# What Counts as Scientific Practice? A Taxonomy of Scientists' Ways of Thinking and Doing

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**Abstract:** Education reformers advocating the use of GIS in K-12 science classrooms claim that the tool provides authentic contexts for students to think and act scientifically. However few studies, if any, have empirically investigated the latter. I observed a marine ecology laboratory to determine what counts as scientific practice, and then an 8th grade oceanography classroom to see whether and how these practices played out there, especially around participants' use of GIS software. This paper focuses on the methods I used to draw meaningful comparisons between the novice and expert settings I studied. In particular, it describes the taxonomy of scientific practices derived from my laboratory observations, and then the nature of work in the lab as seen through this framework.

## Introduction

As globalization and rapid advances in technology change life as we know it on a daily basis, the ability to navigate complex information, reframe problems, evaluate evidence, argue persuasively, innovate, and adapt to ever-changing circumstances has come to comprise the standard repertoire of skills required to survive and succeed in the 21st century. Consequently, preparing students to think and act scientifically is an increasingly critical concern. National standards urge teachers to engage students in the practices of professional scientists as a means of developing these habits of mind, and suggest the use of scientists' tools to support their inquiry. A geographic information system is one such tool, and though around since the 1960s, is gaining popularity among a variety of professions. Earth and environmental scientists, fast food franchise developers, epidemiologists, and others use GIS to capture, store, analyze, and display geo-referenced data, which is information tagged by latitude and longitude coordinates. Layering different data sets atop a base map can reveal spatial relationships among the data that are not ordinarily perceptible in nature.

GIS has also been in K-12 classrooms for more than a decade. In addition to fostering students' spatial skills (NRC, 2006), these tools can help science learning better resemble science practice, heightening the much-desired element of *authenticity* in science classrooms—or so education reformers have claimed (e.g., Edelson, 1998; Gordin & Pea, 1995). To empirically test the assumption that GIS promotes authentic science learning, I observed a marine ecology laboratory first to determine what counts as scientific practice, and then an 8th grade oceanography classroom to see whether and how these practices played out there, especially around participants' use of GIS software. When students have access to scientists' tools, do they use them in ways that scientists do? While the primary interest of my larger study was inquiry learning in science classrooms (Takeuchi, 2008), this paper focuses narrowly on the methods I used to draw meaningful comparisons between the novice and expert settings. In particular, it describes the taxonomy of scientific practices derived from my observations in the laboratory, and then the nature of work in the lab as seen through this framework. As far as I am aware, no other such taxonomy exists. Limitations of the catalog and its implications for science education research are also discussed.

## Past Approaches to Studying Authentic Learning

What counts as scientific practice? Would I recognize authenticity in the 8th grade classroom when I saw it? To be sure, the field of science studies (1) has over the past quarter century generated a multitude of models of scientific practice, but none to date have examined scientists who use GIS per se. And while other studies of authenticity in science learning reference models of professional practice, few have directly compared the naturally occurring activities of novice and expert scientists. Rosebery et al (1992) and Krajcik et al (1999), for instance, focused on classroom inquiry but made comparisons with the generic, composite portraits of working scientists advanced by the science studies literature. Other studies have directly compared experts and novices, but on simulated tasks (e.g., Kuhn, 1989; Lowe, 1999), raising issues of ecological validity.

Another approach to studying the practices of novice and expert scientists involves the comparison of archival accounts of scientific work. Since this approach makes use of audio- or videotaped footage of naturally occurring activity, researchers are able to take into account the situational features that simulated tasks cannot. Hall (1999), for example, examined videotaped footage of people "having a theory" in a medical school classroom and around a family dinner table. Similarly, Koschmann and Zemel (2006) compared audio- and videotaped accounts of professional astronomers "doing discovery" at an observatory and two high school students doing the same using a physics simulation on a computer. Since comparisons were based upon other people's recordings, interpretations of recorded events were necessarily mediated through the original researchers' selection, framing, and view of events. Another limitation of this approach is that researchers have limited access to information about the participants or about the broader contextual features of each situation, as the events depicted in Hall (1999) and Koschmann and Zemel's (2006) studies had long passed by the time these authors got around to analyzing them.

