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# Exploring Mirrors, Recreating Science and History, Becoming a Class Community

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*A teacher narrates from activities and discussions that arose among undergraduates and herself while doing critical explorations of mirrors. Surprised by light's behaviors, the students responded with curiosity, losing their dependence on answers as the format of school knowledge. Inadequacies in how participants supposed light works emerged in the context of reinventing historical discoveries, including Ptolemy's second century AD account of how curved mirrors reflect, Chinese burning mirrors reported in the Han dynasty (206 BC–220 AD), and a ninth century AD Arabic translation of Euclid's surveying proposition. Using historical accounts only as a starting point and motivation, students' improvisational experiments explored personal interests and provided grounds for synthesizing new understandings of light and learning, and for forming relationships of community among each.*

## BEGINNINGS FOR EXPLORING MIRRORS IN MY TEACHING

Looking at mirrors every day habituates us into assuming we know how mirrors behave. My students found this assumption disturbed when they explored mirrors during the opening exercise of the undergraduate science course that this paper describes. Surprises and thoughtful observing arose for students and teacher. Mirrors even raised curiosity outside of class, such as a shopwindow's startling reflection. As the course continued, doing more with mirrors came to involve doing

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more with each other and historical optics. Eliciting curiosity, play, risk-taking, and critical response to each other's thoughts, these class experiences brought about relationships of such sufficient depth that students and teacher became inventive together in exploring, questioning, and learning.

This interweaving of what was learned about mirrors with wider experiences of learning and teaching characterizes the critical exploration research pedagogy of Duckworth (1973/2006, 1986/2006, 1991/2006, 2005/2006) (see Cavicchi et al., this issue 2009) through which I developed course activities. Along with researching my students' explorative experiences, I also studied historical work with mirrors and integrated historical readings and materials into my class activities and assignments. In common with critical exploration, recreating a historical work of science as a classroom activity puts students into contact with complexities of materials, phenomena, investigative process, and cultural settings (Heering, 2007; Stinner, 1995, 2007; Tweney, 2008). As well as widening their experience with science, historical reinterpretation may incite students to question the instructionally ingrained "need to get the 'right' answer" (Tweney, 2008, p. 4), a questioning that also invariably surfaces in doing critical explorations.

As a guest instructor, I taught this science lab course through the Honors Program at University of Massachusetts Boston in fall 2005 (and subsequently in fall 2007). In laboratory sessions, the class explored mirrors, pendulums, batteries, and bulbs, magnets, prisms, and tuning forks (Cavicchi, 2007). We read historical science texts and visited sites having historical science content: an antique light bulb exhibit, a rare book library, a collection of surveyor's instruments, a 1911 power station. Everyone did an investigative project to share. Such a range in activities connects with the requirement that Honors Program courses be unique, multidisciplinary, and engage students interactively in critical thinking. Thus the program encouraged me to try innovating my curriculum and pedagogy. This institutional outlook resonated with my aspiration to teach physical science through critical explorations, and supported my effort at difficult moments in the term.

This Honors science course represents my first teaching of an undergraduate course[1] since my doctoral studies with Eleanor Duckworth. My dissertation involved me in teaching a few learners at a time through exploring magnetism and electricity, and in researching and redoing historical experiments with these phenomena (Cavicchi, 1997, 1999). Previously, I lectured introductory physics for engineers at a public university, where eventually my colleagues encouraged me to design a lab course taking off from my experiences in preparing the *Ring of Truth* public TV science series with Philip and Phylis Morrison (1987). In that lab course, a science distribution requirement, I asked students to observe, experiment, and invent projects. The intensity and creativity that ensued surprised me.

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**[1] I developed, taught, and cotaught courses and exploration experiences for teachers of science and other fields during and following my doctoral studies (Cavicchi, 2005a), and began teaching a lab seminar at MIT (Cavicchi 2008a, 2008b).**

