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*Classroom Explorations:  
Pendulums, Mirrors, and Galileo's Drama*

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**ABSTRACT:** What do you see in a mirror when not looking at yourself? What goes on as a pendulum swings? Undergraduates in a science class supposed that these behaviors were obvious until their explorations exposed questions with no quick answers. While exploring materials, students researched Galileo, his trial, and its aftermath. Galileo came to life both in their presentations about him, and in the context of lab investigations by the emerging class community. Questions and experiments evolved continually; differing perspectives on science and authority were exchanged respectfully. In rediscovering their own capacity for wonder, students developed as critical explorers of the world.

**KEYWORDS:** Critical exploration, experiment, active learning, teaching, drama, historical replication, pendulum, Galileo, mirror reflection, authority.

*Introduction*

Ordinary things pass under our notice. We may assume we know what to expect from them, without ever having set aside the space to scratch beneath those unexamined assumptions, contemplate the behavior, and wonder what is going on. Through carving out space for observing and rethinking everyday things, scientists in history generated questions and understandings that unsettled views prevailing at their time. In the swinging of a pendulum, Galileo gained evidence that contributed to new means of investigating and comprehending motions and relationships in the world. Galileo's trial thrust into prominence the inextricability of that scientific undertaking from a wider matrix of beliefs, pressures, and experiences; its reverberations extend across subsequent science. This paper follows students in my science class as they came to their own curiosities about ordinary things and experienced these curiosities in relation to Galileo's researches and his trial.

Science education often undermines the inextricability among ordinary things, human investigation, and the surrounding worlds of culture and nature. Instruction treating science in isolation from student experiences leaves students feeling that their minds and actions

do not matter in science. Objecting to this practice in her high school physics course, one student told an interviewer, "Don't just teach me the facts ... Let me see and think for myself!" (Hughes-McDonnell, 2000, p. 1). Surveys of science students report that classroom experiments may be fun but do not engender the observation-based critical thinking that this student advocated (Angell, Guttersrud, & Hendriksen, 2004; Coleman, Holocomb, & Rigden, 1998). As an effort to build such an environment in the science classroom and analyze it so as to support students' thoughtful participation, researchers collaborated with five middle school teachers in conducting a three week curriculum, beginning with a competition to design, make, and test model boats and expanding along paths of children's questions about their boats (Schauble, Glaser, Duschl, Schultz, & John, 1995). By the end, most children could articulate what they had done and propose a revision to their experiments. Like the physics student quoted above, these researchers decried science presented in isolation from student involvement, and instead argued for "sustained periods of real experimentation" by students (p. 158).

In making my classroom a space where students investigate ordinary things, I seek to bring about personal experiences relating students to the natural world, each other, and historical efforts (Cavicchi, 2008a, 2008b, 2007, 2005, 1999). While this integration among classroom activities and experiences might seem to be a condition that comes about on its own, in fact it depends on a teacher's observant participation. Teachers in the study of Schauble et al. (1995) found they had to adopt such new classroom practices as becoming aware of opportunities for reasoning as these arose in students' activities and responding with challenges and encouragement. Similarly for me, I find that by interacting with students as their investigation emerges, opportunities arise for extending what they do, develop, and learn. My classroom observing and interactions are a research into the process of learning, just as my students are doing their own researches with pendulums, mirrors, and history. Whereas in Schauble's study, classroom researchers collaborated with teachers, in mine, my teaching is at the same time research.

In teaching, I am seeking to observe, understand, and extend what goes on in: the classroom, students' work, my teaching, and materials of science and history. This research pedagogy, called critical exploration, was developed by Eleanor Duckworth (Duckworth, 1973/2006a, 1986/2006b, 1991/2006c, 2005/2006d, 2001b, 2006c) from the clinical interviewing of Jean Piaget (1926) and Bärbel Inhelder

(Inhelder, Sinclair, & Bovet, 1974) and the experimental teaching of the 1960s Elementary Science Study (ESS – 1970). Critical exploration uses Piaget and Inhelder's findings that children's actions on things, and their thinking, are the means by which they construct knowledge and develop new capacities. A teacher sets up a classroom critical exploration to allow curriculum to evolve as students engage with it. By doing research, the teacher looks for developments in understandings that students express in relation to the curriculum – and of developments in the teacher, in relation to provocatively bringing students together with curriculum. Since these developments happen in the midst of activities, research reports on critical explorations preserve narrative context. Students document what they do; this helps them notice how their understandings develop. The teacher also documents class activities; this assists her or him in making teaching decisions and reporting to other teachers (Cavicchi, Chiu, & Hughes-McDonnell, 2009).

Participants in critical explorations discern properties in everyday phenomena that they had not suspected were there, and realize ways that their study links to wider surroundings. For example, a group of Genevan teachers who explored floating and sinking with Eleanor Duckworth as their teaching/learning researcher, dealt thoughtfully with such ambiguities as that, when they poured more water into a pail containing a sealed plastic bag containing air and small objects, the bag did not lift off the pail's bottom and float (Duckworth, 1986/2001a). At the end of this eight week exploration, one participating teacher reflected that through working out understandings of floating and sinking, her core perception of the world and its behaviors evolved. She was now a questioner:

I have the impression of having understood ... why one object sinks and another floats ... I have opened my eyes to a lot of notions that hadn't interested me before. For example: why in a mountain chalet does the condensation form on the outside window, while in my Geneva apartment it forms on the inside window? One question leads to another and another. You start asking about everything. (Duckworth 1986/2001a, p. 37)

Students in my class also perceived a personal deepening in awareness. One student, Noam, described how rereading what he did and wrote during the course, enabled him "to see the progression and curiosity in my work" (Shabani, 2007). Noam's sense of being in process supported him in making the insight that Galileo too developed in the course of, and by means of, experimenting and living. Rather than being static,

fixed, and over, both science and history became dynamic in myriad ways having dramatic resonances for Noam and his classmates. Looking closely into some of their explorations with pendulums, mirrors, and Galileo, this paper documents education where curiosity grew while continuing to expand relations among what goes on in the classroom, everyday life, and history.