My research is more closely modeled after Stevens' (1999) first-hand accounts of activity in the novice and expert settings he set out to compare by intent. He investigated everyday math activities as they emerged in a middle school design project and in the real-world design projects of an architecture firm. In the seven months he spent in the classroom and year observing architects, he witnessed how tools such as CAD software, available to both students and architects, mediated project activity in ways reflecting the culture of each institution. Comparing the forms of mathematical practices across the two settings, Stevens concluded that the organizational environment of the school—e.g., an assessment system that values equality over diversity, and the structure of the school day—makes it difficult for students to engage in meaningful mathematical practices and, consequently, learn very much.

## Methods

I adapted the design of Stevens' (1999; described above) study to investigate how scientific practices emerge around the use of GIS in an 8th grade oceanography classroom and a university marine ecology laboratory. The unit of analysis in each setting was the activity system (Engeström, 1999) of a small team conducting a research investigation. The laboratory case team consisted of a marine ecology doctoral student and his field assistant, who were studying the movement patterns of a particular fish species. The classroom case team comprised two 13-year-old boys investigating the kelp forest ecosystems of Catalina Island. I collected data intermittently over a 9-month period in the laboratory, and over 11 consecutive weeks in the classroom. In both settings I took field notes, conducted interviews, collected artifacts, and videotaped human-human and human-computer interactions.

### Operationalizing "Scientific Practice"

To identify scientific practices in the laboratory, I first had to define "scientific practice." Operationalizing the concept to support meaningful comparisons between laboratory and classroom settings proved challenging: Framing it too closely around the technical aspects of scientists' work, for example, provided too little to compare or even contrast. Crafting a definition around the inquiry processes we want students to develop, on the other hand, rendered the comparison to professional practice extraneous. In the end, I combined aspects of Rouse (1994), Pickering (1992), and Edelson's (1998) ideas into a definition that I thought would best serve the purposes of this study:

> Scientific practices are sustained, dynamic, and communal acts of purposeful inquiry. These "patterns of activity in response to a situation" (Rouse, 1994) manifest the beliefs, values, and experiences accumulated by the scientific community over time, and include ways of thinking and doing, attitudes, and social interactions.

This definition does not include scientists' tools and resources per se, and it intentionally omits formalized investigative procedures like *run experiment* or *analyze data*. I instead use these organized activities as framing contexts for their more spontaneous acts of scientific thinking, doing, feeling, and interacting. Moreover, since I observed all phases of the students' investigation but just the scientists' data collection phase, the case teams' individual sets of procedures would have been incommensurable.

### Coding for Scientific Practices

Several science studies scholars have contributed to theoretical notions of scientific practice (e.g., Latour & Woolgar, 1987; Knorr-Cetina, 1981; Pickering, 1995; Rouse, 1994). However, I was unable to locate previous work that comprehensively indexed a practical list of scientific practices that could serve as the basis for my cross-setting comparisons. I myself would have to empirically determine what counts as scientific practice. So, once data collection was complete, I used the above definition to generate codes for scientific practices seen in the laboratory. Through the process of analytic induction (Znaniecki, 1934) and deduction, each practice was assessed for its generality across the corpus of data and revised or dropped if counterexamples were found. I made several passes through the data to ensure that all practices fit the working definition—itself revised several times—and that none were subsets or duplicates of others. While the present set of codes is by no means comprehensive, it is a starting point for more systematic efforts to concretize the rather abstract notion of scientific practice.

