beyond simply "being there" (spending time) and even "being active" emerged.

An example is a video clip of an eight-year-old girl (let's call her Sarah), involved in the circuit board activity. This transcript describes the minutes directly after she has created a circuit with a battery, generator, and light bulb, along with a switch that swaps the source of power from generator to battery (see Figure 1):

| | | Utterance | Activity | Image |
|---|---|---|---|---|
| 1 | Sarah: | Oh my god, I'm so. Mmm! I've never done anything, I'm gonna tell my parents that I worked electronics by myself! | *Cranks the handheld generator, making the lightbulb turn on. Jumps up and down in her seat once. At end of statement, throws the switch to swap power source of lightbulb from generator to battery.* |  |
| | | . . . . | *Nearly 15 minutes pass, in which Sarah adds a doorbell and wiggly machine to her circuit.* |  |
| 2 | Sarah: | My adventure! | *Holds the handheld generator with both hands high above her head and cranks it while sticking out her tongue.* | |
| 3 | Sarah: | Take a picture of it all for my Dad, and then you can send it all to my Dad. | *After speaking, she continues cranking the generator to make the doorbell and light bulb turn on. Her tongue flicks in and out as she cranks the generator.* |  |

Note: The images have been slightly altered to mask Sarah's identity.

In reviewing and discussing this excerpt, the r+p team noticed Sarah's high degree of excitement and emotional investment in the circuit she had created. The notion of *investment* (of time, thought, and emotion) became an important construct for the team's discussion of engagement. Below are two excerpts[1] from a discussion of Sarah's video clips between Josh (researcher) and Ryan and Luigi (educators who have worked in the Tinkering Studio for 6 and 7 years, respectively):

Ryan: I was actually looking at this first still frame of her smiling with her tongue out.
Josh: Yes, she has the tongue out.
Ryan: That tongue out like Michael Jordan, fully invested and actually her whole body is invested in a sense.

. . .

Luigi: I mean obviously pride is the main thing I recognize in there. She's just really proud of what she's been doing.
Josh: And what makes you say that? Like where do you see evidence for pride in that?
Luigi: Well, what she says is "I worked electronics all by myself," "I'm gonna show my dad, take a picture of this so you can show it to my dad." And she is voicing self-affirmations, like: "I've never done this before," "it's just so mmm!" [all three laugh.] Like, "I'm good!"

The practitioners were initially attuned to facial expressions, such as the girl's tongue, her beaming countenance, and the excitement in her voice. But when pressed for evidence of how they knew this amounted to "pride" in what she was doing, Luigi references verbal assertions by Sarah. In this sense, Luigi makes allowances for what typically counts as

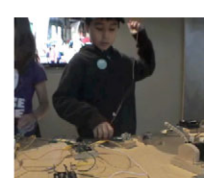
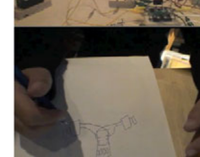
[1]We recorded only two conversations of the scores that the r+p team had, and the recordings were made when only one researcher (Josh) and two practitioners (Ryan and Luigi) were present. Discussions have been lightly edited for readability.

evidence (verbal assertions), although the practitioners' valued forms of evidence may have initially been less verbal (and less indexical).

The team wanted to identify other, nonverbal, indicators of engagement. A valued feature of the Tinkering Studio is the length of time visitors typically spend there, 45 minutes on average, according to the Tinkering Studio leaders, but sometimes hours (as compared to the matter of 1–3 minutes spent on average at most museum exhibits). To capture this phenomenon, the r+p team wanted to identify something more than simply clocking and averaging holding times. After much discussion, the team finally identified an indicator present in many videos that involved learners persisting in an activity at potential transitions or choice points (moments when an activity is "completed" or a process is "stuck"). Such indicators were agreed to be valuable markers for practitioners in part because they allowed for an analysis of program design or facilitation strategies that propelled learners through these moments of being potentially stuck or finished. They also provided demonstrable, countable, and indexical forms of evidence for both researchers and practitioners.