### *Course Overview*

My class, in which Noam and his classmates participated, was a science course in the Honors Program at the University of Massachusetts, Boston. Students are admitted to this program on the basis of grades and exam scores. During their sophomore, junior, and senior years, these students are required to take several enriching courses which are only offered through the non-departmental Honors Program. Honors courses engage students in intellectually challenging work in interdisciplinary areas with in-depth study and resources beyond the classroom such as field trips. Titled "Science Experimenting: Learning from Nature, History and Ourselves," my course fulfilled a lab science requirement as well as meeting Honors Program expectations. Most sessions met in a lab where students experimented with a wide range of materials such as: string, weights, mirrors, water, glass vessels, baby powder, light sources, laser pointers, magnets, batteries, wires. I developed and taught this course first in 2005 with nine students (Cavicchi, 2007, 2009); when next teaching it in the 2007 semester discussed here, the class size doubled.

Like the school's population at large, students in this class came with diverse backgrounds and academic aims. Many had grown up in part outside the United States; having done some of their schooling on other continents including Europe, Africa, Asia, and South America, English was not their first, or only, language. Others were longtime residents of Boston. Most had already declared a major; these included: Psychology, Mathematics, Nursing, Management, Classical Languages, Biology, Computer Science, and Sociology. None had taken a college-level physics course; a few were also attending a chemistry or biology course. While in college, some students worked long hours at jobs or internships in: a hospital, nursing, hairdressing, showroom sales in kitchen décor or computers, and military training. In response to a reflective writing assignment early in the course, students recalled having a childhood curiosity sparked by stars, death, snow, softened candle wax, rocks, and trees. At the beginning of the course, some

students knew no one else while others were friends or previous classmates.

I hoped to develop a science classroom where students could act from the fullness of their personal experience and learn from the particular and differing outlooks of others. Thus I structured assignments, activities, and resources to engage students with the openness of exploration, where “one question leads to another and another” as observed by the teacher quoted above (Duckworth 1986/2001a, p. 37). Class sessions included time for students to explore science materials in small groups, and time to discuss, as a class, what they found in those explorations, and our readings from historical science. Between classes, they did activities at home and wrote about this work and our readings. Readings, assignments, and other resources were available on a class website which I expanded continually. Everyone kept a notebook on their explorations in the class lab and at home. During the last half of the term, I asked each student to select a science phenomenon that interested them and investigate it outside of class. They shared these project activities with others during class and in writing. Topics varied from mirror reflection to bass vibrations from a speaker to the processes underlying granite countertop surfaces.

From week to week, I developed class activities and assignments that related to what students were doing, and at the same time challenged them to take it further or observe by a new perspective. I wrote individual responses to each homework by which I raised questions that might provoke thinking and extend the interests that I saw emerging in that student’s work. Through this responsive method of designing assignments and reacting to individual’s work, I seek to support each student in becoming aware that their own observations and thoughts are fertile grounds for science experiments and understandings.

At the same time that I encouraged individual students to experience themselves as explorers, I also planned activities that brought students to listen to each other and learn as a community. An assignment titled “shared class notes” illustrates this practice. Each week, the students and I documented what unfolded in experiments and discussion. During the first month of meetings, I used these records to compile a summary of what happened in class, which I distributed at the next meeting. These summaries include quotes from discussion, descriptions of experiments, questions, photos, and references. During the remainder of the term, I assigned three students each week to compose a summary of what they observed in class, and circulate it next

time with the others. To prepare a summary meant students had to listen closely to each other and express in their own words the work of others. Then, when the rest of the class read those three summaries, they noticed differing and connecting perspectives on the same shared experience.

I integrated historical materials of science into the class experience in many ways: readings and activities based on historical experiments; a visit to the MIT Museum and its exhibit of historical simple microscopes (Giordano 2006); a visit to a special collections library; guest Elaheh Kheirandish who spoke on optics in the medieval Islamic world and guest Zuraya Monroy-Nasr who discussed history and philosophy of science. These historical resources evoke students' curiosity about people's understanding of science, as documented in other educational studies where students are encouraged to explore history and science together (Heering, 2000, 2007; Klassen, 2009a, 2009b; Stinner, 1989, 2009).

I developed a major assignment on Galileo and his trial. The students presented on Galileo during two class sessions using a variety of formats, including powerpoint presentations, posters, recreations of Galilean experiments, blackboard arguments, conducting a provocative class discussion, and a short original drama. Everyone wrote a short reflective paper based on these Galileo presentations.

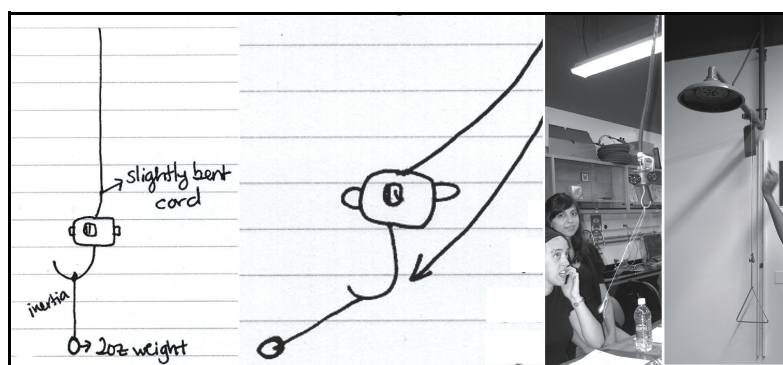
The research that I was doing, as a teacher, to attend to each student's interest, confusions, and potential, also records developments in teaching and learning during the course. The discussions below excerpt from those records, kept by the students and myself, in explorations and experiments done in and out of class, in my own teaching responses, and in work that emerged through the Galileo presentation assignment. Since teaching is a process reflective on itself, more can be learned by reviewing, narrating, reentering. In the possibilities that came to be, we see the resilience of the subject together with students' curiosities.