I then used HyperRESEARCH qualitative data analysis software to code instances in the laboratory case's field notes and video content logs for the identified practices. I also chunked these data by *task*, which I've defined as "a clearly delineated piece of work that is of short or limited duration and performed to move the investigation forward." The task served to bound the scientists' work activities into discrete units of analysis so that scientific practices could be tallied within each task. However it is important to note that these tallies may be more indicative of my observational sampling than the quality or complexity of the corresponding tasks.

## The Laboratory Setting and Participants

Kinder Marine Laboratory (all names are pseudonyms) is a large, ocean-side research facility of a prominent West Coast university. Between July 2006 and April 2007, I observed marine ecology doctoral student Fred (age 33) and his field assistant Kyle (age 28) during the fourth of Fred's five-year long dissertation study. Fred's research focused on the movement patterns of individual spotted purplefish in relation to features of the local purplefish population (size, density, reproductive behavior) and environment (bottom types, biological habitat). Findings would have implications for the design of marine protected areas (2), since the effectiveness of these reserves depends on the extent to which they accommodate the full range of movements of the individuals they aim to protect. I started observing the team one year after Fred began collecting data, and just one week after Kyle started as Fred's field assistant. The case scientists belonged to the smaller, 20-person Coniglio-Ross Lab for Marine Ecology Research at Kinder (nicknamed the CR-Sea Lab), and were the only ones there at the time using GIS in their research. In fact, when I met Fred, he was just learning GIS because he knew the tools would facilitate his research.

I observed Fred and Kyle in three locations: (a) at the CR-Sea Lab; (b) *above* Fred's research site out on Cabezon Harbor (I went out on their research vessel the *Otter's Nest* but did not accompany them underwater on their scuba dives); and (c) inside the van they used to transport the *Otter's Nest* between these two locations. Although I focused my attention on Fred and Kyle's activities, I also captured some of their interactions with members of the wider Kinder community, including faculty scientists, technicians, and other graduate students.

## Scientific Practices Observed in the Laboratory

In my 40 hours observing and interviewing the case study scientists, I recorded the following 45 scientific practices. They are listed in Table 1 order of frequency logged, from highest to lowest. Since I did not visit the scientists on a daily basis, and was not able to observe them over the complete course of their five-year-long project, the practices on this list do not represent the complete repertoire of their work. As such, the corresponding frequencies should also be taken as relative indicators and a specific reflection of the days I chose to observe there. Following this list are discussions of the top 15 observed practices. (See Takeuchi, 2008 for descriptions of all 45 practices.)

Table 1. Scientific practices observed with the case study scientists

| Practice | Frequency | Nature | Practice | Frequency | Nature | Practice | Frequency | Nature |
|---|---|---|---|---|---|---|---|---|
| Use inscription | 34 | d | Connect study to personal exp. | 9 | e | Be meticulous/organized | 5 | d e |
| Maintain equipment | 20 | d e | Hypothesize | 9 | e | Communicate data/findings | 5 | d e |
| Divide labor/expertise | 18 | d | Partake of comm. resources | 9 | d | Compete for resources | 5 | d |
| Accomm. natural phenom. | 17 | d | Reason with others | 9 | d e | Discover/Achieve insight | 5 | |
| Identify pattern | 17 | d | Seek help | 9 | d e | Make meaning | 5 | d |
| Let tool shape research | 17 | d e | Seek new knowledge | 9 | d e | Put safety first | 5 | e |
| Apprentice | 15 | d | Strive for reliable data | 9 | e | Reframe problem | 5 | e |
| Follow ritual | 13 | d | Tweak tool/technique | 9 | e | Take risk | 5 | e |
| Save time/resources | 13 | d | Ask question | 8 | e | Be driven by ulterior motive | 4 | e |
| Accomm. misbehaving tool | 12 | d | Camaraderie | 8 | d | Deal with messiness of data | 4 | d e |
| Be committed/persistent | 12 | e | Modify plans/thinking | 8 | e | Ideate | 4 | e |
| Master routine | 12 | d | Participate in community | 7 | d | State limits of data/tool | 4 | e |
| Plan/Prep | 12 | d e | Appropriate new tool | 6 | e | Connect study to world issue | 3 | d e |
| Be uncertain | 10 | e | Tinker with tool | 6 | d e | Do politics | 3 | d e |
| Reason with tool | 10 | d | Apply background knowledge | 5 | d e | Invent | 3 | e |

Notes: d = Practice is a manifestation of or response to the *distributed* nature of work.
e = Practice is a manifestation of or response to the *emergent* nature of work.

