Opening Possibilities in Experimental Science and its History: Critical Explorations with Pendulums and Singing Tubes

ELIZABETH CAVICCHI
Massachusetts Institute of Technology

ABSTRACT: A teacher and a college student explore experimental science and its history by reading historical texts, and responding with replications and experiments of their own. A curriculum of ever-widening possibilities evolves in their ongoing interactions with each other, history, and such materials as pendulums, flame, and resonant singing tubes. Narratives illustrate how questions, observations, and developments emerge in class interactions, along with the pair's reflections on history and research. This study applies the research pedagogy of critical exploration, developed by Eleanor Duckworth from the interviewing of Piaget and Inhelder and exploratory activities of the 1960s Elementary Science Study. Complexity as the subject matter opens up possibilities which foster curiosity among participants. Like Galileo, Tyndall, Xu Shou, and others, this student recurrently came upon new physical behaviors. His responses to these phenomena enabled him to learn from yet other unexpected happenings. These explorations have implications for opening up classrooms to unforeseen possibilities for learning.

KEYWORDS: Critical exploration, active learning, teaching, pendulum, history, experiment, historical replication, narrative, resonant phenomena, complexity.

> Teaching … is more about a conscientious participation in expanding the space of the possible by creating the conditions for the emergence of the not-yet-imaginable. … Teaching, like learning, is not about convergence onto a pre-established truth, but about divergence – about broadening what can be known and done. In other words, the emphasis is not on what is, but what might be brought forth. Teaching thus comes to be a participation in a

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> recursively elaborative process of opening up new spaces of possibility while exploring current spaces. (Davis & Sumara, 2007, p. 64)

In their recent essay, quoted above, Davis and Sumara (2007) dispute such teacher-dominated assertions about education, as that teaching can directly cause pre-specifiable outcomes or indirectly trigger learners to undergo change. Instead, their view on what teaching can accomplish is both more modest – we cannot say in advance what will result from an educational intervention – and more expansive – the possibilities are not even imaginable beforehand. The work of teaching is to bring about conditions of ever-widening possibilities for exploring and engagement among learners and materials. Excerpting episodes from their own English and math education classrooms, Davis and Sumara show how the vibrancy of students' work is rooted in the diverse materials, ideas, and expressions that students engage with collectively while composing a poem or defining a mathematical operation. Not only is the poem or operative definition not something that could be extrapolated from the start, but it also resonates with the many provisional ideas and forms that arose in the students' creative process. As the students developed what they were doing, they became more attuned to new possibilities that surface through involvement by them and their teacher.

To teach by opening possibilities and following them responsively while letting curriculum emerge, is also to research, explore, and create. The story of what happens through integrating teaching, learning, exploring, and researching is in itself a resource for understanding the process and developing in our awareness of the emerging and unforeseen possibilities that it engenders. This paper relates such a story, based on the lab experimenting of a teacher – myself – and one student during a one-semester seminar course. The experimental phenomena we worked with, such as pendulums and resonating tubes, have a standard, formulaic description in conventional science texts. Yet these same phenomena also have a human history of discovery, confusion, and development. That history offers the potential that anyone subsequent may respond to these phenomena with curiosity, engagement, and emergent understanding. Encouraged by the example of history, I look for "what might be brought forth," both for me and for my student. By learning together with my student, I watch for what we notice, wonder about, find confusing, or try out with materials. Our experiences become a threshold for where we might go next. The curriculum of what we do evolves out of our interactions together and with physical and historical materials.

Critical Exploration as a Setting for This Study

In conducting our class through doing experiments by which we uncovered ever-widening possibilities, my student and I engaged in the combined pedagogy and research methodology of *critical exploration* developed by Eleanor Duckworth (2005/2006c). In describing this work, Duckworth likens the teacher's role to that of a poet:

> Just as the poet seeks to present his thoughts and feelings in all their complexity, and in so doing opens a multiplicity of paths into his meaning, likewise a teacher who presents a subject matter in all its complexity makes it more accessible by opening a multiplicity of paths into it. (1991/2006b, p. 133)

I found this poetic analogy also to pertain in teaching science experimenting. As we became aware of complex, seemingly unruly behavior in the phenomena, that more textured view at the same time harbored clues or means by which we might probe it further. Since teachers do not customarily regard a subject's complexity as an asset; Duckworth seeks to arouse that appreciation in teachers of all levels and subjects: "the ability to recognize unsuspected complexities in what seems like straightforward, even elementary, material. … It is always in confronting such complexities that one develops real understanding" (Duckworth, 1991/2006b, p. 140).

The "straightforward" depictions of science instruction were more available, to me and my student, than the subtle ways that materials, motions and other physical behaviors interweave. We had to work at seeing the underlying complexity. Apart from meetings with my student, I explored our lab materials on my own. In that way I attended to expanding my observations, experimental responses, and openness. My ongoing research of science history further assisted me, by extending the range of experimental possibilities beyond today's well-worn routes of conventional instruction. Along with noticing that there was not just one way to work with materials and perceive their physical behaviors, my interest deepened. The narratives below describe some of my inquiries which provoked me to continue widening the explorative options in our curriculum.

The openness and inquiry that I sought to develop in teaching, lay not just in relation to the lab materials and their physical behaviors, but also in my responsiveness to my student, his activities, and learning. Duckworth associates this quality in a teacher's work with researching:

> One is in a position through teaching to pursue questions about the development of understanding that one could not pursue in any other way. If as a researcher one is interested in how people build their understanding, then the way to gain insight is to watch them do it, and try to make sense of it as it happens. (Duckworth 1986/2006a, p. 185)

While working with one student, I sought to follow, as closely as I could, what he did and observed with experimental materials, and the ever changing ways he understood his work. Viewing the various forms of my student's participation as integral, I did not consider any one form, such as speaking, to disclose more of his provisional understanding than any other form, such as manipulating materials. During our sessions, my researching activities included: watching closely, taking notes, photographing experimental configurations, asking questions as well as allowing space for my student to just think and look without talking. Between sessions, I transcribed audiotapes made during class and wrote journals from what we did and observed, along with my thoughts and questions. These interactions and reflections involved me in apprehending my student's experimenting more fully than what I grasped in the moment. This fuller record of our experimenting, with the confusions or surprises emerging for him and me, enriched my relation to its vagaries and not-yet-expressed possibilities. Researching our ongoing work sustained and enhanced the teaching and learning within it.