### Learning Dimension 2: Initiative and Intentionality

A key dimension of tinkering is developing a purpose through personal authorship and pursuit of a goal and idea (Petrich, et al., 2013). In the video clips, we observed the ways that intentionality could drive learning, including learners requesting and responding to feedback, persisting through setbacks and even explicitly committing to a new direction. But in addition to the idea of pursuing a purpose, r+p team discussions revealed the ways in which practitioners valued something more than persistence, something akin to what Duckworth (2006) has called *intellectual courage*, as shown in the following example of an 11-year-old boy (Ken) engaged in the circuit board activity.

| | Utterance | Activity | Image |
|---|---|---|---|
| Ken: | This is not working. | *Looks away from his circuit of devices.* | |
| Staff: | You've got a lot of complicated stuff going on here. | *Points and circles with her finger to indicate his circuit of devices.* |  |
| Ken: | Yeah, I think I'll start a new thing. Something new. | *Begins to take apart his circuit.* | |
| Ken: | Wait, do you have a piece of paper? | *Stops and looks up at facilitator.* | |
| Staff: | Um, yeah. | | |
| Ken: | And a pencil? | | |
| Staff: | Yeah, sure, how come? | |  |
| Ken: | So then I can plan out— | | |
| Staff: | Yeah, great idea. | | |
| Ken: | —the design. Instead of just like aimlessly building. | *After getting paper, boy draws his circuit of a four-rotor helicopter for 6 minutes before working with electrical components again.* |  |

In the r+p team discussions of this clip, the practitioners noted that, beyond open-ended exploration, Ken had a clear idea of what he wanted to make:

Luigi: There is that moment where you are like, I don't wanna keep going with this, but I need to focus it. It's pretty weird [great] to see somebody who goes, "I wanna make a thing! I'm gonna build something that has a purpose out of these parts!"

The discussion evolved to describe Ken's intentions to design a circuit modeling a four-rotor helicopter (an activity not explicitly suggested in the Tinkering Studio) as an act of intellectual courage:

Luigi: The thing that's rare about it is: He wanted to plan it out and write it out and make a diagram and all of it. But this reminds me of one of the things we talked about, those moments that you feel show, what do you call it, intellectual bravery? Or . . .

Josh: Yeah, courage.

Luigi: Courage, intellectual courage. Because the facilitator, who in theory is the expert and the person that knows what's going on, has been so far saying: "Oh, you can try this, you can try that, you can try this," but it's all limited to the stuff that's in front of him. I think it takes a little bit of guts to be like, "Look, my vision is grander than this crap right here!" [all laugh] "I need some pencil and paper, I'm gonna plan this stuff out."

Josh: Yeah, yeah.

Luigi: So, I think that's an instance of intellectual—

Josh: Yeah, and I think it belies that he really has a vision. He knows what he wants to go after here. He has an idea of what he wants to do.

Through discussion, we came to recognize these moments of courage as more than just intentionality but also initiative—moving beyond the general expectations or activities modeled in the Tinkering Studio to do or create something completely different.

While the r+p team equally shared value for the dimension of *initiative and intentionality*, it raised challenges for the researchers. In scouring the videos for discrete events that would illustrate *initiative and intentionality*, researchers found that "self-direction" was happening constantly. Each time a learner tried anything, started or ended an activity, or even spoke with someone, she or he showed intentionality. For the practitioners, this made sense, because this was something they were deliberately trying to foster. For the research team, this proved difficult, because if something was always there, in every video and without a moment of transition, no single video clip would be able to show how it was supported by activity designs, facilitation strategies, or environmental features.

This fundamental tension—of moving from the holistic experience of the practitioner to the more granular object of inquiry of the researcher—was ultimately resolved by agreeing to categorize video callouts using the construct of a "problem space," meaning a particular problem that a learner was trying to solve during the tinkering experience. For instance, in the case of a *circuit board* activity, we analyzed when a learner was trying to add a switch and get it to work. The timeframe of analysis encompassed the process of adding the switch. Did learners exhibit initiative and intentionality within this problem space? This compromise required the practitioner group to think differently about the relationship of the videos to the enacted experience, in the service of producing results that had greater consistency and validity, and advancing both theory and practice.