## 1. Use Inscription (34)

Fred and Kyle used inscriptions (3) in nearly every task I observed, plus the ones that took place underwater. They printed waterproof maps of the harbor's depth to serve as underwater guides to the seafloor; analyzed individual fishes' home ranges on the GIS; and projected slides of fish tag expiration timelines on the lab wall to solicit help from advising professors, among other things. As the study's principal investigator, Fred spent much more time than Kyle did constructing and managing inscriptions for the planning, data collection, analysis, and communication activities they performed together.

## 2. Maintain Equipment (20)

While Fred took care of preparing inscriptions, Kyle was often occupied with maintaining the *heavy* equipment required to do their scientific work, including the 30-foot research vessel the *Otter's Nest*, the trailer that transported the *Otter's Nest* to Cabezon Harbor, and the rusty old van that towed the trailer 100 miles roundtrip to and from the harbor. Equipment maintenance involved packing up transport vehicles with equipment used on dives, filling vehicles with gas, fixing broken items, cleaning up and storing equipment, and making arrangements for regular servicing. Kyle also maintained the team's scuba tanks and the four buoys—each weighing 43 kilograms—that served as receivers for the acoustic tracking system set up in the harbor. I emphasize *heavy* above because the lighter equipment associated with inscriptional work—i.e., Fred's laptop, the lab's GIS desktop computer, and the GPS unit—for the most part fell under Fred's jurisdiction, as did the tiny and expensive acoustic tags that were surgically implanted into the fish for tracking by the telemetry system.

## 3. Divide Labor or Expertise (18)

Fred and Kyle often assumed responsibility over separate tasks in order to accomplish the maximum amount of work out of available time. Divisions of labor usually fell along lines of expertise, professional rank, location, or individual commitments. Fred, for example, managed the fish tag equipment because he possessed more specialized knowledge about the technology than Kyle did. And it was Kyle's job to load the van up each morning at 6:30 AM because this is the type of grunt work that field assistants are hired to do. On lab days—versus days spent in the field—Fred often worked inside completing paperwork, writing research grants, or working with software, while Kyle could be found outside in the storage sheds fixing or maintaining equipment. In many cases, work could only be accomplished on this two-man team if tasks were divided. Fred, for example, always steered to position the boat using his GPS unit as a guide while Kyle dropped anchor. Divisions of expertise also contributed to the efficiency of the work team, as when Fred had Kinder's resident geneticist run DNA tests on the fish eggs he collected.

## 4. Accommodate Natural Phenomenon (17)

As much as scientists attempt to maintain control over all aspects of their research, nature often evades management. Fred and Kyle had to adjust their plans, tweak their equipment, and redesign their investigation to accommodate the occasional unforeseen and uncontrollable behaviors of the fishes under study. In the spring, when Kyle was having no luck locating egg nests of the fishes they had tagged the previous summer, Fred decided to extend their egg hunts beyond his study site to untagged fish. Doing so would increase his sample size, but disassociate a set of genetics tests he wanted to run from the home range aspect of his study. The scientists' work was also at the mercy of the sea and the sky. Environmental events—e.g., high surf, cold water temperatures, algal blooms—regularly altered their course of action on a moment-by-moment basis.