Historical knowledge production in the classroom carried over into each facet of the course. In experimenting with mirrors and pendulums, and watching the night sky, students became aware of much going on in the physical world that they had overlooked before. By encountering readings and artifacts from historical science at the same time, they realized that others in the past witnessed and wondered about these things. While the students were used to academic settings that privilege answers, under this course's requirement that they look closely, interact

with materials, and interpret what happens, relying on answers began to seem inadequate and limiting. Through my teaching efforts to continually open up domains for further activity even in what students assumed they had already covered, I tried to unsettle their inclination to accept premature conclusions. In addition, the historical examples from Galileo and others connected with students' own experiences and supported them in developing as explorers that seek questions and are critical of authoritative answers.

### *Pendulums*

I started off our first class activity saying: "suspend a weight on a string. Pull the weight back, let it go, watch. What do you notice? What can you vary?"<sup>1</sup> From structures around the room, the students improvised supports: hands, ringstands, handles on the lab shower, the electric plugs over each lab bench! Hanging on long electric cords, these plugs looked so much like pendulums that someone set them swinging. Then, strings bearing weights were tied to the hooks ending these plugs. Releasing the weight put both plug line and string into motion. The plug line went like a pendulum and the weighted string acted as a second pendulum on its end!



*Figure 1.* The hanging power cord with a weight on a string hung from it, while at rest (left) and swinging (next). Drawings by C. Gomez (2007). Photo of power cord and pendulum assembly. Right: Bar of lab shower supports a string pendulum and its hanging handle; both swing side-by-side.

Two students tied a weight on a string to the plumbing of the lab shower (Figure 1, Right). They pulled back and released that weight together with the shower's handle, which hung from the same support. The



weight and the handle made up two pendulums. Was one going faster? How were the two motions relating to each other? At first both went back and forth, then the paths became circular. The handle kept swinging longer than the weight.

The following week, I handed out a summary based on what I observed during their first pendulum activity:

- Try 'same weight, shorter string;'
- Hang two pendulum strings from the same point or hand, or beside each other;
- Two types of string: try with one string, and then 'change the type of string;'
- Compare the two strings: Does one have less tension, go for longer or further?
- Compare two pendulums of same length string, where the weights are different;
- Is it proportional to weight?
- 'I wonder what happens if I do this?'
- Do two pendulums sway together? Is one driving the other?
- Is one going faster?
- What makes it swing longer?
- There are a 'ton of things to write down'... 'a lot of factors.'

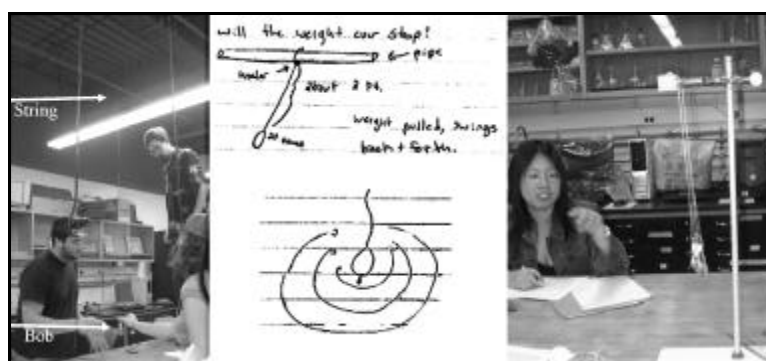
Questions, trial runs, ideas for experiments, inferences about what affects the motion, emerged from what the students did. I see this as an emergent curriculum. Amid the playfulness of pitting one pendulum against another and the seemingly odd assemblies like the swinging shower handle, the students were identifying core features of the phenomena and proposing experimental tests in the interest of working out how these matter.

Already, in taking what they noticed seriously enough to recognize that there are "a lot of factors," the students engaged with swinging motions through a complex context of associations. Through their further explorations, the students' contact with that complexity would branch out and interconnect yet more in physical factors and human experiences, including historical ones. Other critical exploration studies (Duckworth, 1986/2001a; McKinney, 2004; Schneier, 2001) show that when a subject matter is provided in its full complexity, students find their own entries into it. The personal curiosity excited in this process moves them to continue looking closer, exploring, and reflecting on what they observe. At the same time, the subject matter itself, by being

complex, sustains the multitude of students' investigations while invariably confronting them with its distinctive properties and relationships.

For example, the next week, I asked the class to talk about their pendulums along with a paragraph they'd read by Galileo (1638/1914, sec.140-1, p 97). I wrote what they said on the board. Questions like – Does weight matter? Will it stop? – coalesced with techniques like – Start two same weights on different length strings; and use the ceiling pipes to hang a long pendulum. The class broke into groups.

The long line group set up a single pendulum and successively refined its mounting. John climbed on a table, tossed a washer tied to a fishing line over the ceiling pipe, and looped it into a knot (Figure 2, Left).



*Figure 2.* Left: The long string hangs from a ceiling pipe down to the paper where Yelana's hand is about to pull the bob back. Middle Top: Diagram of pendulum on ceiling pipe. Middle Bottom: Interpretive sketch of the bob's successive oval path. Drawings by Y. Zhadanovsky (2007). Right: Two pendulums hang from a single labstand support.

Our largest weight, 20 oz, was tied at the line's bottom end. Immediately after it started swinging, someone bumped it; they had to start over. Now Noam, a biology major, noticed that the washer at the top interfered with the motion. On redoing the attachment without a washer, the line slipped. An attempt to reduce friction and anchor it better with tighter knot, gave rise to Noam's idea to drill a vertical hole in the ceiling pipe and thread the string through it. He explained what drove this persistence to ever-improve the apparatus: "We are trying to

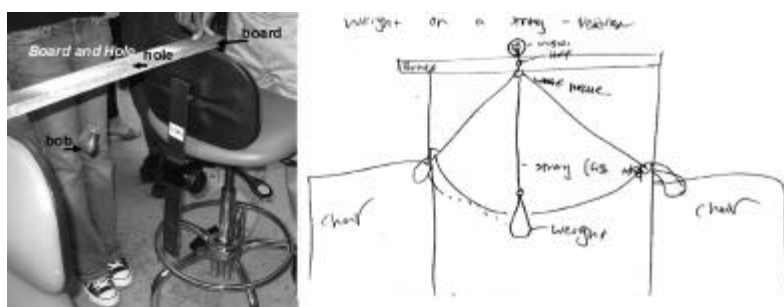
get it perfect. Because maybe in a non perfect situation, it would stop and in a perfect situation, it wouldn't" (Shabani, 2007).