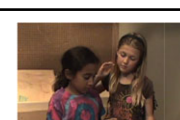
**Figure 2.** Wiffle ball and pipe cleaners hovering in the wind tube.

## Learning Dimension 3: Social Scaffolding

The dimension of social scaffolding reflects the ways that the creation of a social environment in which learners help and inspire one another to persist and solve problems supports an individual's learning (Gutwill & Allen, 2010; Packer & Ballantyne, 2005; Pea, 2009; Zimmerman et al., 2010). Learners demonstrate social scaffolding by assisting one another while working on the same project or across different projects. In the Tinkering Studio, social scaffolding sometimes involves strangers interacting in a helpful way, either audibly by discussing ideas or silently by observing and inspiring one another.

For example, two friends, let's call them Sarita and Molly, have been working independently on their own creations to float in the wind tube. The wind tube activity involves a plexi tube, about 2 feet in diameter, placed over a fan that blows air upwards. Visitors use a variety of interesting materials—strawberry baskets, pipe cleaners, cardboard tubes, Wiffle balls, etc.—to build contraptions that might float, bobble, or shoot up through the wind tube (see Figure 2). After seeing how they work the first time, visitors tinker with the objects to alter their flight characteristics (e.g., to stabilize, streamline, or weigh down the objects). In this video clip Molly, our "target" learner for the data collection process, has engaged in more testing and refining than Sarita.

After tinkering for over 25 minutes, Sarita's creation includes several small cardboard cylinders on the bottom, but they are placed asymmetrically on one side. Meanwhile, Molly has finished working on her own creation and has turned her attention to helping Sarita. In the moment detailed below, Sarita notices the asymmetry in her creation and decides to add more cylinders. Molly intervenes, stating that the creation already weighs too much to float. Molly's assistance saves Sarita from wasted effort and inspires her to try something else.

| | Utterance | Activity | Image |
|---|---|---|---|
| Sarita: | Uh oh, now we need three more. Sorry. Yeah, three more. | *Looking at the three small dowels placed on only one side of the bottom.* |  |
| Molly: | I'd try it out now, because it's already really, really heavy. | *Lifts Sarita's creation and feels its weight.* |  |

| | Utterance | Activity | Image |
|---|---|---|---|
| Sarita: | But look at this. | *Points to the asymmetry.* | |
| Molly: | It's OK. | | |
| Sarita: | Alright, I think, I can try it now. | *Moves from the "work table" to the wind tube.* | |
| Molly: | I'd try it right now. | | |
| Sarita: | If this floats, then I [garbled]. | *Approaches the wind tube.* | |
| Molly: | Come on. Fly! | *Sarita places the creation in the wind tube, but it does not float.* | |
| Sarita: | Nope. It's too heavy. | *Molly raises and releases the creation in the wind tube. It does not float.* |  |
| Molly: | Too heavy. | *Sarita removes the creation from the wind tube.* | |
| Sarita: | I'll fix it up. I have my own supply of tape. | | |

When the team viewed this clip, the conversation focused on how Molly provided scaffolding for Sarita and even demonstrated behaviors indicative of joint ownership.

Luigi: She [Molly] has no investment in [Sarita's] contraption. It's not hers, it's her friend's. But she has an investment in the experience. At this point, she wants her friend's experience to be good. So it's part of that sharing, I think what we're calling Social Scaffolding. I think scaffolding is a very good term. She's literally scaffolding her friend so that she can have a better experience ultimately.