## 5. Identify Pattern (17)

Scientists often craft visualizations of their data to reveal patterns that remain hidden in rawer formats. These patterns help them make predictions and make sense of the represented phenomena. In a laboratory meeting convened around the mysterious disappearance of several fish Fred had tagged earlier in the year, the participating scientists rarely referred to one of the displayed graphs, tables, or maps without extracting some less-than-obvious pattern from it. The three senior scientists in the room surfaced patterns in Fred's data that even Fred had never seen. They were so generative in this regard, in fact, that it was as though they couldn't look at an inscription without looking for underlying patterns. By meeting's end, their interpretations of the data led the group to the conclusion that Fred had perhaps ill advisedly constrained his study site to the published receiving range of the buoys, and needed to expand it to cover the region that his tagged fish actually inhabit.

## 6. Let Tool Shape Research (17)

The scientists often allowed the affordances and constraints of their tools influence how they designed or proceeded with their investigation. What Fred and Kyle managed to accomplish in a day's data collection expedition, for example, depended on the number of scuba tanks they brought with them on the boat (also limited by the size of the boat) and the oxygen composition of each tank. A tank holding 1,200 pounds of air gave each diver 45 minutes to complete a fish density or UPC survey of one reef in their study site. The oxygen-enriched tanks with a 20/80 oxygen to nitrogen mix allowed Fred and Kyle to perform more physically exerting tasks, such as underwater fishing (4), in the same amount of time, but were harder to obtain at Kinder. Sometimes Fred and Kyle's air supplies dictated their dive itineraries. As Fred once instructed Kyle just before their final dive of the day, "Let's just make sure that we come up with enough air to switch the buoy out, and if we catch one (a fish), that we come up with enough air to bring it back down."

7. Apprentice (15)

Fred hired Kyle as his field assistant just two weeks before I started observing them, so I got to witness a critical stretch of Kyle's on-the-job training. Very little time was set aside for direct instruction. Instead Kyle was expected to watch Fred perform a procedure once through, such as locating and unmooring the telemetry buoys, or preparing their rods and reels for underwater fishing, before taking responsibility for the task the next time. Although it was up to Kyle to direct his own learning—by asking Fred questions rather than waiting for Fred to provide lock-step instructions—Fred was fully cognizant of the training session in progress. In fact, when there were new techniques for Kyle to learn, Fred often made sure his apprentice stayed near enough to see him model the activity. These learning episodes were among the rare occasions that the teammates worked on the same task simultaneously.

8. Follow Ritual (13)

During the summer field season spanning July through October, the scientists ran scuba expeditions four days of the week to collect data and maintain their telemetry equipment on the harbor. Field days began at 6:30 AM loading up the boat and van at the lab, and included a 100-mile round trip drive to and from Cabezon Harbor, where they took three or four scuba dives over the course of four or five hours. Days often ended past 6:00 PM, after hosing down and storing all of the equipment. Between tasks, scientists participated in a number of social rituals to take the edge off of this grueling work. Morning trips to Emmy's Bakery for muffins and coffee, for example, were mandatory even when the scientists were running behind their on-the-road-by-7:00 schedule. Other social rituals included the "hot water bucket" that researchers would pour down their wetsuits after their last dive of the day to warm their bones, and chitchat on the long drives between Kinder and Cabezon Harbor. These commonly shared experiences helped build rapport within the Kinder community, and were passed down from old-timers to newcomers.

9. Save Time or Resources (13)

Fred and Kyle constantly sought to make the most of their limited time and resources. Some of these efforts were built into routines—as described in *divide labor* and *apprentice*, which are not included in this count—but others involved a conscious pursuit of the most efficient path through their work. Fred, for instance, spent a couple of days constructing and then printing 25 percent contours of the tagged fishes' home ranges so that on scuba dives they could more easily locate egg nests to collect samples. More time spent at the computer meant less time swimming around underwater in search of the nests, expending energy and oxygen stores. Kyle's efficiency-motivated acts include creating drop-down menus in an *Excel* file to speed up data entry and minimize error, and inventing a special belt holding eight large vials and cuticle scissors to make it easier to harvest fragile fish eggs while underwater.