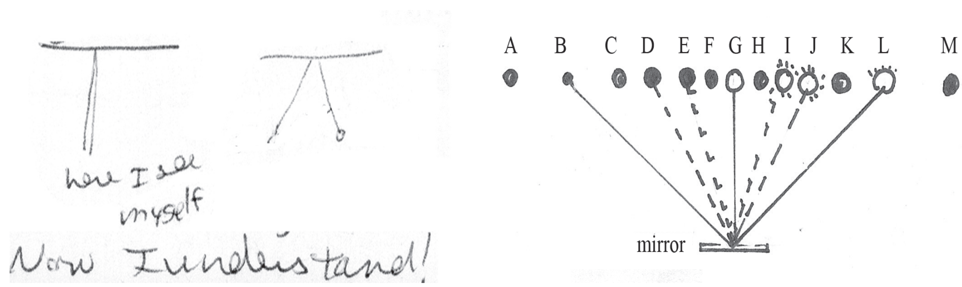


**Figure 1.** Left, middle: My journal diagram illustrating how Susan saw herself (leftmost sketch) and more of the room when looking at a mirror (horizontal line) along a nearly face-on and a more oblique angle (Cavicchi, 1992b). Right: My diagram depicting a line of people *A* through *M* standing in front of a mirror in the dark. A flashlight is passed to each person in succession. When each holds the flashlight at face level and aims it at the mirror, the face of another person lights up. The angle between the mirror and the person holding the flashlight is equal to the angle between the mirror and the illuminated person (for example, in the pairs *BL*, *DJ*, *EI*).

Mirrors were the context through which a schoolteacher, who was my student in that lab class fifteen years ago, reached a special classroom moment in her thinking, and made it shared. With a reading about Alice from *Through the Looking Glass* (Carroll, 1800/1960), I had passed out mirrors, tape, rulers, and protractors, and asked the class to work on "What is the relationship between the positions of you, the mirror, and the object whose reflection you see?" (Cavicchi, 1992a) I wrote in my journal:

> They turned their mirrors at different angles, argued vigorously about it. I was thinking I'd have to tell them [the law]... Susan began drawing what she saw (Figure 1, left) "here I see me.. here I see more" …understanding the normal [equal angle relationship[2]] realizing that the angles… were the same. Saying "Now I understand! Now I understand!" she had us line up in the dark. She stood in front of us holding a mirror (Figure 1, right). We passed a lamp from one person to the next, aiming it on Susan's mirror. Reflected mirror light shone on the face of another person in the line…at equal angles…(Cavicchi, 1992b)

Before taking this course with me, as a participant in a teacher workshop, Susan had performed the activity of passing a flashlight down a lineup of people. Each person in succession aimed that flashlight at a central mirror opposing the lineup. Upon each pass of the flashlight, a different person's face lit up. That activity had meant

**[2] Light reflects off a mirror (or reflective surface) at an angle equal to that by which it arrived at the mirror. The two angles are equal and symmetric about a line that can be constructed perpendicular (or normal) to the mirror at the spot where the light met it.**

little to Susan then. Now, through her own awareness of confusion and close looking to sort that out, she found a pattern, realized its connection to the earlier teacher workshop, and used it to bring her new understanding to life in our class.

In doing so, Susan also moved her teacher's understanding, not just about working with mirrors, but also about the heart of teaching. During the activity, as I considered whether I would tell my students the equal angle law, I was groping toward ways of teaching other than presenting laws and giving students exercises in their use. When I inverted that protocol in asking my students to find out how mirrors work, I had no idea how challenging this would be—for them and me—nor did I yet appreciate the depth of intellectual and emotional achievement to be gained in the process. The mirrors, and Susan's persistence, brought me into contact with all of that risk and potential. While this fullness was just forming in my teaching, for Susan and the other schoolteachers in my class it was already going on. One articulated a feature of which I was just becoming aware in writing: "I make my students search for the answers they seek in the same way we were made to seek" (Kokko, 1992). Learning happens, whether for students or teachers, as the questions and the seeking become their own.

Mirrors came again into my evolving teaching experience over a year later, as an assignment in my first course with Eleanor Duckworth, "Teaching and Learning." In groups of three, she asked the class to explore a mirror when we were not looking at ourselves, and consider how to know what a mirror lets us see (Hawkins, 1978/1985; Duckworth, 1990). The whole class activity, with its bodily movement around mirrors, conjectures, and discoveries, moved me profoundly.

However, when I attempted the homework assignment of redoing the same activity with an individual while following that person's emerging efforts, I faced frustration and ineptitude in posing questions and relating to my learner's struggles with it. There sometimes appeared an awareness on both our parts that I knew something [law] that the learner needed to know. This felt "inequality in our roles" was "problematic" for me, particularly where I sensed that differing status set us apart (Cavicchi, 1993).