Critical exploration has historical origins in the clinical interviewing of Jean Piaget (1926/1964, 1937/1964) where by engaging children with ideas and activities, the researcher learns about the structure of their thinking. Realizing that the processes of learning could be interactively observed and demonstrated, Piaget's associate Bärbel Inhelder (Inlhelder, Sinclaire, & Bovet, 1974) first characterized the methodology for doing this research under the name "critical exploration." Inhelder's description of the researcher's challenge bears much in common with the teacher's role in the examples here; through listening without being suggestive, the researcher seeks to know the span of possible child responses. Surprise is revealing: "the more unexpected the child's responses, the more productive" (p. 21) for stretching the researcher's understanding.

In his last books, Piaget (1981/1987; 1983/1987) expanded on these observations by describing a subject's engagement with an ever-emerging field of possibilities as the means and motor of the equilibrating process by which he represented development in their thought and action. A new possibility presents us with something to react to, in the course of which we stretch ourselves while becoming aware of unforeseen limitations, uncertainties, and possibilities. Its emergence is enriched by all our past and ongoing experiences, without being either stepwise predetermined by them or linearly directive toward a particular next step. The process of developing ourselves through and with possibilities is "an infinite sequence of reequilibrations" (Piaget 1981/1987 p. 152), where even that "sequence" is widely sporadic as evolving experience.

A second historical basis for critical exploration lies in the exploratory activities of the 1960s Elementary Science Study (ESS), developed with participation of philosopher David Hawkins (1974/2002b), physicist Philip Morrison (1964/1970), teacher Mike Savage, and others. Curriculum activities were organized around materials, not abstracted topics, such as: light and shadow (ESS, 1965), batteries and bulbs (ESS, 1966), or sand (ESS, 1968). Hawkins' description of childrens' "messing about" with pendulums during an ESS class exemplifies the fertility of possibilities in classroom exploration:

> Simple frames, each designed to support two or three weights on strings, were handed out one morning in a fifth grade class. After two hours … we allowed two more … [*for*] weeks … [*with*] no evidence of boredom. … Most of the questions we might have planned for came up unscheduled. … They varied the conditions of motion in many ways, exploring differences of length and amplitude, using different sorts of bobs, bobs in clusters, and strings, etc. And have *you* tried the underwater pendulum? They did! There were many sorts of discoveries made, but we let them slip by. … So discoveries were made, noted, lost, and made again. (Hawkins, 1965/2002a, p. 68)

Hawkins' sense of emergence and re-emergence of insights from possibilities inherent in phenomena relates to experimentation in science history, as well as to the children. Anomalies or unexpected behaviors attract historical experimenter's intereest, giving rise to new investigations and observations that branch out by nonlinear paths (Gooding, 1990; Holmes, 2004; Steinle, 1997). Studies conducted by historians to replicate historical experiments come upon yet other kinds of observations and investigative paths (Cavicchi, 2006a, 2008a; Heering, 1994; Sibum, 1995; Staubermann, 2007; Tweney, 2006).

Similarly, the redoing of historical experiments in science classrooms elicits unexpected questions, ideas, and further lab activities (Cavicchi, 2006b, 2007a,b,c, 2008b; Crawford, 1993; Heering, 2000, 2007). The historical dimensions of science experimenting affirm the authenticity of multiple possibilities that are essential to genuine inquiry, yet are routinely suppressed under the requirements of most science labs as actually conducted in schools (Hofstein & Lunetta, 2003). By intertwining history with the educational laboratory, this study seeks to illustrate the inherent productivity of opening up possibilities for a student's experimental inquiry.

The setting of this study was an elective undergraduate lab seminar with the theme of recreating historical experiments as the jumping off point for our own investigative work (Cavicchi, 2007c, 2008b). Mingwei Gu, the student, enrolled in this seminar during the second term of his freshman MIT coursework in science and engineering. Our readings and activities were diverse – broadly spanning history and phenomena – yet these interconnected in the process of our experimental experience. We looked at Persian manuscripts in a rare book library; discussed the optics of Ibn al-Haytham (1989) and Shen Kua (Needham & Ling, 1962); read historical writings on electricity; viewed scientific notebooks ranging from Galileo (1999) to Thomas Alva Edison (2004) to Harold Edgerton; contemplated science in China(Needham & Ling, 1962; Elman, 2005, 2006; Wright, 2000); reconstructed Volta's pile (1800); visited Ray Giordano's collection of simple microscopes in the MIT Museum (Giordano, 2006); watched *The Powers of Ten* video (Eames & Eames, 2000); explored flames, mirrors, and lenses; blowpiped candle flame to melt glass rods into bead lenses; redid Tyndall's production of sound from flame (1867/1889).

I prepared these activities by conducting my own investigations in the lab, library, and internet resources. Some readings and lab materials were challenging to find. Dealing with something unexpected was as much a part of my work in preparing our curriculum as of experimenting during our sessions. My close documentation of lab work by myself and my student, as well as my narrative and reflective writing between sessions provided a resource for developing my ideas while teaching, and for writing subsequent to class meetings.

The two narratives below embody a subsequent analysis, integrating all the forms of our experimental data and records, as well as later reflections. The first passage comes from early in the term, as we read Galileo and explored pendulums. The second narrative discusses work near our semester's end, as we attempted to produce sound from tubes lowered over gas flames, in analogy to the examples of Faraday (1818) and Tyndall (1867/1889).