Ryan: They kind of have a shared ownership of the project for a second. One of them is holding it, one of them is taping it, one says "oh, we need three more," we need three more tubes I'm assuming? I think that has to do with the arrangement of the space, the lack of defined [ownership], like these are *your* materials, these are *your* materials. The materials are open, the people are working next to each other. It allows the facilitator girl [Molly] to sort of join in with her friend and for the moment, both be working on the project. I also like how she phrases the testing, like "Oh, I might test if I were you." Not taking it apart or doing it [for her]. But also that she goes over with her to do it.

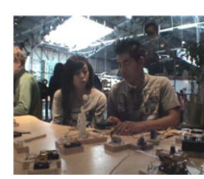
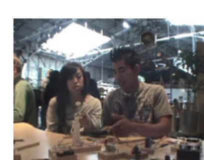
Luigi points out that Molly is scaffolding Sarita by offering advice that will lead to a "better experience" for Sarita. Moreover, in this conversation we can see how Ryan attributes the collaborative and facilitative support provided by Molly to the design and organization of the Tinkering Studio, in this case, the centralization of materials and space that encourages sharing and also builds networks of assistance. In this way, r+p team discussions continually fluctuated from the practical choices and expertise involved in designing the activities to the demonstrated results for learners captured in the videos. Notably, too, this segment of conversation shows Ryan offering evidence from the video to support his claim that Molly assumed shared ownership of Sarita's creation ("one of them is holding it, one of them is taping it . . . "). This move to evidence-based discussions occurred throughout the r+p team's collaboration. It was a facet of the project deeply appreciated by both practitioners and researchers and was a longer term outcome related to the development of the r+p team's capacity to articulate connections between design choices and learning outcomes.

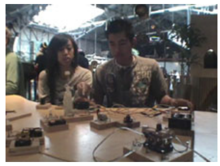
### Learning Dimension 4: Development of Understanding

At the start of this study, the draft Learning Dimensions Framework (Table 2) included the construct of “innovation.” For practitioners, this was a highly valued feature of tinkering: When they saw learners doing something new, meaning new in the Tinkering Studio, there were moments of excitement for the staff (e.g., Ken and the helicopter). For the staff, these moments of something new represented moments of breakthrough or of learning. However, in the r+p team discussions and analysis of the videos, it soon became clear that, because we did not know the learners (who were drop-in day visitors to the museum), we could not know what was new (innovative) for the learners, even if it was new to the staff. After much discussion, over the course of a year, this construct was dropped and the team focused instead on the construct of “understanding.”

Creating a learning category called “understanding” had become a communications imperative for the practitioners. Many colleagues, funders, and policy makers expressed support for tinkering, but raised a need to identify the kinds of STEM understanding that learners develop through it.

The type of “understandings” that the practitioners valued included, but were much broader than, accountability era definitions that primarily focus on domain knowledge and factual recall. We found that some facets of understanding (such as vocalizing explanations or hypotheses) reveal themselves through causal reasoning or scientific vocabulary. For example, when two 18-year olds connect two devices at *circuit boards*, the young man (“Eric”) explains with terms such as “Ohms” and “load,” whereas the young woman (“Sharon”) struggles to link these terms and her prior knowledge to what she sees happening with the circuits. The snippet of conversation viewed by the team is provided below.

| | Utterance | Activity | Image |
|---|---|---|---|
| Eric: | This thing has more ohms so it’s taking more of the load. | *Points at the fan (Device 1) in a series circuit.* |  |
| Sharon: | Oh, that’s why that one’s not as fast. | *Points at the wiggly device (Device 2) in a series circuit.* |  |
| Eric: | Yeah. But if you connect . . . | *Connects Device 2 to battery, circumventing Device 1. Device 2 speeds up.* | |
| Sharon: | Wait but this one’s still . . . | *Points to Device 1.* | |
| Eric: | Cuz it’s not connected to anything. | *Picks up a spare wire and connects Device 1 to the battery via its own (parallel) circuit.* | |