10. Accommodate Misbehaving Tool (12)

Just as the scientists altered their plans or even goals in response to the unanticipated behaviors of the fish, the weather, or the sea, they also accommodated the equipment that broke down or failed to produce some desired outcome (Pickering, 1995). Small misbehaviors, such a leaky O-ring on a scuba tank, might alter the day's data collection agenda, but bigger ones affected changes at a greater scale. The disappearance of half of Fred's tagged fish from telemetry reception, for example, prompted him to spend several weeks catching more fish to tag and include in his study. It also prompted him to rescale his study site in order to monitor a wider region of Cabezon Harbor and, hopefully, to recover reception of those missing fish. Fred and Kyle eventually solved the mystery of the disappearing fish—the batteries in their tags had simply died—but the time, effort, and expense spent in making these adaptations were significant. In a final act of accommodating the faulty fish tags, Fred decided to set the end point of the data collection phase to whenever the batteries in his remaining tagged fish petered out.

11. Be Committed or Persistent (12)

Only the most devoted make it in this field. Based on physical demands alone, those who can't take five months of 12-hour field days and scuba diving in 54-degree waters are weeded out at the level of field assistant. Fred's acoustic telemetry system required that he cycle a charged buoy into the harbor every week of the year, including stormy winter months, so that it would continually monitor Fred's tagged fish without interruption. The considerable commitment of these scientists extended beyond physical work. The unpredictable and often unwelcome behaviors of their fish and tools *(accommodate natural phenomenon* and *misbehaving tool*) often required extra time, money, and exertion to put the study back on track. Patience and perseverance are necessary to deal with the uncertain outcomes and regular disappointments associated with this type of work (Edelson, 1998; Kurz-Milcke et al, 2004):

> Fred: All these tagged fish that I tagged last summer... I did it for two years, right, and they all stuck around for the entire two years. And so I did them all last summer thinking, "Oh, this summer I'll just jump right into manipulating all this stuff." And now I just came back and half of

> them are gone! Ahhhh! It's really disappointing. I mean, but that's part of it. And you get other data from it. But I can totally see like if you don't have that interest and commitment to it, you can get that stop-doing it attitude. It's definitely kind of long and ongoing and always changing.

### 12. Master Routine (12)
The scientists repeated many of the same routines—defined here as regularly repeated procedures—on a weekly, if not daily, basis. Weekly routines included the buoy switching mentioned above. This involved unmooring the least-charged of three telemetric buoys from the harbor floor and transporting it back to the lab for recharging and replacement the following week. Daily routines included loading up the van and boat with the necessary dive and data collection equipment each morning, and unloading it at the end of the day. Certain routines involved complicated procedures that both Fred and Kyle became more skilled at with practice, as they did with their underwater fishing techniques. Other routines, such as loading and unloading transport vehicles at the lab, were familiar practices among members of the wider Kinder community. On the day that Fred couldn't dive due to an ear infection, the field assistant he "borrowed" from another crew was able to step in and perform a number of these institutionalized routines with little instruction.

### 13. Plan/Prep (12)
Due to the tremendous material aspect of their work, along with the fact that it often took the coordinated actions of several people to accomplish a single task, the scientists spent quite a bit of effort orchestrating upcoming tasks. Poring over the minutiae of their data collection, analyses, and presentation activities beforehand helped Fred and Kyle obviate unwelcome complications. It also ensured that minimal time and money were wasted in the implementation. The scientists often spent far more time prepping for than executing target tasks, as examples cited in *save time or resources* suggest. Fred spent months preparing his dissertation proposal, which, once approved by his dissertation committee, served as the official blueprint for his study. But most of the planning I saw took place on a more impromptu basis—on van drives to and from the harbor, while suiting up in the parking lot, or just before putting their face masks before a dive. Fred and Kyle were in constant communication about how to best coordinate their upcoming actions.