Pendulums with Variability

Our pendulum activities began with talking after reading Tom Settle's essay on Galileo's explorations of motion (Settle, 1996). In a fictional passage about Galileo watching a lamp swing back and forth during a musical performance, Settle portrays the confusing array of observations and questions that an experimenter faces. Telling it in his own words, Mingwei reanimated Galileo's effort to check out the beat's consistency:

Mingwei: Its amplitude got shorter every time … the period of this pendulum was very very constant. … He *[Galileo]* knew … he couldn't trust his musical ear, although he had a very good one; he couldn't depend on his heartbeat staying the same. … He did have a way of testing this, which was … using multiple pendulums, of the same length, and starting them at the same time, stopping one and starting it again, he showed that how the different [*ones*] that went through a cycle, had the same period.[1]

The story impressed Mingwei with a new realization: neither heartbeat, nor music, nor anything else in Galileo's day, kept steady time. About this historical context, Mingwei said: "there wasn't exact measurement of time." In turn, his sense that Galileo introduced ideas about what Mingwei called time's "constancy" intrigued me so I asked how he saw this. Mingwei then pondered whether Galileo's analysis of time might underlie the famous conflict between his new science and the old "tradition of beliefs."

Moving from Galileo's science to our own harbors such unseen assumptions as that we already know what the relevant tests and outcomes will be. When I asked Mingwei for his ideas about something we might try with pendulums, I supposed we would apply the variables length, mass, and angle which have become conventional in instructional physics. In his response, Mingwei inverted Galileo's observations into questions that he supposed would be straightforward to confirm:

Mingwei: We could test out the pendulum … to have same string, same kind of object at the ends, and test out things … like: Do they go at the same time? and letting one go for a period or two, and then let go. … The set up should be fairly easy.

After class, I tried making my own pendulums. A sewing thread, weighted at one end, slipped from its tape anchor while the weight swung and spun. This problematic support provoked me to look around the lab for something more secure. Spotting the drill press, I attached a fishing line to a hole in its table. From this suspension, the weight swung more evenly in a plane, then it circled in coming to rest. These explorations attuned me to notice aspects that are typically not addressed in instructional treatments of the pendulum, such as the string's mounting, weight's path, and observer's position. As my own awareness of the complexity of experimenting with pendulums grew, I decided to leave these features available to my student to explore. Thus, for our next meeting, I gathered only various strings and weights, but I did not provide instructions, specify the supports, or demonstrate other experimental techniques.

At our first lab session with the pendulum, Mingwei picked up a squat soda bottle, filled with water and having a string tied to its cap. Swinging it from his hand, Mingwei said: "I think if this has no experimental value, it is still very fun!"

While its fun attracted Mingwei to the soda bottle, a sense that certain materials possess more "experimental value" than others induced him to give it up. The soda bottle presented a difficulty in that its label gave a weight in grams, while the lead fishing weights on the table beside it were marked in ounces. Mingwei lacked the conversion between grams and ounces. To support his consideration of these materials, I suggested that the bottle's label might give a clue. But, supposing that the unit conversion was essential to doing an experiment, he set down the "toy" and took up the weights.

Next, faced with devising a support for his pendulums, Mingwei improvised on the spot. He took a handy bicycle pump from under a table and lay its shaft across the space between two lab benches (Figure 1 left). To it, he tied two cotton strings of about the same in length, each bearing an equal fishing weight. He prepared to launch them into motion by raising both weights so their strings were nearly horizontal. He said he would release one, wait for it to swing back, then let the other go. This plan put into action the interpretation of Galileo's pendulum that he had proposed in words the week before.

In practice, it was not easy either to release the second weight at the other's return, nor to observe and compare the two motions. On his second try at releasing the two weights a period apart, Mingwei described them as "going in the same path … or in the same period." As

I watched the same swinging weights, I was less sanguine than he, that we had yet any basis for drawing comparisons. To myself, I considered possible questions that I might ask to involve Mingwei in looking more closely at what was happening. However, as Mingwei went on experimenting, many of these issues arose for him, without my intervention.

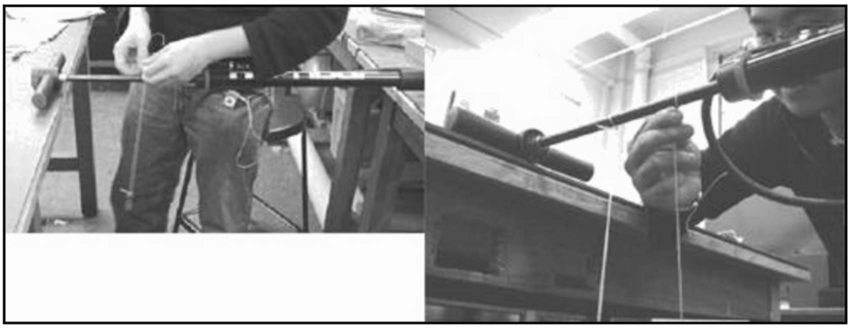

Figure 1. Left – Mingwei uses a bike pump's shaft as the support for a pendulum's string. Right – Mingwei adjusts the length of two pendulum strings.

The length of the two strings was one of these features that increasingly drew more notice from Mingwei. At first Mingwei cut similar, unmeasured lengths of string, supposing it was "alright" if they were a little off and regarding the two strings as interchangeable. He acted on this assumption by releasing the two weights at different angles with the expectation that they would exhibit the same period, no matter their release angle. However, instead of going in synchrony, the weights swing around each other, tangling their strings. On separating them and trying again, irregularity soon recurred, and he observed:

Mingwei: Now they are starting to get off. I suppose this throws some insight into how difficult it is to use the pendulum and /or, how long it took to discover!

Mingwei's comment suggests that his historical appreciation deepened through experiencing for himself the unexpected complexity of pendulums.

The formula relating a pendulum's period to its length surfaced in Mingwei's thoughts. In his partial recollection, the relation of length was represented as that of an inverse square, rather than square root. An effect of this general confusion was that Mingwei became concerned that the pendulum's period was so sensitive to its length that he despaired of ever getting the strings of two pendulums close enough in length that they would swing the same (Figure 1, right). The interest in this passage, for me as a teacher, lay not in the misconstrued formula, but in Mingwei's effort with it to extend his reasoning, and his growing realization that this experiment might not be as straightforward as he initially assumed. Although inadequate, if judged against the correct formula, Mingwei's mathematical allusion enhanced his attention to the actual experiment and raised questions that he had not considered before. It added possibility.