"*Will it stop?*" Surprising to me, this question of the students reveals the different grounding of their view, from conventional instruction. Their concerns to reduce friction, their patience to count all the swings, respond to the role of energy. This relates to the Pendulum Project's identification of the study of energy conservation as a counterpart to that of time, in history (Stinner, 2007; Bevilacqua, et al., 2005). Having that outlook, my students observed effects that are not typically acknowledged. Noam wrote: "The one thing that puzzles me is why the swing stops moving back and forth, and eventually takes the shape of an oval" (Shabani, 2007). Nothing he did eliminated it – he even looked up the oval online and found nothing! The oval path was a genuine finding. Yelena sketched it (Figure 2, Middle). Participants in the groups doing string length comparisons corroborated it too (Figure 2, Right). And when they spoke of the longer string lasting longer, they meant – longer until it stops. The short string had stopped sooner by hitting its ringstand support.

By contrast, the Galileo quote took a time perspective, in reporting that whether a pendulum goes through a large or a small arc, its swing time is the same. It intrigued and puzzled me when students did not pick up on this analysis in writing reflectively about it. Yet they found other entries into this rich quote which connected to the experimenting they were doing and its surprises. Resonating with Sagredo's comment that "from such common and trivial phenomena, you (Salviati/Galileo) derive facts which are not only striking and new, but which are often far removed from what we would have imagined" (Galileo 1638/1914, sec.140-1, p. 97), Christina wrote "people are able to accomplish amazing things if they pay attention to every detail" (Buonomo, 2007). The students were recognizing some of these details in the attachments and motions of their pendulums. The Galileo quote provoked Carolina to ponder "What were Galileo's experimental capacities? How can I relate them to my own?" (Gomez, 2007).

Next week, I assigned a reading where Galileo described his experiment with a pendulum string passing through a hook so it can be shortened while swinging (Galilei, 1632/2001, p. 522). Redoing this, they passed the string through a hole I had drilled in a board, in response to Noam's idea that a drill hole would make a more ideal string support (Figure 3). On pulling the string from above the hole, while swinging the weight below, the swing rate quickened with its shortening string. Veronica expressed wonder: "It was EXTREMELY cool how the speed

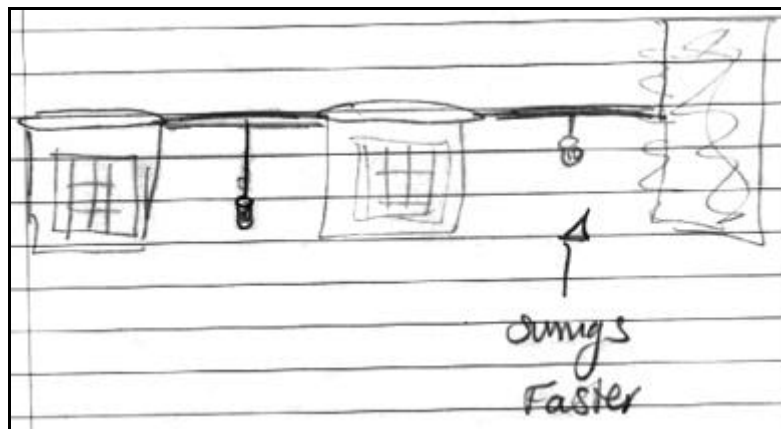
of the pendulum was affected by the length of the string” (Lantigua, 2007). Noam, focused on extending the swinging time, found that with the drill hole support, a constant-length pendulum swung for the entire class! (Shabani, 2007).



*Figure 3.* Left: The bob swings on a string that passes through a hole in a wood board which is mounted between the backs of two chairs [whose seats faced out away from the swing area, as in the diagram, right]. Pulling on the string from above the board shortens the pendulum length. Right: Drawing by N. Shabani (2007).

While our classtime activities went on to other things from there, several students pursued their own questions about the pendulum in investigations done at home, parts of which were shared with the class. By timing a single pendulum swing at different lengths and weights, Koffi, a math major, concluded that only the first of these variables mattered – and wondered what else might affect it. Interestingly, John, a classics major who in our first class swung a pendulum from his hands, researched a pendulum’s magical associations with truth-telling. He asked class members to hand-held a pendulum while saying something false or true. According to the tradition, the pendulum’s swing direction exposes either veracity or deceit.

Curiosity about the pendulum clock’s origins in history infused Murielle’s extensive research of the pendulum. Like Noam, she was looking for the conditions that made for a better pendulum. She was not looking to establish a particular time interval. Calling her project “The Weight of Time,” Murielle, a nursing student, wanted to know “whether different masses of a pendulum effect the time of a pendulum swing. If so how did early scientists decide the appropriate weight of the pendulum to be used in clocks in order to keep exact time?” (Casseus 2007).



*Figure 4.* The board supports for two pendulums rest on clothing hampers (left and middle) and a dresser (right). By watching the two different length pendulums swing side-by-side, Murielle observed the shorter one swings faster. Drawing by M. Casseus (2007).

Borrowing my drill hole boards, she rested them between clothes hampers at home, so as to have side-by-side pendulums (Figure 4). She tracked down discrepancies between the two boards and their mounting. With this setup, she tested many factors alone and in multiple combinations including string length, string thickness, string texture, wire strings, weight, string thickness combined with weight, and string length. By generating experimental possibilities that she projected in advance and tested directly, Murielle worked out an understanding of multiple dimensions going on in the phenomena. For example, she found that a heavier weight on a lighter string persisted in swinging for longer than if either factor was altered.