### 14. Be Uncertain (10)
Never knowing what to expect next in an unfolding investigation—especially ones marked by *misbehaving tools* and *natural phenomena*—instills in scientists a comfort with uncertainty. The scientists demonstrated this comfort by openly admitting to colleagues what they didn't know, couldn't understand, or were willing to accept as unanswerable, in one-on-one and lab-wide meetings alike. They also demonstrated this comfort in their ability to carry on in their work and make important decisions despite unknown outcomes. Kyle, for example, spent several hours fabricating a special belt to facilitate their underwater egg sampling excursions using random materials he pilfered from around the lab. He had no idea if the belt would work—he had yet to try it out at the time of our interview—since the whole egg collection process was uncharted territory for Fred and Kyle. A common corollary to the scientists' uncertainty was a desire to bring clarity to a situation, and this required a high tolerance for risk. As Fred's advisor Joe pointed out while counseling Fred on whether to shift the scale of his study midway through the investigation, "It's just one of those things that you have to take a shot at and see what's going to happen. That's the way science is. It sucks! Ultimately [...] you're trying to figure out what's the best effort to put my time into."

### 15. Reason with Tool (10)
The scientists reasoned with tools when they used artifacts in their environment to (a) offload complex cognitive tasks or (b) extend their cognitive capabilities. In an example of the former, Fred used a dive watch to help monitor his oxygen usage so that he could instead focus on his underwater tasks. In an example of the latter, he calculated statistics using software. Fred reasoned with the GIS for both purposes. Here Fred describes the advantages the tool brought to his research:

> Well, one thing that it really does the most for me is just to think about all this stuff. To just sit in front of it and actually look at it instead of just having a number. And you can get these distributions of points where the fish is and then you calculate an area and then you know the home range is 500 square meters. But actually looking at the shape and seeing how that fits into the habitat, really that's a big help, I think. And kind of coming up with ideas, and thinking about, "Oh this looks interesting, I should actually do the stats on that."

The spatial and layering capabilities of the GIS freed Fred up from having to translate the text data into something meaningful, and inspired analyses that he wouldn't have come upon unaided by the spatial display.

## The Distributed and Emergent Nature of Science

In the process of sorting through the 45 observed practices, I characterized the science that took place at Kinder Marine Laboratory to be both *distributed* and *emergent* (see tags in Table 1, above). I also established a pattern of *efficient* and *adaptive* responses to the problems presented by distributed and emergent systems. Though these findings merely confirm what empirical research in science and technology studies documented in the 1980s and 1990s, they are worth discussing briefly here, as these constructs helped guide my analyses of the 8th-grade classroom case.

Science is no longer construed as the solitary endeavor of brilliant individuals such as Isaac Newton or Albert Einstein. Scientific research and progress is more readily recognized as the joint achievement of people, organizations, places, and tools, all of which are distributed across space and time (Goodwin, 1994; Dunbar, 2000). I observed Fred and Kyle participate in 28 practices that were manifestations of and/or responses to the distributed quality of their work. Twelve such practices describe social interactions (e.g., *divide labor/expertise, apprentice, partake of community resources, seek help, participate in community, communicate data/findings, compete for resources, reason with others, do politics*), and seven describe their relationships with artifacts (i.e., *use inscription, maintain equipment, let tools shape research, identify patterns, reason with tool, accommodate misbehaving tool*, and *tinker with tool*). This dispersion of knowledge, reasoning, and labor across individuals, artifacts, institutions, and spaces both facilitate and pose particular challenges to the accomplishment of work.

Fred and Kyle often responded to the challenges with efficient measures. Some of these efforts were built into their routines, such as dividing tasks and Kyle shadowing Fred in an apprentice style of learning. But others involved a conscious pursuit of the most efficient path through their work. In some of the examples cited above—e.g., mapping out dives on the GIS to spend less time underwater, or creating drop-down menus in Excel to facilitate data entry—the scientists "sacrifice short-term efficiency to retool [their] knowledge or context for the prospect of long-term gain," in what Martin and Schwartz call a "prospective adaptation" (in press, p. 5). Because Fred's investigation took five years from start to finish, the time investment on any prospective adaptation paid itself off many times over.