Mingwei went on to try several other experiments before resuming with string length. He started each of these trial runs as a standard test, such as comparing different weights or release angles. However, instead of demonstrating the behavior he expected, based on instructional models, each run's results raised new experimental issues such as about the influence of the string's support knot.

Confusion about the functional relationship between period and string length re-emerged when Mingwei hung two pendulums such that the length of one string was nearly twice the other's. To fine-tune the length, he tied an extra knot in the shorter string. On release, these two pendulums went at markedly different rates. As Mingwei counted the shorter one's beats out loud, saying "one, two," he realized that doubling one pendulum's string length did not carry over linearly to describe the ratio of the two pendulums' periods(T_1/T_2=(L1/L2)^($^{.5}$)):

Mingwei: Oh wait no it is supposed to be square root of two. Instead. Oops. Yeah. … This is 1.4 this is, we should, we should …

Mingwei took down his pendulums. I asked if he was making one "four times the length?" Seeing that our time was nearly up, he held off, saying:

Mingwei: I guess we will leave this one to the experts.

Elizabeth: We can work on it next time.

Both of us, teacher and student, were in contact with historical and instructional guides on the pendulum that cast expectations of straightforward results. However, so much more was going on in our actual explorations with weights and stings that those guides became just another element of the confusing environment, not meaningful without direct manipulation and observation. In the course of successive trials that were initially framed by partial understandings, Mingwei came upon substantial details that mattered experimentally: adjusting string lengths, release timing and angle, the string's support, other influencing motions, and our own ways of observing and describing what the pendulums do. As his ideas and explorations evolved, mine did too as I considered what in these activities was extending the space for his involvement with materials and motions.

Between sessions, I continued in the lab with revising my pendulums and rereading Settle's essay on Galileo. Focusing on the string's upper support, I threaded string through the small hole of a metal nozzle that I clamped to the drill press. From this suspension, the weight swung yet more evenly, and its motion interested me. I became curious about how to check whether it swung in a plane, and wanted to follow more closely its transition from planar-like swinging to a diminishing, circular motion. In rereading, I was struck by Settle's description of the many different motions that Galileo explored by relating them to variants of the pendulum. Wondering if our classroom activities with one phenomenon might shed light on other behaviors, I wrote in my labbook "How can understanding the pendulum help us work with something else?"

When we met again, Mingwei talked reflectively about questions that came up in his experimenting during our previous session: did the string's tautness change when it was released; did the string's support "bias" the swing; could this "bias" be measured? While listening, I realized that Mingwei's questions connected to my similar concerns with the string's support. I also perceived a difference in his emphasis that opened the potential for investigating in ways that I had not done. It seemed to me that Mingwei's acknowledgement of "bias" in the support offered something different to explore, and I raised this possibility.

Elizabeth: One way might be by trying to eliminate it but another way might be by trying to exaggerate it. I don't know; what you think of that?

Mingwei re-expressed his curiosity about the support by working fluidly with string and weights, devising many variant pendulums. Instead of using a narrow support rod, he tied the weight's string around a wide diameter spool (Figure 2, left). He predicted that the greater surface contact between string and the spool support would increase the friction and give more stability to the string's support. Holding the spool in his hands, he tipped it to set the weight swinging. As the weight swung, the string wound up around the spool's far side and then unwound! Mingwei described the complexity of what he had produced (Figure 2, right):

Mingwei: Well so, if we are measuring the period of this … within the period it is changing length.

Creating a thought experiment by greatly extending the scale of the spool, he remarked that if the spool was "huge … this is going to be much more pronounced."

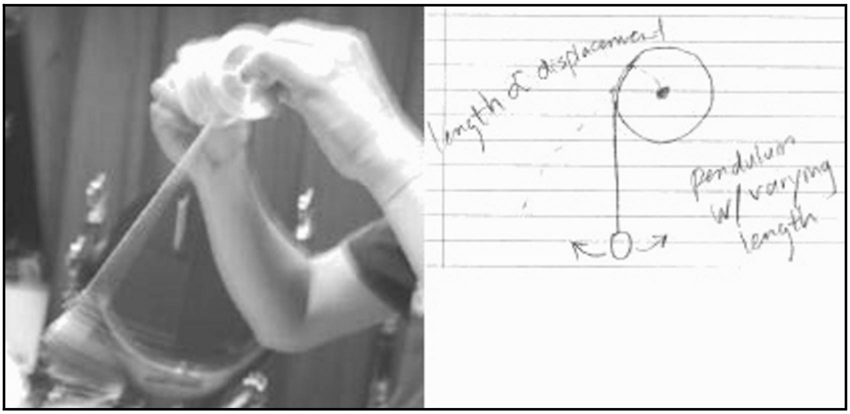

Figure 2. Left – Mingwei swings a weighted string from a spool support. Right – Mingwei's notebook recording his interpretation that the pendulum's length changes as it swings from the spool.

Recalling Settle's speculation that perhaps Galileo worked with variable length pendulums (1996. p. 18), I asked Mingwei what he thought that might involve. Mingwei quickly improvised. Supporting a pendulum from one hand, while grasping it lower down between the other hand's fingers, he slid those fingers down the string while the weight swung, steadily shortening its length (Figure 3, left). Alternatively, he draped the weighted string over one hand's thumb, and by pulling or relaxing his grip (with the other hand) on its non-weighted end, the string shortened or lengthened, while the weight swung out and back (Figure 3, middle and right).

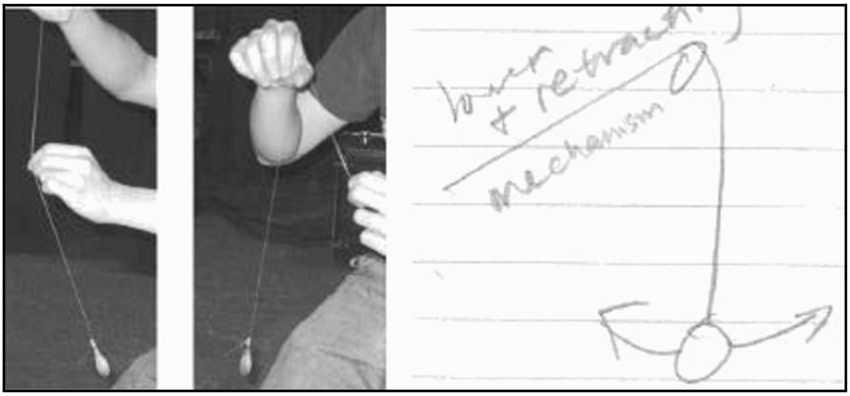

Figure 3. Left – Mingwei varies a pendulum's length, while swinging, by sliding his hand down its string. Middle – Mingwei varies a pendulum's length by pulling or releasing on its string (draped over his thumb). Right – Mingwei's notebook drawing of this variable length pendulum.