Coming to this inference took critical work on Murielle's part. She had to trust, and recheck, her experimental work, even as it disproved both her own initial hypothesis and one class member's authoritatively delivered statement that physics says "weight doesn't matter." This took courage – courage which Murielle expressed in other ways within the class community, and on her own. In Galileo, and the history, she found nourishment for having fortitude in making sense of science for herself. She wrote:

Galileo's persistence towards finding and executing his theories motivated me in my own experimentation ... I did encounter some opposition to my project ... [I was condemned for] making too much noise ... while this is no comparison to the opposition Galileo faced ... it is still an opposition to discovery. (Casseus, 2007)

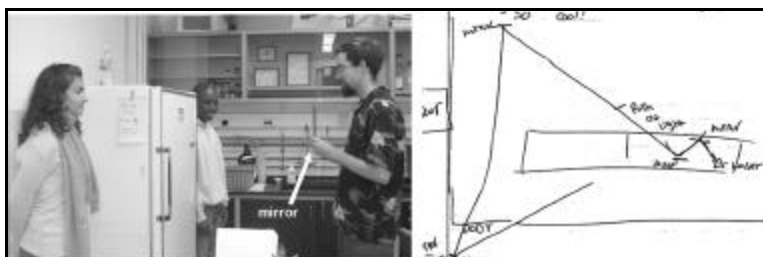
### *Mirrors*

Mirrors and light were another area of class activities and a theme in our historical readings and museum visits. Since we use mirrors everyday, students assumed that there was nothing to find out about mirrors. When I first introduced mirrors in class, what the students did bore out their limited experience – and yet already there were curiosities to notice. For example, two students, Gabriela and Koffi, stood on either side of a refrigerator and did not see each other directly, but when John put a mirror before them, one saw the other (Figure 5, Left). Similarly, a mirror held over the heads of two people let them see each other. But, quickly becoming facile at placing a mirror so something else could be seen with it, some students called this activity “very easy,” and one wondered what she was “missing.”

Seeking to bring about more provocative involvement with mirrors, I looked for passages in their work that might open to future exploration. I did this as a piece of research: I studied my notes, photos and other records of the class activities, and I examined everyone's homework assignments. From this data, I compiled a list of questions and activities that originated directly or indirectly in what the students were puzzling about:

- Size of mirror: What is it like when a mirror is very big or very small? What can a mirror show, based on its size? Can any size mirror show any thing?
- What size of mirror is large enough for a person to see all of their own face? Does it matter how far they are? What is going on with the size of an image seen in a mirror?
- What is going on with letters and things seen backwards in mirrors?
- Looking in multiple mirrors, seeing behind you. Seeing behind an object, at different distances;
- Where does light reflected back from a mirror go?
- Changing positions and distances of viewer and object from mirror;

- Read, try to understand and try out, Euclid's passage on the mirror.



*Figure 5.* Left: Gabriela and Koffi stand on either side of a refrigerator, seeing each other only in the mirror held by John. Right: Top-view diagram using a line to show light from a laser, at the right of the table, passing to one mirror on the table, then another, then a third mirror at the top of the diagram, and a fourth mirror (bottom) that is outside the classroom door. Drawing by N. Shabani (2007).

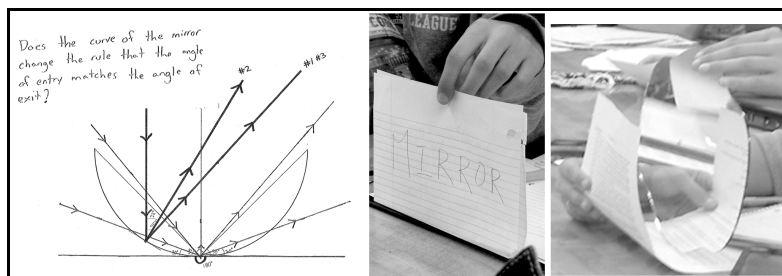
Crediting those students whose work engendered these questions, I asked the class to select something from the list as the starting place for their next exploration, whether it was theirs, or not. I also expanded the array of lab materials that were available to use, including curved mirrors, mylar, and small lamps.

This time, activities conducted with intent, playful, and sustained participation broke out in our lab rooms, exhibiting light's behaviors in diverse ways.

Whereas so far, students had only used the mirrors to view reflected images, this time one group shone a lamp's light at a mirror and tried to follow what happened to the light. Frustrations over working with the lamp in a lit room gave rise to the idea to use a laser pointer. One student had brought a laser pointer, but its batteries died. An attempt to run it off AA batteries failed. Disappearing for awhile, Koffi returned with a much stronger, borrowed laser pointer. When shone at a mirror, the laser's light went elsewhere in the room. Placing another mirror to intercept that reflected beam, someone sent it off in another direction. Challenging themselves to get the laser's light into the next room, the group set up a sequence of mirrors with tape and stands (Figure 5, Right). Finding where to put the next mirror was an exploratory process. Through trying to locate the laser's light with a hand or a shirt, Noam and Carolina conceived the idea to expose the beam's path. With

the room lights off, they sprinkled sand into the beam. Its light briefly sparkled in the sand.

Wondering about how a cosmetic mirror magnifies and a convex mirror shrinks, Shannon tried to analyze that with diagrams (Figure 6, Left). In a prior study exquisite in its emergence of inference through observation, she had already established for herself its equal-angle path at a flat mirror. Trying to apply it to the curve, she became confused. She doubted her diagram. Doubt deepened; she was unsure about the rule for reflection. This struggle was productive; it brought her to see how dependent she'd been on teachers telling her what was wrong. Here, she had to work that out for herself. The reality of her doubt became a resource in realizing that learning encompasses failures.



*Figure 6.* Left: Diagram using arrows to represent light's reflections at a flat and concave mirror. Drawing by S. Kiley (2007). Middle: Lettering of the word MIRROR. Right: Viewing MIRROR written on the page held upright at the left, as it reflected through multiple mirrors, as the one held by the hand at the right.