| | Utterance | Activity | Image |
|---|---|---|---|
| Sharon: | So what are all these wires? Are you like distributing the— | | |
| Eric: | Power. | *Removes an extraneous device from the area containing their parallel circuit.* | |
| Sharon: | —the power? | | |
| Eric: | Yeah. | | |
| Sharon: | So with more wires, the more . . . | | |
| Eric: | Well, it's just helping you connect them from, to the battery . . . | *Holds the battery with one hand and Device 1 with the other.* | |
| Sharon: | Yeah, but this one's fast and this one's fast, so then you're distributing the power through both. | *Points to Device 2.* |  |
| Eric: | Yeah. | | |
| Sharon: | Versus just like two . . . | | |
| Eric: | Yeah, so instead of sharing one current, this is two different currents. | *Makes a circular gesture, then holds up two fingers.* |  |
| Sharon: | Oh. Oh, now it's all coming back, ok. That makes sense. | *Leans back and smiles.* | |
| Sharon: | Aren't ohms the omega sign? | *Eric begins disconnecting circuit in preparation to create a new one.* | |
| Eric: | Yeah. And then there's Ohm's Law. | | |
| Sharon: | Yeah. I like learning about electricity. | | |

During the discussion of this clip, the researchers and practitioners concentrated on how the two learners in the video (Eric and Sharon) seemed to be developing their own understanding differently, probably stemming from different prior knowledge of circuits. Luigi begins by postulating that Eric is applying his prior understanding, demonstrating to himself and Sharon that the circuits will behave as he expects. Sharon, in contrast, is verbalizing efforts to connect what she sees to her current and prior understandings and experiences.

In the analysis discussion, Luigi begins by offering evidence for his interpretation ("Like when she says . . . "), but then begins to speculate about Sharon's school experiences with Ohm's law. At that point, the researcher, Josh, jumps in and asks for evidence to support his speculations:

Luigi: They're both trying to relate concepts they've learned before to what they're doing physically on the table. He seems more confident in what he's doing, that he's just kind of . . . confirming to himself that things actually work the way that he thinks they should work. He has a pretty clear idea that if I do this, this is gonna happen, if I do that, that's gonna happen, and that's what he's confirming to himself. And she's more trying to remember from what she's learned before, like "what is this and how does it apply?" Like when she says, when he hooks up two things in parallel and they're both going fast, and she says: "these are both going fast, so what's going on there?" It feels to me like she has some sense that there's two different ways to hook things up. And in one, they're both fast, and in one, one goes slower than the other. She doesn't quite make that full connection but she knows there's something relevant about the fact that they are both going fast. And the thing that she says at the end, "I like learning about electricity," I interpret that to mean that I like what we're doing now, and I like that it is learning about electricity but not like "oh yeah, I loved it when we studied Ohm's law." You know what I mean?

Ryan: Yeah, I think, um . . .

Josh: Can I just jump on that? I feel like I don't have enough evidence to know which of those—

Luigi: No, that's why I'm saying it's complete interpretation.

Josh: The other stuff, I feel like there's good evidence that she's really trying to bring, where she says "ohms, is that the omega sign?" she's trying to connect it, I think, to prior knowledge, to school knowledge. But I don't know when she says "I like learning about electricity" I can't tell if she meant, at least from this clip, "right now" or . . . ? She definitely meant "right now" I would say, but did she also mean "back then" or not? I don't know.

Luigi: Sure.

Ryan: For me it's enough just that she considers this [to be] learning about electricity, because I think it is very different. How I would imagine based on their comments about load and distribution, omega sign and ohms, that however they learned about electricity before was somewhat theoretical and I think that—

Luigi: Yeah and coming probably from a voice of authority.

Ryan: Right, so I think that just the fact that they see this not as just playing around with stuff, but that this is learning about electricity and that they identify that and verbalize it, I think to me that's enough.