The immediacy with which Mingwei conceived these possibilities and tested them as pendulums was accentuated through having access to use his hands as both the support and driver. By these means, Mingwei developed a variability in pendulum length and support that was interactively responsive to his motions. Most instructional pendulum labs start at a different place, with a prescribed fixed length and support, where these hand-and-string pendula might be considered to have no "experimental value."

Mingwei took the variable length pendulum further by attaching a different weight to each end of a string that draped across his two fingers (Figure 4, left). His idea was that the weights would continue to swing as one shortened and the other lengthened. But the string simply slid in the direction of the greater weight. Mingwei then passed that string through several support loops (that hung from a yardstick) and reduced the difference in the two weights. The delicate imbalance that he sought, was still not achieved.

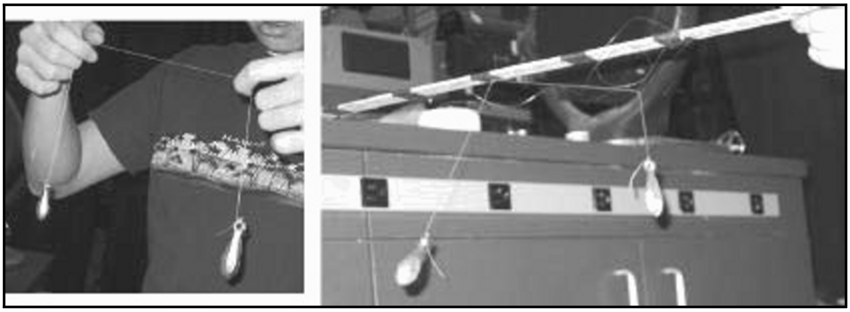

Figure 4. Left – A pendulum string has unequal weights at both ends and drapes over Mingwei's two fingers. Right – The two terminal weights are now equal, suspended from loops attached to a yardstick that Mingwei vibrates to set the weights in motion.

On replacing the string's unequal terminal weights with equal ones, Mingwei revised the experiment again and in doing so produced new effects. The two equal weights, being on opposite ends of one string, were still free to slip through the support loops. He set the weights in motion in two ways: by releasing each from a position above its rest point, and by vibrating the yardstick once the weights began to swing (Figure 4, right).

Mingwei: [I was} trying to see if I move this [*yardstick*] at a certain frequency if … it's [*the weight is*] trying to go to that length, whatever it is, and also if I look at one pendulum, and I try to go at its frequency, it tends to get longer.

As Mingwei varied his rate of moving the yardstick, he sought to match the natural frequency of either pendulum. I asked if the swing amplitudes changed with his stick vibrations; Mingwei thought so. On linking the two weights more closely by attaching a rubber band between them, he found that they swung together even if one's string was longer. Properties of frequency rates, coupling, and the driven pendulum emerged as Mingwei's hands responded to the swinging weights.

As Mingwei explored pendulums, his creativity and spontaneity in experimenting developed. During our first session, Mingwei derived ideas for experimental tests from what he remembered in our reading and in prior conventional science instruction. Confusion arose as the real motions did not behave as expected, and even those expectations were incomplete. While it was not easy to work with that kind of confusion, Mingwei made personal observations about the string's support and swinging that widened the experiential basis of his next phase of experimenting. By drawing on these self-generated questions, he expanded his experience with complex, linked motions. What the weight did, whether swinging or falling, gave immediate response to how he jangled its support in his hands. He used this response to dynamically revise how he researched the motions.

In the close cycling between Mingwei's hand in setting a support in motion, and the weights' responsive motions, his understanding about experimenting changed even when he had not articulated what it was. I observed his learning through the playful intensity of what he did, adding support loops, adjusting the string's balance, vibrating the yardstick. In my own pendulum exploration with its focus on support stability, the cycle between materials and manual actions was not as close. I reflected on the role that such a close cycle of action and response plays in encouraging a novice experimenter – and about the general dismissal of such experiences from conventional science instruction.

The Singing Tube Roars

Mingwei and I did not take up the pendulum again, although I continued collecting materials that might add further possibilities to his vibrating arrangements, such as springs, flexible rods, tuning forks, and malleable weights. Once when I offered the pendulum as an option for a day's activity, Mingwei declined, preferring to do something new. Yet, near the semester's end, we came back to resonant phenomena by way of the acoustical response of tubes to stimulation by flames and a frequency generator. The historical sources for this activity were the 19th century "musical flames" or "singing tubes" that John Tyndall (1857, 1867/1889) demonstrated in his lectures on sound at the Royal Institution on the basis of prior work by Faraday (1818) and others (Leconte, 1858).

The impetus for me to develop an activity with flame and sound lay in my previous teaching of this course on historical experimentation. While my two students explored the sounds of a transparent tube by driving it with a speaker hooked to a frequency generator, they devised a way to make its sound visible by breaking Styrofoam into bits and placing those into the tube. During that term, I collaborated with David Pantalony and Markos Hankin in reactivating MIT's 19th century tuning forks, made by Koenig and Kohl. My students then used these authentic instruments to project Lissijous figures from pairs of forks mounted cross-wise to each other (Cavicchi, 2007c, 2008b).