A similar self-realization arose for Cintia, who started off that day by writing across her notebook the claim: "today we are going to finish up on mirrors." Selecting from my list John's question about backwards letters, she lettered the word "MIRROR" and traced its surprising reversals through multiple reflections (Figure 6, Middle, Right). How did it work? Cintia was unsettled. Later she reflected:

I wanted answers ... I was missing the point at first. But eventually I caught on. The history of mirrors and how they were built before were all fascinating stories. I finally stopped and realized that mirrors are very cool and if we pay attention to the details of the shapes and materials, we would appreciate them more. Now when I look at mirrors anywhere, I'm more aware of them and I stop to observe them. Something I never did before. (Crespo 2007)



For Cintia, reading about ancient mirrors of the Olmec civilization in Central America (Carlson, 1981) assisted her in working through the unsettledness of not having definitive answers, to really look and wonder at the world.

As for Cintia, class explorations were disequilibrating for Gabriela. Wanting to do things right, Gabriela's outlook in approaching these activities was "Ok, what am I suppose to do?" (Antunes, 2007). She came to a new place in relation to exploration through many many interactions across the term, including her in-depth study of Cardinal Bellarmine for the Galileo presentation; watching classmate Carolina's spontaneous curiosity, the complexity and interest of the historical stories our guest speakers shared, and class assignments.

Experiencing what it was like to "crack open my wonder," Gabriela aspired to facilitate this for others with her project sharing (Antunes, 2007). Gabriela laid out flat, concave and convex mirrors on the table. Being with two or three classmates at a time, she asked: "How does reflections/mirror allow you to see more? ... What intrigues you about what you see in the reflection or using a mirror?" (Antunes, 2007). Gabriela's effort resonated with Cintia, who collaborated with Noam in her activity. Gabriela recorded in detail what they did with the mirrors. Confusion and delight spurred Cintia and Noam to put convex with concave mirrors in sequence in search of a normal sized image, or in opposition to produce an "infinity" of imaged "mes." (Figure 7; Antunes, 2007).



*Figure 7.* Left: Noam and Cintia use concave and convex mirrors in sequence to try to produce a “normal” sized image. Right: Noam looks between two opposing mirrors at “an infinity of mes” (Antunes 2007).

Afterwards, Cintia wrote:

[with Gabriela] I got another chance with the mirrors. This time around, I was much more into really focusing my observations and saying what I was thinking out loud. I will always remember the different shapes and their purposes. If they are convex or concave they reflect differently. It was wonderful to understand the purpose of thinking science. I gave the mirrors a chance and I explored them, and I discovered many things I didn't know, or never stopped to think about that were right in front of me. I finally saw how interesting it is to think about things in a scientific way. (Crespo 2007)

For these students, what mirrors do was no longer obvious, no longer in any danger of being “finished off.” Through mirror views, they gained access to seeing in a more probing way – to actually notice that the reflective surface's shape makes a difference, and that maybe, as Shannon considered, there are rules or patterns at work in what light does. By bringing themselves into relation to phenomena of the world, these observations provided key grounds for beginning explorations. Yet the students' development in exploring took place by a bigger context than just mirror reflections. In connecting students such as Cintia and Gabriela with mirrors as part of a process and culture of making and use, our historical readings opened space for them to see and value their

own interactions with mirrors. They had to claim that space from intrusions by the customary educational practice of making and using answers that students accept without realizing their role in acceptance, or that there could be alternatives. Galileo's story brought this issue into relief in the tension between authority and inquiry.

### *Dramas Evoked Through Galileo Presentations*

Into the course, I interwove activities relating to Galileo through topics of pendulums, astronomy, history, and Galileo's works. These included:

- reading short quotes from Galileo's pendulum work, relating those to our pendulum experiments, discussing in class;
- observing the night sky, reading Galileo's *Sidereus Nuncius* (Galileo 1610/1989), writing Galileo a letter, discussing in class;
- reading introductions to Galileo's work by Heilbron (2001) and Einstein(1953/2001), writing a reflection and list of questions, discussing in class;
- looking through many volumes of Galileo's *Opere* (1688/1929-1939) in Italian in the library study room, writing a reflection.

These activities formed a context relating to Galileo that the class shared in common, as a backdrop for the diverse themes of their Galileo Presentations. In addition to informing their work on Galileo, the students drew on these readings, activities, and discussions as a core from which their investigative work developed. For example, many students continued watching the night sky, documenting it in drawings, photos, and writing.

Taking time to look at pendulums or the sky opened their awareness of things they had seen, but not truly noticed before. In the wonder that students experienced, they identified a personal connection with Galileo. Linda wrote: "I could feel what he felt. The surprise of such profound thinking and striking findings derived from such trivial things such as an object dangling from a string" (Chu, 2007). Jeiyng wrote: "I can see a little dark spot on the moon ... that Galileo mentioned" (Lin, 2007). Noam realized:

The moon that he drew is almost exactly the same as our moon today. Obviously this isn't anything new, but to me it really brings me close to Galileo. We both see the same things; in a way ... it makes him more real to me. (Shabani, 2007)

Renata asked Galileo "How did you get into all of this? What sparked your interest?" (Decarvalho, 2007).

I adapted my Galileo assignment from the historical simulation titled “Debating Galileo’s Trial,” that Douglas Allchin developed and demonstrated at meetings of the International History, Philosophy, and Science Teaching group and the History of Science Society.<sup>2</sup> Allchin’s students recreate Galileo’s 1633 trial by opposing a “Church Team” against a “Galileo Team.” He acts as the Grand Inquisitor. The class votes on the outcome. Galileo is invariably convicted by the class vote. I broadened the story to include history prior to the trial, and its aftermath into our future.

My students shared their individual or group presentations on Galileo during two class sessions. The presentations spanned many perspectives and delivery formats, from a short blackboard lecture on logic, to a thorough study of Galileo’s thinking on Scripture, to quotes excerpted from students’ writing about Galileo, to a participatory class discussion, and to an original monologue involving Galileo’s trial set in the future. While there were various mishaps in setting up powerpoints on the projector and keeping the presentations in time, the talks held everyone’s interest. The anxiety some felt about speaking traded with fascination in hearing everyone else’s efforts. Renata wrote “Presenting my project was exciting because I got to share all I learned; hearing others present was interesting because it was things I never knew about” (Decarvalho, 2007). One student who had to leave early said she felt bad to miss any of it.