In the course of going on to conduct many subsequent activities with learners and materials, for me this issue receded. I found a central quality of teaching and learning lay not in having and making answers, but in evolving through exploring and in opening possibilities for development and understanding. By contrast, most learners struggle with the issue of answers withheld by the teacher. They, like me as a student in the education course, assume that providing and repeating answers is an essential classroom function that the teacher still expects during a critical exploration yet does not support. Likewise, students entered the class described here with the view that answers were something they needed to get; eventually other outlooks on learning became available to them.

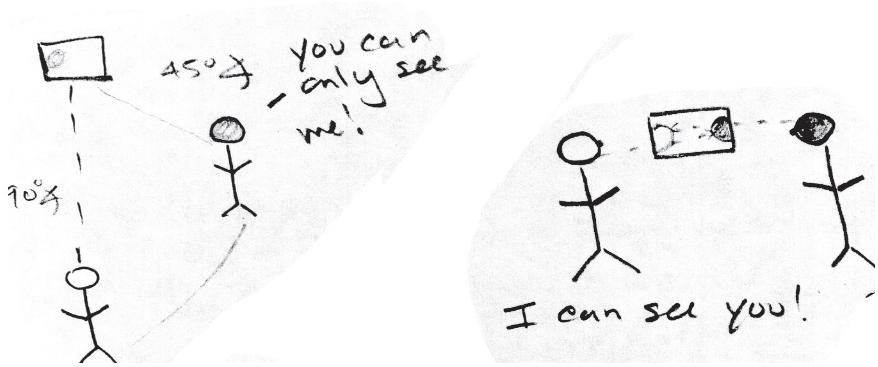


**Figure 2.** Left: In Anna's first drawing, her partner (white head) faces the mirror and sees her image (dark head). The partner is depicted on a perpendicular to the mirror's plane while Anna is located to the side. Right: In her second drawing, Anna and her partner see each other. Anna depicts how this works by drawing dotted lines that go from each head to the other head's image (Tsui, 2005).

## LOOKING IN MIRRORS TO SEE SOMETHING ELSE

On the first day of the science course that this paper presents, spoken and written words about exploring preceded the activities with mirrors and pendulums that would alternate across most sessions that term. After introducing the course as an experiment for both students and teacher, I asked everyone to select, read, and discuss one of four scientists' memoirs on early experiences with nature (Levi, 1984; Payne-Gaposkin, 1984; Vermaik, 1997; Vermeij, 1997). In these stories about flowers, shells, and the sky, the students noticed human affinity for nature even where disability might seem to rule it out. Students' personal recollections, done a week later, related childhood fascinations with dinosaurs, the beach, or music, that made them want to find out as much as they could. Renewing that fascination at depth was a hope I had for the course.

Our first effort to explore something physical began in the hallway with small mirrors about the size of a business card. Students self-selected into small working groups. What students did with mirrors disclosed their limited experience. Taping mirror to wall, one student, Anna, moved while looking for her partner. Upon finding each other, they supposed they were done and asked me what to do with a protractor found among the supplies. It surprised me that the activity had stopped already, and that the protractor was a total mystery to them. To urge them past the narrowness of a single result, I suggested that they move to other places, keep looking for each other in the mirror, and disregard the protractor.

Anna's notebook from that day beautifully follows her creative development beyond these initial moments in a series of four sketches (Tsui, 2005; Figures 2 and 3). While it is not clear what the actual positions of Anna and her partner were