As I went on to learn more about Koenig's acoustical apparatus, his use of flame as an indicator of sound intrigued me, as did the historical descriptions of the beauty of these vibrating flames. I chose to begin my own explorations of flame and sound by observing flame, its response to sound, and its provocation of sound in a tube. In several lab sessions on my own, I investigated activities with flame and acoustics described by Faraday (1861), Mayer (1878), and Tyndall (1867/1889). My preliminary studies in library and lab evoked my interest in the singing tube. During a visit to the Smithsonian National Museum of American History, Steve Turner showed me two historical singing tubes in the Physical Sciences Collection (Figure 6, left). These fixtures resemble the gas or oil lamps in common use in the 19th century homes, from which people reported hearing musical sounds.

Although the singing tube did not seem to need an elaborate set-up, it took much groundwork on my part during the semester preceding our class, before I convened the starting conditions of: a gas line functioning in an instructional lab, Bunsen burners to run off that gas, and flame-resistant tubes to mount vertically over the active burners. Since our classroom lab lacked a gas line, these materials came together in the MIT Foundry Lab of Mike Tarkanian. Mike and I conducted several trial runs with metal, plastic, and glass pipes or tubes before I ordered the four foot long, 48 mm outer diameter tube of borosilicate glass that provided our test apparatus. During a preliminary investigation that Mike and I did with the glass tube, we observed flame shoot up within its column, and out the top. The glass became so hot we shut off the flame, giving breaks to cool. A soft ringing in the tube transformed into a pronounced roar as we lowered the tube over the flame. Regulating the flow of gas and air into the burner affected the flame and its sounds; on turning the gas on or off suddenly, the tube sounded an abrupt shot.

Unlike most of our class sessions where Mingwei and I explored physical materials together, others joined our sessions with the singing tube. Through their excitement, unique perspectives, and techniques for experimenting with flame and tubes, our guest participants widened the possible ways of developing our work. Mike Tarkanian facilitated and assisted Mingwei's explorations of the burner's flame and the tube's acoustic response, and introduced Mingwei to techniques for working in his shop. Dedra Demaree, then a physics instructor at Holy Cross College in Worchester, MA, observed Mingwei's first test of the glass tube and engaged him and me in a discussion reflecting on our experimental course. Following through on the interest expressed by MIT glassblowers Peter Houk and Martin Demaine, Martin participated in our class by demonstrating his glassblowing of a vase and joining our second test of the four foot tube. MIT physics lecture demonstrator Markos Hankin put into action his six foot long Rijke tube for a special session of our class. Former MIT student Bo Chiu contributed to a class discussion and observed Mingwei stimulate the glass tube using a speaker and frequency generator.

For our first class trial of the glass tube, Mike and Mingwei erected it in lab clamps, slightly above our large Bunsen burner. By having already done two stints of blow-piping with the Bunsen burner's flame, Mingwei had gained familiarity with turning the gas line's valve to start and stop its flow, and using the flint striker to ignite the gas. Mingwei developed these skills further in the course of the complex coordination that was needed to sustain the flame in the presence of the tube, and amplify its sound. Mingwei became involved in seeking a balance among many factors (Figure 5). The interactive exchange between his manipulations of burner and tube, and the outcome of sound and flame, recalled his work with the interlinked pendulums, but was more subtle.

Figure 5. Left – Mingwei adjusts the valve to the burner's gas line. Middle – Mingwei lowers the tube over the burner (Photo Martin Demaine). Right – Mingwei adjusts the air flow into the burner.

First attempts to lower the tube over the flame extinguished it. When, at Mike's suggestion, Mingwei increased the gas flow, flame shot up through the tube's entire length, coming out its top in a blue glow! While the column of flame and light was awesome, the sound just murmured. Mike remarked that in the preliminary trial he did with me, the sound was more distinct.

Mingwei varied the position of the tube over the flame as well as the flow into the line, and the air opening in the base of the burner. Now the sound rose into a windy whistling, becoming more intense. When Mingwei felt the heat of the tube through his work gloves, we shut the flame off. During the break to let it cool, Mike and Mingwei repositioned the clamps on the tube and lowered the tube over the burner. After these changes, the sound was windy, shimmering, more intense, and sustained.

I described a loud sound that Mike and I heard in our preliminary trial, occurring at the moment of switching the gas off. Previously, Mingwei had lit the burner first, then lowered the tube over it. Now he tried to turn the gas on and off with the tube already in place covering the burner. Unable to light the burner directly, Mingwei had the idea to apply the striker to the top of the tube! As the striker lit the gas, bright white sparkles appeared at the tube's top and were visible within.

Now the sound's amplitude exceeded what Mike and I had experienced before – and continued to grow. Its tone shifted. A pulsing, interrupted, whistle superimposed onto the hollow windy sound. Mounting in clamor until like a train, the halting interruptions smoothed into steady vibrations. Rising in amplitude until the sound felt deafening in the room, it showed no signs of letting up. We turned the gas off; stopping the sound and ending our experimental work for that day. Comparing the glass tube to the saxophone which he plays, Mike supposed: "with different diameters and different lengths, you would get different tones … an alto sax versus a tenor sax."

Mingwei wondered: "do you think it was feedback? it sounded like it was getting louder." And I concurred saying "it seemed to be escalating." I was struck by Mingwei's observation about the resonance behavior, and asked him later for more about what he was thinking. Lacking a way to take the idea any further, he said "I don't know how physically that would work though."

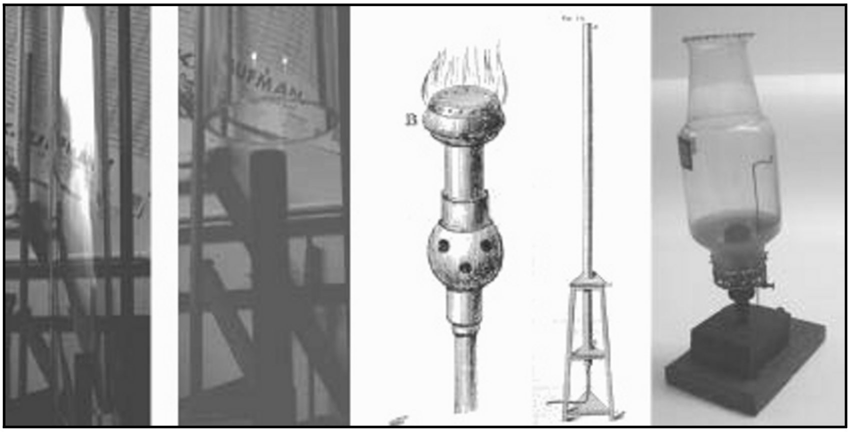

Figure 6. Leftmost photos show our burner's flame within the glass tube. Middle drawings show John Tyndall's burner and tube apparatus (Tyndall 1889). Right photo shows the singing tube in the Smithsonian's National Museum of American History physical sciences collection.