The multiplicity of responses to one historical story both amazed my students and brought about personal curiosity and connection to Galileo. Murielle wrote: “I felt like everyone adapted their own way of presenting Galileo’s story” (Casseus, 2007). Yelena observed: “I loved how even in the story of one man, everyone found something that they were interested in and could present on” (Zhadanovsky, 2007). Shannon perceived a relationship between the Galileo presentations which came together as a class activity and the investigating she was about to commence on her own:

When we had concluded our historical exploration with the Galileo presentations, I was amazed at how much information we had all collected about different aspects in his life. From his daughter, who was a nun, to the church trials. I was also very intrigued by the introduction of other scientists through history who were both inspirational to him and inspired by him. It really helps to exemplify how interconnected the learning experience is, or should be. It was therefore quite daunting to venture off on a project I

would be doing myself since most of the course we've relied on one another for ideas and support. (Kiley, 2007)

The intensity of Galileo's story gave rise to dramatic reverberations in the class and for students personally. Drama is explicit in Brecht's play (1937/1994) that a group reported on, and one student's evocative enactment of her own futuristic vision of struggles between exploring and authority (Light, 2007). Yet qualities of drama – development, reflection, and realization – arose through other students' presentations as well. As Ødegaard (2003) observed in reviewing uses of drama in the science classroom, students are reconstructing and reworking their understandings in blending personal experience with elements of drama. Four examples from my class illustrate the ways drama enriched students' personal experiences with historical insights:

- Noam and Linda's sharing on the tides;
- Murielle's question for discussion;
- Veronica's insight from politics;
- Henry's experimental project.

I assigned Noam and Linda to read Day 4 of Galileo's *Dialogue* (1632/2001), redo some pendulum experiments, and show how Galileo argued about the tides in support of Copernican views. A scuba diver, Noam knew the lunar explanation of tides. When he started this project, it appalled him that Galileo got the tides so wrong. Wanting his classmates to hear from him how tides work, Noam was uneasy about just reporting on Galileo without adding an update. Noam and Linda took their partnership seriously. The understanding they worked out showed beautifully in their presentation as they switched off antiphonally from each other, sometimes completing each other's thoughts (Figure 8, Left). They projected Galileo's diagram on the whiteboard. To illustrate earth's motions around the sun and its axis, they moved their hands along the paths and drew directly on the board in superimposition with the historical drawing. Linda and Noam demonstrated the back and forth motion of a pendulum, then of water in an aquarium and a test tube, while describing how Galileo interpreted tidal motions as evidence of the vessel earth's motions (Figure 8, Right).

Noam ended their tightly interwoven presentation with scholar Stillman Drake's appreciation of Galileo's efforts to observe nature, not accept what others said. Then Noam concluded with a passionate statement: "to say Galileo was wrong" about the tides, is to miss what he did. "Galileo's exploring, even though incorrect, is a step forward"

(Shabani, 2007). While Noam's spontaneity imparted dramatic closure, it did more. With it, Noam expressed his personal transition from preoccupation with Galileo's failure to get the "answer," to awareness of how curiosity opens up the world and leaves answers behind. In his final paper Noam reflected on how studying Galileo's story became a process for himself:

[Galileo] paved the way for so many explorers! ... Linda and I instantly recognized this. It was incredibly humbling to see what Galileo went through, and as a result we tried to put ourselves in his shoes. Amongst many things, this required us to be curious and imaginative. Looking at his theory on the tides, it became very apparent to me how much thought must have gone into all of it. In many ways Galileo's theory was so beautiful, so elegant. ... It has never been more clear to me that sometimes it's not about the answer, but about the journey. This semester *has* been a journey; in more ways than one. I have learned a lot about myself and my ability to be able to think and explore. Creativity has been my pen,

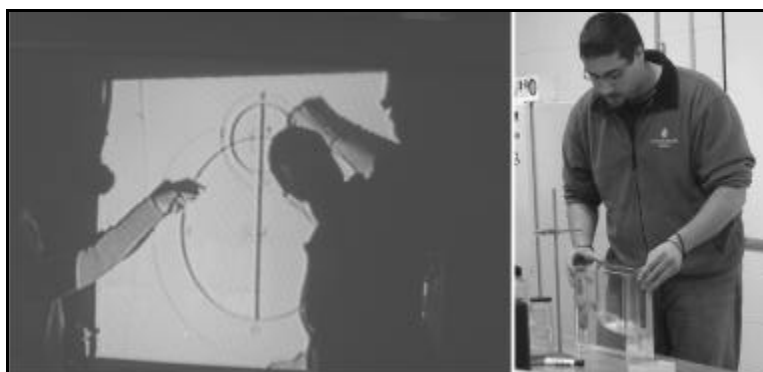


Figure 8. Left: Galileo's diagram is projected onto the classroom whiteboard; Linda (left) and Noam (right) gesture over it to show the earth's motions. Right: Noam uses water sloshing in an aquarium to demonstrate Galileo's argument about tides on vessel Earth

and curiosity my paper, and together they have created my scientific doctrine. (Shabani, 2007)

Drama is diverse and we experienced drama in a form differing from Noam's reliving of Galileo's process, through a question that Murielle initiated. Presenting with the group on Brecht's play and modern science, Murielle identified opposition to stem cell research with opposition to Copernican ideas in Galileo's time (Figure 9, Left). She

ended this report by asking the class “what do you think? Do you think the advancement of science will always be impeded by morality?” The class immediately took up Murielle’s question. These quotes, each voiced by a different student, suggest their responsiveness to the issues and each other’s outlooks.

- There is always going to be someone saying no;
- Morality is an uncertain thing. Whose morality?
- Who are the people making science? Galileo believed in the church ... Some people doing science might say I want to make sure it doesn’t contradict my ethics. Those scientists would say we can’t do that, we can’t destroy something;
- Who is going to fund your experiment if no one cares about it?
- War has a tremendous impact on science. War is not moral;
- Morality nowadays does not play a role in science;
- The places where science is happening now (Northeast and West coast U.S.) are places where scientists don’t have that much religion influence;
- Things have changed since Galileo. Now you don’t have to take the Bible word by word;
- It may not have to do with religion or morality. Maybe it is about control. I think progress is always going to have problems;
- People will oppose ideas;
- Give credit to Murielle for asking the question.