This snippet of conversation highlights both the active work of separating speculation from evidence-based interpretation and the refinement of some of the indicators for development of understanding. Ryan and Luigi offer evidence to support their claims, and in response to Josh's distinction between supported and unwarranted claims, Luigi refers to his unsubstantiated ideas as "complete interpretation." Developing shared understanding of what constitutes evidence in support of claims illustrates one way such jointly negotiated research work can build capacity for continued engagement between research and practice. In terms of refining the Indicators, Luigi and Josh note that Eric seems to be offering explanations, applying prior knowledge and using science vocabulary, whereas Sharon seems to be striving to understand. All these behaviors became indicators in the Framework, including traditional notions of understanding, evident in explanations and rationales (Allen, 1997, 2002; Falk & Dierking, 2000) as well as indications of meaning making (asking questions or struggling to resolve confusion) that underlie the process of developing understanding (Duckworth, 2006; Gutwill & Allen, 2012; Humphrey & Gutwill, 2005).

## DISCUSSION

The current Tinkering Learning Dimensions Framework (Table 4) describes key attributes of learning in the Tinkering Studio that are valued by science museum practitioners and supported by research-based evidence. The study we described adds to the research literature on making by articulating key dimensions of learning through tinkering (a branch of making that stresses improvisational problem solving) that can, in the future, be more explicitly defined and tested in particular disciplinary contexts such as computational thinking, engineering, media literacy, or ISE as well as in different learning settings (e.g., museums, schools, afterschools).

The findings of the study contribute to emerging theories related to learning through making or tinkering. To date, research on making in educational contexts has focused primarily on program design and enactment and analysis of settings (e.g., Blikstein, 2013; Kafai & Peppler, 2010; Resnick, 2012; Sheridan, in press; see Vossoughi & Bevan, 2014 for a review of the literature). Vossoughi et al. (2013) have reported on a multiyear ethnographic study that has elucidated equity-oriented pedagogical practices that support student engagement in tinkering in afterschool settings. As understanding of the design and enactment of tinkering continues to expand, there is growing interest in documenting the learning possibilities and supports for young people.

Across the making literature, researchers note the deep engagement of young people, the opportunities provided for developing and authoring ideas, and the potential for the development of new dispositions, understandings, and directions (e.g., Sheridan et al., in press; Vossoughi et al., 2013). The study we reported here advances and elaborates some of these key ideas by detailing, for example, how researchers and practitioners can begin to operationalize and identify indicators for what *engagement* looks like in the context of tinkering. As noted above, in addition to baseline indicators of engagement related to simply being present and active, this study identified points of transition or choice, which emerge naturally in the open-ended nature of tinkering programs, as moments where young people's levels of investment and persistence can be documented as they commit to new or continued courses of action. Furthermore, these transitional moments, instantiated both in actions, and in the evolving nature of the objects young people are working on, can shed light on children's ideas and thinking as they express *initiative and intentionality* in their work and choices when they devise and pursue new ideas and challenges.

Another contribution of the study is the operationalization of the social and collaborative nature of the tinkering setting, a feature of tinkering that is reflected in much of the extant literature on making (e.g., Brahms, 2014; Sheridan, in press; Vossoughi et al., 2013). In the dimension *social scaffolding*, the Framework draws explicit links between the social group and the social individual, by noting the dynamic interplay within the tinkering setting as ideas and tools travel (i.e., are offered or taken up by learners, explicitly or tacitly). The example of Sarita and Molly, and also of Eric and Sharon, shows how different actors support and inspire one another to push their understanding. Finally, in addition to operationalizing *developing understanding* as including verbal statements that indicate learning, the study identifies the development of questions, verbal or embodied in action, and struggle, as indicators of a process of developing understanding through tinkering.

Further exploration, testing, and elaboration of these dimensions and indicators is needed to advance research as well as evaluation frameworks for making and tinkering programs.