Our exploration with the glass tube, Bunsen burner, and the terrific sound between them echoed John Tyndall's feats with a 15 foot long metal tube housed over a large Bunsen's burner (Figure 6). In describing the variations of the sound in synchrony with the manipulations of hand and gas flow that gave rise to them, Tyndall wrote as if performing now in the great lecture hall:

> You hear the incipient flutter; you now hear the more powerful sound. As the flame is lifted higher the action becomes more violent, until finally a storm of music issues from the tube. On turning the gas fully on, the note ceases – all is silent for a moment; but the storm is brewing, and soon it bursts forth, as a first, in a kind of hurricane of sound. …With a large Bunsen's rose burner, the sound of this tube becomes powerful enough to shake the floor and seats, and the large audience that occupies the seats of this room. (Tyndall 1889, pp. 246-247)

In his own way, Mingwei had recovered some dramatic effects and experimental techniques of Tyndall, Faraday's worthy successor who introduced sound's behaviors to popular and elite London audiences (Howard 2004). Mingwei accomplished these effects by interacting with the phenomena, widening his experience and awareness of which actions enhanced the sound. This was doing science, equally for Tyndall as for Mingwei. Mingwei's delight showed when he exclaimed: "I don't know exactly how that worked. That was cool!" He went on to say something about what he'd noticed:

Mingwei: Yeah so things like, pressure … that was feeding into it from the bottom and bearing down on it from the top. So it seemed like for any given position or … any given flame there was a, like resonant position.

Dedra Demaree, the physics educator observing our class that day, spoke to Mingwei afterward about his playful systematicity, a characteristic she missed seeing among students in typical physics labs:

Dedra: I notice you were playing … with controlled things. Like you would keep the height fixed and try a different strength of the gas and then you'd change the height and change the gas, rather than try and change two things at once.

Within Mingwei's spontaneity of responding to the ever-emerging behaviors of flame, gas, and tube, he was expressing what he wanted to know and developing the systematic practices that Dedra identified. Each turn of a valve or lifting of the tube responded to a different constellation among the physical behaviors and Mingwei's understandings of them. His experimental cycling through readjustments was not literally repetitive, more like a spiraling whose new inputs included the instance just-completed – recalling Piaget's image of "an infinite sequence of reequilibrations" (Piaget 1981/1987, p. 152).

Mingwei's sounding of the long tube was not a one-time event. A few days later, Mingwei, Mike, and I gathered together with glassblower Martin Demaine and his student to try the tube again. As Mingwei adjusted the rate of gas and air flow into the burner, the tube's sound evolved from halting, interrupted honking, to a continuous more steady sound, to interrupted, to airy tones. At the same time, the surface of the blue flame was visibly changing in its shape, height within the tube, tremor, and form. We had not noticed the flame's fluctuations before; now Martin drew our attention to them – a new observation with experimental possibilities.

When we switched from using a large Bunsen burner to a smaller one, more delicate adjustments were needed. The small burner's flame went out readily and its sound was more subdued. Substituting metal pipes for the glass tube produced heat, smelly smoke, and a duller sound. Acting upon Martin's interest in Faraday's report of sound from a tubes lowered over an alcohol lamp's flame, we substituted an alcohol lamp for the gas flame. These attempts met with silence, extinction of the flame, and more questions to try another time.

This second session with the tube opened up more to explore, benefiting from a community of wider experience. Ideas, questions, wonderment spun off each other, seeded by Martin's infectious delight in the tube's sounds, the use of glass, the historical work of Tyndall and Faraday. Marveling in these explorations uniting history and ourselves, Martin expressed a theme of our class, saying: "It's amazing! How people play with things and discover stuff like this!!"

The singing tube figured in our few remaining class sessions, as I sought out multiple connections with what we had done, that took it further. For example, in the context of Mingwei's interest in science in China, I found that the first publication by a Chinese scientist in a Western journal was that of Xu Shou, critiquing a statement in John Tyndall's work on sound (Wright, 2000; Elman, 2005). Mingwei and I read Xu Shou's paper together. Xu Shou was disturbed by a discrepancy between his own experimental determination of the length of a tube that sounds the octave, and that asserted by both the ancient Chinese tradition, and Tyndall. Should Xu Shou trust his own experiment, or these established authorities?

On another occasion, we visited MIT's lecture demonstration lab where Markos Hankins astonished us by the foghorn blare projected by a six foot long Rijke tube (Rijke, 1859), after heating with a blowtorch. There I became so caught up with the Rijke tube's novelty as to interrupt Mingwei while he was explaining our tube's sounds to Markos. I not only failed to hear Mingwei's observations, but also prevented him from articulating it and extending both his understanding, and that of our small community.

I responded to Mingwei more directly by adopting, as the starting place for some closing class activities, his idea that the tube's sound had "something to do with the frequency of the flame resonating in the tube." As means to explore this idea, I provided Mingwei with a speaker and digital frequency generator. When my students in a previous semester had used similar tools to explore resonant sounds, they oriented the tube horizontally, filled it with small syrofoam bits, and looked for agitation among these bits while varying the sound (Cavicchi, 2007c, 2008b). For a moment it surprised me when unlike them, Mingwei mounted the tube vertically, not horizontally! Mingwei thus introduced me to an experimental arrangement that I had not expected in advance. I grasped the context and source of orienting the tube vertically when Mingwei played with putting the speaker under and into it, similar to what he had done with the burner flame. The new experiment emerged out of his experiences with the previous one, in a way that surprised the teacher while making the student's learning evident.