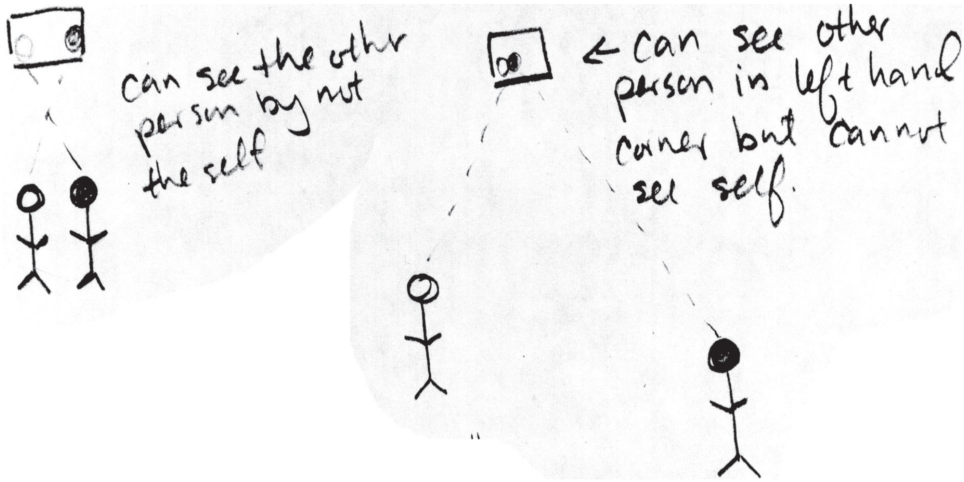


**Figure 3.** Left: With her third drawing, Anna tried to work out how each head could see the other by putting each head's image across from the head and crossing in air the viewing lines from one head to the other's image. Right: Anna's last drawing shows the imaged heads almost overlapping at the mirror and the dotted viewing lines meet and nearly coincide at the mirror (Tsui, 2005).

that gave rise to each sketch, these diagrams are a window into the questions she was working on and the tentative and evolving sense by which she construed her observations. Surprise grows from her first sketch where she wrote "You can only see me!" to the next—"can't see self", to the next, "can see the other person but not the self". She invented the symbol of a black head and a white head to represent herself, her partner, and their respective images, while a dotted line depicted her understanding of light's path. The first sketch's dotted line (Figure 2, left) goes from black head to mirror to white head along a route that would not be taken by reflecting light. In the second (Figure 2, right), a dotted line goes from black head to imaged white head (and vice versa), allowing each person to see the other. Drawn like a top view of the previous sketch, the next (Figure 3, left) represents the like image of each head in the part of the mirror directly in front of it. Dotted lines suggest the dark head sights the white head's image, and vice versa, by way of lines that cross in the air! Last (Figure 3, right), Anna brings the imaged black and white heads so close together that the dotted viewing paths of each head coincide at the mirror. The image heads are no longer placed at the spot in the mirror corresponding to a perpendicular from the mirror to the imaged person; instead, the imaged heads are almost on top of each other. In her words, "what the mirror sees" had become "very strange" for her. Now, being intrigued, Anna wrote "try to find a pattern". Her curiosity became self-sustaining, in contrast to when her original work with a partner came to an early halt.

A group of five went further in displacing their bodies while watching each other in reflection. They devised means of documenting and analyzing what they

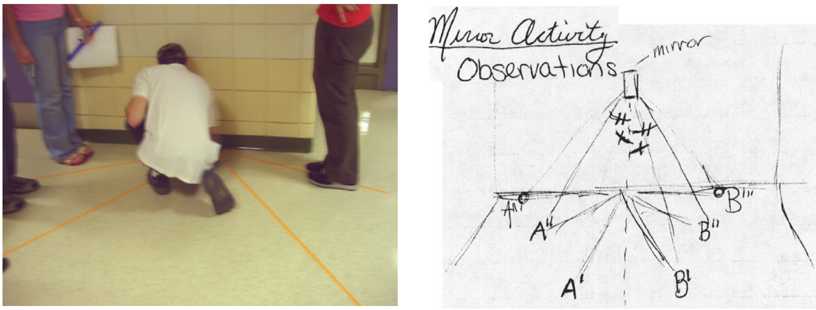


**Figure 4.** Left: Students tape two pairs of walking lines on the floor, extending out from a point below the mirror. People walking on these lines see each other in the mirror. Right: Jennimae's diagram showing three pairs of walking lines of two persons, *A* and *B*, paired with lines going from *A*, to the mirror, to *B*, at equal angles to a dotted center line (Cronan, 2005).

did (Figure 4, left). These students found that once a pair could see each other in a mirror taped to the wall at eye level, the two could walk in such a way that they continued to see each other, even as they moved. Onto the floor they put down orange tape along those walking lines. They extended each tape line to the wall where the mirror was. The two tape lines, from the two observers, met at the wall. They laid down a second pair of orange lines, corresponding to another mirror-linked path. The taped lines displayed a relationship about the middle like that of the edges of a fan opened wider, or less wide.

A drawing made during the activity by group member Jennimae, provides analysis (Cronan, 2005; Figure 4, right). It demonstrates the respective walking lines of two persons, *A* and *B*, paired with lines going from *A*, to the mirror, to *B*. She drew the angle between a center line and the line from *A* to the mirror as equal to the angle between the same center line and the line from *B* to the mirror. She marked these angles as the same, for *A* and *B*, no matter how wide or narrow those angles were. In adding the restriction that *B* must be at least as far from the mirror as *A*, Jennimae's notes suggest incomplete exploration along those walking lines. Lucienne, another group member, expressed that experience more fully in recording "ANGLE MATTERS, not distance" (Pierre, 2005).