### Research Used in Practice

We undertook this study as a jointly negotiated project to increase the likelihood that results would not only inform research-oriented educators, such as readers of *Science Education*, but also would address the immediate needs and practices of ISE educators. As it turns out, practitioners within the r+p team are using the Tinkering Learning Dimensions Framework in several of their current endeavors. For example, in the summer of 2014, the Framework was used in a 6-week online Exploratorium Fundamentals of Tinkering MOOC designed for formal and informal educators. The course, offered via Coursera, enrolled over 7,000 people and had an extremely active discussion forum with more than 5,600 posts. In one of these posts, a participant commented about the Framework (the posts have been lightly edited for readability):

> I always believed that tinkering promotes initiative but my concern was how can a tinkering classroom maintain high levels of intentionality from students? So, I was relieved to see in the videos [of tinkering in the museum and in classrooms] how students were setting goals for themselves, asking deep questions, interacting with the facilitators and responding to their feedback. Of course engagement was quite apparent as I expected. However, it was surprising to see clear evidence in the short videos of students developing understanding. Many students were having Aha moments, offering explanations, testing their designs and retesting them.—Coursera Participant A

Another participant wrote:

> . . . I agree with your point about the importance of playfulness and discovery when tinkering, but I also think that intentionality is important when it comes to the act of tinkering. What I understand from this learning dimension is that whoever is doing the tinkering has to have a purpose to what he or she wants to accomplish. Whether it's attaching a battery onto the wires of a motor to make something spin, or taping some markers into the sides of a plastic cup to create a scribbling machine, it's all very "intentional." One of the examples I can recall that better explains my point is when a teacher from one of the videos was saying that a student made her scribbling machine make circles, and as soon as other students saw that, they wanted to have their machines do the same thing. They were intentionally tinkering with their machines to make it have a specific purpose- to make it draw circles and this was after they had a chance to play with their materials. This makes me wonder if intentionality naturally follows playfulness, but I agree that this is one of the harder dimensions to pinpoint.—Coursera Participant B

Interestingly, in the Coursera class, most participants wrote that *engagement* was easy to see, but that *intentionality and initiative* was more difficult because it required more time and close attention, two factors that were not always available in the classroom. For example:

> . . . Engagement is the thing that jumps out right away from the framework, while I also thought Initiative and Intentionality is the most difficult to observe. As far as setting one's own goal, I imagine that often learners wouldn't even be able to articulate their goal when they had one. I guess as a teacher you could check in with student to ask about what they were trying to accomplish. I thought the "intellectual risk" criterion would be difficult to observe as well. I guess a little later in the school year, I might know which students were taking risks, but if the student were a stranger to me, would I know if the kid was pushing or just coasting? (Not that the framework is designed to that, of course, just trying to answer the prompt.)—Coursera Participant C

And

> Intentionality and social engagement could be difficult aspects to see or hear because this means as a teacher you really have to be down and listening to the students. Listening to the students sounds obvious I know however, I am thinking 22 students, all this gear out, and time constraints, and a point to be made. I am middle school and each class is 50 minutes, I'm not saying impossible just a challenge.—Coursera Participant D

The pragmatic concerns that teachers described in their reflections on the learning dimensions, and particularly the idea that observing intentionality and understanding takes time, might suggest a special role that out-of-school-time programs, such as summer camps or regular afterschool programs, could play in supporting tinkering opportunities. These programs generally have lower student-to-teacher ratios and the potential ability to spend more extended time on one activity or set of activities (because of the lack of pressures for covering a broader curriculum). The teachers' concerns also suggest a need for more research and documentation on how teachers can effectively adapt and implement tinkering into the school day.

In addition to their use as a professional development structure to draw educators' attention to key features of the process and the experience, the dimensions were used to develop a video library of examples of learning in tinkering. This tool organizes the video callouts in a searchable FileMaker™ database that we call the *library of tinkering exemplars*. Each exemplar includes a link to the final video clip, an analytic description of the salient moment, as well as tags for various characteristics such as the type of activity in the clip (the video clips themselves are hosted on a password-protected server). We made the entire video library available for download from the Exploratorium's Web site, hoping that researchers would be interested in our categorization scheme and practitioners would find the videos useful for professional development. So far, we have received an enthusiastic response from the community, with both researchers and practitioners downloading the library.

## The Role of Jointly Negotiated Research

We posit that the active use of the results and products of this study stems from the process of jointly negotiating both research questions and interpretations. We note that time, forms of evidence, and the judicious introduction of specific techniques or craft were critical to this process.