Then Mingwei systematically dialed the generator through frequencies ranging from under 100 Hz to over a kilohertz. At some frequencies, the tube sounded more pronounced and Mingwei wrote these values down, as a spontaneous collection of numerical data. While he noticed that many frequency differences were similar, they did not quite match a formula that he partly remembered. As with the relation between pendulum period and string length earlier in the term, again confusion over a formula foiled his effort to interpret observational data. For an alternative approach, I suggested looking for the resonances of our tube with one end closed. However, under the shortness of remaining class-time, the lower fundamental resonance of the closed tube was missed and no pattern suggesting the odd harmonics came readily to view.

Mingwei's conjecture about feedback in the tube's rising sounding applies as an analogy to his own adjustments of gas line, tube height, or frequency setting, and to my responses to our lab work with new activities and materials. With physical systems, feedback describes the return of an output effect to influence, perturb, or amplify the input source. Applying the analogy, our human interactions are part of the system that includes physical and experimental behaviors, where in the course of participating, we change in how we interact.

But whereas human efforts are not required to keep feedback going in a physical system, in the analogy our human efforts are essential. Trying something, looking at what happened, reflecting, having an idea, trying something new are ways that we learn while making use of the feedback of our undertakings. Mingwei's learning through this interactive process shows in his successive trials with the tube and large burner on two days, his adaptations for sounding the small burner's flame in glass and metal pipes, and stimulation of the tube with a speaker. My teaching, learning, and curriculum development went in parallel with Mingwei's explorations. On seeing him try something, wonder, ask questions, I sought out materials, historical resources, and fellow experimenters that might integrate with and expand our next experiences. The singing tubes, the student, and the teacher interacted as a system that – only through our efforts – continually opened out in relation to other phenomena and experimenters of the past and present.

"A Recursively Elaborative Process of Opening" (Davis & Sumara, 2007, p. 64)

New possibilities for learning lie in any current exploration. Unforeseen in advance, the prospect of acting on these possibilities depends on the openness of the teacher to encourage travel down unknown paths, and on the openness of the student to venture into unfamiliar grounds. While teacher and student may lack such openness at first, it too grows as a part of the ongoing recursive process of their experimenting. When I realized that my interest in stabilizing my pendulum's support was only one possible approach, that realization freed me to encourage Mingwei in exploring the string loop supports that in turn gave rise to his first attempts at matching and driving the pendulums' resonant frequencies. Mingwei's pendulums, involving him in close cycling among arrangements made with his hands, string loops, and rubber band, contributed to his productivity in exploring the glass tube's resonances. An openness on the part of the teacher can foster observation, curiosity, and openness on the part of the student. Exploration cycles recursively and interactively, from small beginnings into widened domains that remain interconnected through personal experience.

Where possibilities and openness evolve interactively in a classroom, the examples in texts, history, instructional scripts, and even our own past teaching, only offer a jumping-off place or sounding board. Whereas close observation and keen inquiry into what is underway feed the developing process, reliance on a prescribed model can stifle it. As a teacher, I tried to employ my awareness of prior examples and models so as to enrich the possibilities we might try, not to direct them. While I often felt the pull of these examples shaping my expectations for a session, I felt a corresponding delight when something different and wonderful happened instead, such as Mingwei's pendulum weights terminating the far ends of a single string. In parallel, confusing constraints were imposed on my student by equations for the pendulum's period and a tube's resonances that had been superficially treated in his physics training.

It was my sense that the further we were from standard physics equations, the more fluid were Mingwei's explorations and willingness to take his own observations seriously. Mature experimenters, such as Galileo and Faraday, retain the balance of curiosity in both the realms of what is considered known, and unknown. But for a student to do this is not only hard, it opposes the dominant message in their training. Perhaps the most essential role for experimental teaching is to support students in opening possibilities for discovery that are latent within their current experience even where their training – and ours – has closed down the space for questioning.

In his final paper, Mingwei expressed what it was like to encounter unexpected behaviors while experimenting, in contrast to what he called the "prescribed" or "proclamation based" format of his school science training:

> It wasn't until my senior year of high school that I had an opportunity to perform a variable-control experiment – not a "lab" but a bona fide experiment. Even so, I went into the experiment with a very clear theoretical idea of what to expect. Such is the approach I try in the seminar when starting a new topic. It is only after playing around with the materials that I may find something I hadn't expected. I believe only in these instances am I put into the shoes of a scientist like those we've read about. I'm discovering "new" concepts (at least new to me) instead of purely demonstrating ones I'm familiar with. I believe that this type of attitude provided me a new level of learning that I otherwise would not have been able to achieve. (Gu, 2007)

Being in someone else's shoes brings insights about being in our own shoes. Mingwei expressed this interrelatedness early in the term while discussing Galileo's pendulums and by experimenting to make these work. He realized then that Galileo had no reliable clock and that his own struggles in experimenting with pendulums suggested this was also hard to do historically. Mingwei took these realizations further in his closing reflection about a "new level of learning" (Gu, 2007). Mingwei had recurrently come upon physical behaviors that were new to him, and, like the historical scientists, his widening observations and responses to these phenomena enabled him to learn from yet other unexpected happenings.

"Not-yet-imaginable" possibilities (Davis & Sumara, 2007, p. 64) arose in the experimenting of Mingwei, Galileo, Tyndall, Xu Shou, and others. For them, as for Inhelder, the "more unexpected" these were, the more "productive" the research (Inhelder et al., 1974, p. 21). The new possibilities not only involved experimental phenomena, techniques, and analysis, but also such human issues as what it means when one's own observations challenge the authority of a textbook equation or an established interpretive tradition. The explorations of these scientists suggests an analogy to teachers. Opening our classrooms to "not-yet-imaginable" possibilities does not allow for an end, a delimitable boundary, a prescribed answer, a directable outcome. And it might provoke us to question in deeply productive ways, what it means when our teaching disrupts established educational traditions.

NOTES

1. Unless otherwise noted, all indented quotes from Mingwei Gu are from the SP726 class transcripts of Spring, 2007.

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Author's Address:
Edgerton Center,
MIT, Cambridge, MA
U.S.A.
EMAIL: Elizabeth_cavicchi@post.harvard.edu
ecavicch@mit.edu