That mirrors work for up and down, not just side-to-side, emerged from the pairing of our class's tallest and shortest members. The shortest, Samantha, couldn't see Andrew's face in a mirror set to his eye level. Moving the mirror between their eye levels, they saw each other. When the class talked about their mirror work a week later, someone said that people can only see each other in the mirror if they are the same height. Having direct evidence to challenge the limitation inherent in that observation, Samantha expressed [by words that came out backwards from the respective observation, either in her telling or in my notes]: "If you look down on a mirror, you can see the floor, or the other way, you can see the ceiling."[3] That Samantha and Andrew's problem in sighting gave rise to innovation in placing and understanding mirrors, moved me to ponder how in diverging from the classroom activity and their customary experience, individual students may perturb everyone's thinking.

On that second day with the mirrors, Samantha amazed us by telling about the store front window where she works. Standing at the cash register and looking toward the window, she saw an image of the cars approach, until a point where the image met itself and broke off. Then the car was seen directly, but from the rear, driving away.

Samantha's strange story provoked questions about what we see in a mirror. On the board, someone diagramed a line from object to viewer, bouncing off the mirror like the orange tape. An additional dotted line went behind the mirror, along the viewer-mirror angle. To me, the dotted line suggested that students viewed the image as being behind the mirror. However, I did not want to impose my interpretation, or even the word 'image,' on the class. So, repeating a question raised by Lucienne, "can we find out more about where the thing seen in the mirror seems to be?" I passed out mirrors again. I made this teaching decision on the spot, as a result of the class discussion.

One pair tried to redo Samantha's shop window, but could not coordinate placements of object, viewer, window, and light. Peter and Aaron teamed up, intently peering into a mirror while trying to measure an imaged object's height. Jenniemae wished she could remember what her physics class said about a mirror's "focal point" (however, there is nothing about a focal point involved in the activity with a flat mirror). Working with Andrew, she placed a quarter away from the mirror, and moved a dime closer. They got the dime's image in the mirror to match in size the quarter's image! They told the others that the further back something goes from the mirror, the smaller it looks. Lucienne and Samantha set up mirrors on top of paper covered with print. By looking while jostling the paper, they followed reversals in lettering to tell whether the imaged print had reflected off more than one mirror. Lucienne observed, "This is making me think more than before."

Each experiment uniquely responded to what the students wanted to know. It was their own creation and yet it put them in contact with something they did not understand or control: the reflection of light. When we left off that second day, what stood out for my class was the complexity of factors that affect mirror images including "angles, positions, height of objects" (Bramhill, 2005). Although someone predicted that an object seen in a mirror would look to be twice as far back from where it is, no one provided evidence to support this claim and it passed from view. No rule emerged. Although more was going on with mirrors than anyone in the

**[3] All direct quotes are from my notes and transcripts (Cavicchi, 2005b), unless otherwise designated.**

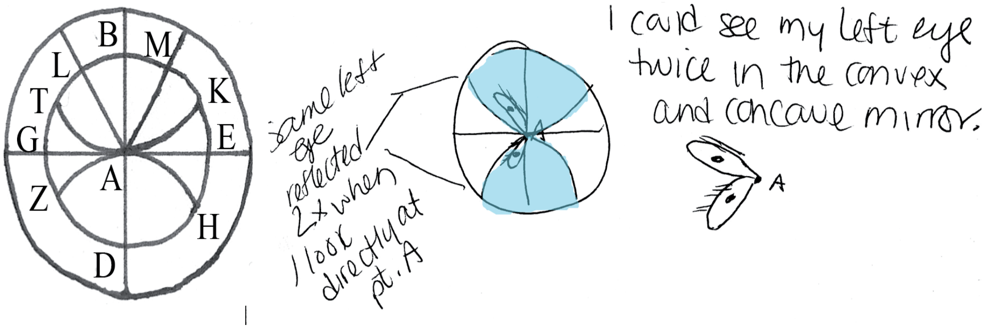


**Figure 5.** Left: Ptolemy top-view diagram where a person looking from *L* to *A* views an object placed at *M*, no matter whether the mirror at *A* is flat (*GAE*), concave (*TAK*), or convex (*ZAH*). Right: Interpreting the mirror shapes as lying within the plane of the paper, Lucienne cut pieces of mylar corresponding to *TAKBT* and *ZADHZ* and pasted these over Ptolemy's digram. Puting her eye over its center at *A*, she viewed it reflected in each mylar cut-out (Pierre, 2005).

class previously supposed possible,[4] in my inexperience and because the image question remained unresolved, I doubted the productivity of my students' multifarious activities.