Yelena, a member of Murielle’s group, wrote later:

I was really excited about the discussion ... I was very happy that our presentation set in motion what I really liked about the class, people from different backgrounds, ethnically, academically and whatnot, all bringing to the table what they had to say. (Zhadanovsky, 2007)

The power of the discussion figures in Christina’s pondering:

After our discussion, I am not even sure what my exact opinion is. I do think that we should be open minded, but to what extent I am not sure ... I am looking forward to personally reflecting on this more in the future and throughout my life. (Buonomo, 2007)

Veronica and Henry came to personal realizations that something in their lives echoed Galileo’s. Veronica presented on Biagioli’s analysis (1993) that those who, like Galileo, were most successful in gaining a court’s patronage, were also most at risk for becoming its target when times changed (Figure 9, Middle). After working through this argument based on the historical case, Veronica recognized that it paralleled the

dynamics that led to her removal from a job controlled by a political boss. She wrote:

In Galileo's situation many things contributed to the issues he was facing: changing allegiances, bad timing, misplaced trust. The same issues I faced when my political umbrella of protection was taken from me. (Lantigua, 2007)



Figure 9. Left: Murielle presenting her analogy between stem cell research and Galileo. Middle: Veronica presenting on the politics that led to Galileo's fall from papal favor. Right: Diagram of Henry's experiment to see if direct current affects a magnetic compass. Drawing by H. Lo (2007).

Henry came to a different self-realization while investigating the magnetism of coils. A seemingly knowledgeable friend told Henry that magnetism only comes from alternating currents. Henry's experiments showed otherwise. Doubting his results, he redid the experiments to focus on testing the wire's magnetism under constant current (Figure 9, Right). Again, magnetism appeared where his friend said it would not be. This discrepancy facilitated a critical development for Henry:

I realized I hadn't tested his idea thoroughly before accepting it. I trusted that he knew what he was talking about since he has experimented with similar things a lot more than I have, yet his idea was either flawed or wrong.

This reminded me of Galileo. In his time, many people simply believed without testing the truth of the information they were given, and because of that were sometimes led to wrong conclusions. Though Galileo opened a new way of thinking, there are many people today that believe whatever is told to them. (Lo, 2007)

With each example, from Noam and Linda, Murielle, Veronica, and Henry, a lesson passed from an academic assignment into the student's everyday life, adding critical and reflective perspective to personal and collective experience. Putting themselves in "the shoes of Galileo"



(Shaboni, 2007) at the same time brought into new balance a query and struggle that was somehow at the core of where each was in their development. For Noam, walking with Galileo gave impetus to his own tentative steps of exploring in a terrain without ready-made answers, a maturation of relevance to his aspirations for pediatric practice. For Murielle, the torment of Galileo's trial gave voice to her own struggles just to do her self-chosen pendulum project in an inhospitable environment, and to her concerns, as a future nurse, that society – including her classmates – seriously debate and weigh its moral objections to the pursuit of science that may have possible or unknown human benefits. For Veronica, a scholar's exposure of the ins and outs of political intrigue by which the papal court orchestrated Galileo's fall from favor thrust into stark relief the backstage machinations that had closed down her early career. From this analysis, she gained cautionary wisdom toward her future in business. Unaware that in planning his project, he had accepted ungrounded claims about its outcome just on the basis of the claimant's authority, Henry came into perplexity when the experimental materials behaved opposite to that guidance. Henry redid his experimental work with sufficient care to convince himself that what he had been told did not hold. Further, by reflecting on Galileo, Henry gained awareness of his own complicity in accepting an authoritative word without questioning it. From the diverse, complex story of Galileo, each student reached depth with facets that were most needed to illumine and sustain their own development.

Galileo became more than a long-ago story for my students. Rather than being put off by his astounding accomplishments and viewing his political battles as antiquated, they saw what he saw, followed his thinking, and experienced surprise, wonder, betrayal, and opposition with an intensity that met up with Galileo's. The dramas of Galileo's history accommodated student participation wherever they were in their developing as questioners of nature, and in their engagement with the human dilemmas of research, authority, and power.

### *Having and Making Space for Exploring*

As explorers themselves, my students were doing science and history and that action deepened their relation with the phenomena, their predecessors, and their learning. Everyday things, such as pendulums and mirrors became in their hands links to a world of curiosity, patterns, and unexpected behaviors. Finding their own struggles, questions, and confusions there and – crucially – having space to reflect

on these individually and collectively, my students came into respectful dialogue with each other and explorers of the past.

Teaching in this classroom encompasses creating spaces where everyone can explore and reflect while having the safety to attempt something as tentative as holding a mirror so it sends light out a doorway or as risky as broaching a discussion regarding morality among participants who act from differing grounds. In doing this work, I found myself becoming curious about each student's explorations, imagining possibilities, and noticing what they overlooked. I used this observational and reflective research in responding, whether by planning the next activity, selecting readings and materials, or addressing a question or email. My seeking to support and provoke fuller explorations on the part of my students had a part in enriching their exposure to materials and experiences that became integral to developments in understanding science, history, and themselves. While my students, individually and as a class, were the ones who applied themselves by all the means that produced these developments, I as their teacher had a role, one that worked more through the medium of interaction than by directing others.

Such interrelated investigation by students and teacher depends on tolerating, and working within, confusion, doubt, and unsettled openendedness – an unwelcome condition where education hinges on answers. Noam found Galileo's contribution could not be reduced to right or wrong answers on the tides. Similarly, where science, history, teaching, and learning are evolving, the students and I found there is always more to wonder about. Not mirrors, not the story of Galileo, not our own story, are ever finished.

#### NOTES

1. Unless otherwise identified, quotes and excerpts are from my notes, assignments and records of the 2007 class.
2. Douglas Allchin of the University of Minnesota developed a historical simulation assignment titled *Debating Galileo's Trial*. <http://my.pclink.com/~allchin/1814/retrial/profile.htm> I provided my students with the readings referenced on Allchin's website, and supplemented these with many additional readings.

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