Efficiency in the form of procedural speed and accuracy benefits distributed work systems, especially when these systems are stable and see little change. But the work of Fred, Kyle, and most scientists are far from predictable. No matter how meticulously they plan out their investigations, circumstances beyond their control have a way of altering the science that gets done. Pickering (1995) attributes the "temporally emergent" structure of scientific research to the nonhuman or material agency of scientific practice. When a machine fails to produce expected outcomes, humans often accommodate the machine by revising their original goals, or by tweaking the machine or the investigation itself. Other researchers (e.g., Knorr-Cetina, 1981) have documented how the particularities of a research situation—material, personal, or otherwise—influence discoveries in unexpected ways. What becomes scientific fact depends, to a great extent, on the context in which the science is conducted.

This emergent quality of science is also revealed in the taxonomy, with 30 of Fred and Kyle's observed practices falling into this category. I observed the scientists adapt to unanticipated events (i.e., *let tools shape research, accommodate natural phenomenon, accommodate misbehaving tool, appropriate new tool*, and *tinker with tool*), and take action to either anticipate the unknown (e.g., *maintain equipment, plan, seek new knowledge, strive for reliable data, hypothesize, take risk*) or rearrange the environment to handle new problems or information (e.g., *seek help, reframe problem, ideate, invent*). The emergent nature of their work also elicited certain attitudes: *commitment* is what kept Fred and Kyle coming back to work day after day in the face of recurrent surprise and disappointment, and their comfort with *uncertainty* is what permitted them to do so.

## What else counts as scientific practice?

Once developed, I took this taxonomy into an oceanography classroom, where it guided my analyses of a pair of 8th graders' GIS-based investigation of Catalina Island's kelp forest habitats. The students participated in many of the same practices I observed at Kinder Marine Laboratory, suggesting that the GIS provided an authentic context for their science learning. However, they were less inclined to engage in practices classified as adaptive than the scientists were, with evidence indicating that aspects of the school setting steered students toward more efficiency-oriented patterns of response. For a more detailed discussion of the classroom case study vis-à-vis this taxonomy, see Takeuchi, 2008.

Although the 45-practice taxonomy was sufficient for the types of comparisons I drew between the laboratory and classroom settings, it represents just one year (elapsed) of the scientists' work and primarily the data collection phase of their investigation. I imagine that others in the science studies and science education communities might also find value in such a catalog, but to be useful to a wider audience, the list would need to capture the complete investigation cycle. I would enjoy returning to the field to expand and refine the current list by watching practicing scientists over a longer time frame, and by augmenting the data on marine scientists with observations of other types of natural scientists (e.g., seismologists, meteorologists, stem-cell researchers, astronomers). The resulting universal catalog of scientific practices would provide a powerful set of images that could be used for practical and theoretical purposes in science classrooms, research, and policymaking.

## Endnotes

(1) Science studies is a blanket term for the genre of research that examines what scientists do and the nature of scientific knowledge. Within this genre there are a number of disciplines with their own specific methodologies and epistemologies (e.g., sociological studies of knowledge, philosophy of science, postmodernism).

(2) A marine protected area (MPA) is any area of the marine environment that has been reserved by law (federal, state, or local) to protect endangered plant or animal species, ecosystems, and important historical and cultural sites.

(3) Scientists' representations of their objects/phenomena under study. Inscriptions are materially embodied in some medium, such as paper or computer monitors, and include maps, graphs, photographs, equations, diagrams, and hand-scribbled notes.

(4) To implant the fish with acoustic tags, Fred and Kyle had to gently capture them from the seafloor and bring them up to the boat's deck for surgery. They took 2-foot long fishing rods underwater with them and dangled hooks baited with live shrimp right in front of individuals of the target species.

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