A defining characteristic of the study was the investment of time made by both research and practice groups. The group met over the course of 2 years, at times as frequently as every 2 weeks, with scores and scores of hours spent on discussion and joint analysis alone. In retrospect, we believe that this investment of time was essential for developing trusting relationships that could equalize power relations such that the experiences and insights of both researchers and practitioners came to be valued by one another. Reaching complete agreement, a goal essential to the study to raise the probabilities that the products of the research would be used in practice, took a great deal of time. But walking away before reaching complete agreement might have produced Frameworks that could have served future research, but not current or future practice.

Videos were an important form of evidence for practitioners because they easily lend themselves to sharing and reflection in professional development contexts. But to support the aims of creating a consistent and validated video library, only actions (statements or gestures) that were countable and indexable could be included as indicators. While this approach supported the research aims, it meant that practitioners had to let go of some indicators that they might have otherwise employed, such as learners creating something novel in the Tinkering Studio. The limitations of the form of the data were a point that came up many times during the project: Practitioners were sometimes frustrated that things they intuited, felt, or even concretely experienced were not visible in the videos. The overriding concern of producing valid results, that could be used confidently in practice, along with the time and iterations invested by the r+p team, ultimately made the limitations acceptable to the practitioners, and conversations became increasingly evidence based. Coming to understand research as providing important, but necessarily incomplete, views into practice—as opposed to providing the whole and complete "answer" —was an important breakthrough. We contend that adopting this sophisticated view of research will enhance the team's capacity to engage in jointly negotiated research in the future.

Important practitioner insights related to "craft knowledge" or tinkering techniques allowed researchers to gain new ideas about indicators for learning, such as when practitioners suggested that clearing away a space before restarting an activity indicated a learner's engagement or intentionality. Similarly, the deep value that tinkering practitioners placed on learners' struggles (becoming stuck and achieving a breakthrough) pushed the research team toward viewing the *struggle* to understand as an important indicator of learning. Similarly, the introduction of the research construct of a "problem space" significantly accelerated joint analysis in that it simplified the unit of analysis away from the holistic experience (which may include intentions and interpretations on the part of the analyst) toward a definable unit characterized by visible and audible actions and expressions. Until this research construct was introduced, the team had struggled with the tension of holism versus indexicality.

This kind of give and take by both researchers and practitioners took time but produced a Framework and a video library that the practitioners are actively using. Most importantly for our work together at the museum, the overall capacity of the group to engage in joint, evidence-based discussions has been greatly enriched by the experiences of struggling together to develop a shared understanding for the Framework.

## CONCLUSION

Tinkering and making are potentially powerful contexts for learning. But although they have deep roots in leading theories of pedagogy, in the present era of educational accountability, they challenge many stakeholders' ideas of "what learning looks like." We believe that it is essential that researchers in the learning sciences directly engage with tensions or contradictions between educators' expansive visions of what learning looks like and the sometimes more restricted accountability era definitions of learning (Booker, Vossoughi, & Hooper, 2014). Booker et al. argue that this is most important for addressing issues of equity in education. The Tinkering Learning Dimensions Framework is one attempt to capture the powerful dimensions of learning that have meaning to both ISE practitioners and learning scientists working in ISE contexts. The findings link to theory, to research, and to the design and implementation of future practice. But more research is needed to further develop our understanding and expand our examples of learning through tinkering, across a wide array of communities, participants, and organized settings.

In close, we note that at the intersection of the learning sciences and ISE are a permeable set of ideas, people, values, and methods. We posit that, by supporting critical engagement among researchers and practitioners, research will address questions that are more salient and important to both ISE researchers and practitioners, will employ methods that more effectively account for the realities of practice, and will produce results that may better inform practice. We suggest that as collaborations in the learning sciences and ISE advance, researchers would benefit from undertaking and documenting more jointly negotiated research, in particular accounting for the allowances made to produce usable results, and documenting the use of such knowledge in practice.

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