## REINVENTING ANCIENT MIRROR OBSERVATIONS

To further the class' involvement with mirrors between sessions, I gave out shiny mylar sheets and assigned historical readings on reflection (Smith, 1999) and mirror-making (Melchior-Bonnet, 2000; Pigett, 1992). I asked the class to use diagrams and the mylar in reconstructing how the Greek authors Euclid, in the third century BC, and Ptolemy, in the second century AD, discussed the equal angle relation of mirror reflection. While Euclid argued with geometry, Ptolemy empirically demonstrated that concave and convex mirrors reflect by equal angles just like flat ones. Ptolemy asked the reader to look along line *L* toward point *A* on the mirror while someone moved an object along curve *BMK* (Figure 5, left). The object could be seen only when it was at *M*, the equal angle position, no matter whether the mirror was concave (*TAK*), convex (*ZAH*), or flat (*GAE*).

Concerned that students might take these readings as an "answer" about the mirror, I was indecisive about using them. However the result was the opposite: the historical texts and arguments confused my students without settling what mirrors are about, and these responses were commensurate with the educational work I hoped to bring about. Ptolemy's top-view diagram of his test apparatus baffled

**[4] See Fynn, 1974 for evocative descriptions of a child's exploratory and creative observations with mirrors.**

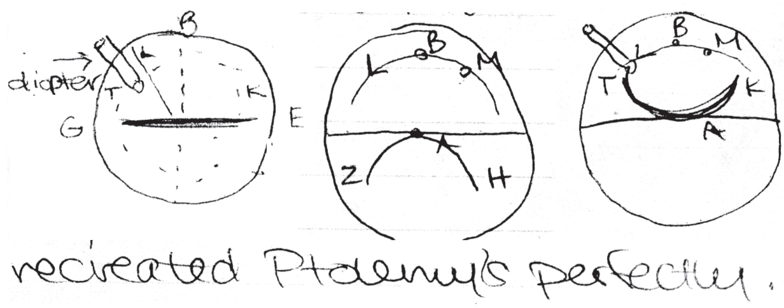


**Figure 6.** Samantha "recreated Ptolemy perfectly" by sighting into a mylar mirror that she formed flat (left), convex (middle), and concave (right) (Pitchel, 2005).

students who attempted to remake it with mylar. Lucienne was perhaps least troubled by the reading. Interpreting the mirrors as lying flat not upright, she cut mylar shapes that mimicked the curves of Ptolemy's diagram (e.g., the form within *TAKBT* and *ZADHZ*) and pasted them on a flat circle, between the marked curves (colored shapes in Figure 5, right). Putting her eye right up against the circle's center, she saw her eye reflected in each mylar cut-out, and sketched it.

By contrast, in viewing the diagram as representing three mirrors viewed from above with overlapping centers, Samantha was thrown into such uncertainty as to write lots of questions: Is it all flat? Do you "leave all the mirrors up simultaneously?.. How would you see past the first mirror to the other two?" (Pitchel, 2005) Through considering these successive possibilities, Samantha moved into mounting the mylar strip upright on a cardboard so she could flex it into three configurations: flat; concave; convex (Figure 6). She doubted her set-up was what Ptolemy had done, and her first try with the concave mylar did not produce an equal angle outcome. But when, with both flat and convex arrangements, she sighted a mirrored object only when it was at the true reflection angle, she knew that she had, in her words "recreated Ptolemy perfectly." This success motivated her to reform the mylar into the concave shape and repeat that observation. Now her "results matched Ptolemy" for all three cases (Pitchel, 2005).

When we discussed this assignment in class, Jennimae delighted everyone with her wonderful mylar construction having a paperclip sighting-aid, carried in a mirror-case or purse (Figure 7). She said it took an hour "to understand exactly what needed to happen" (Cronan, 2005). Her notes show that she first analyzed the Euclid reading closely to check its geometrical claims; perhaps this detailed study unlocked a path for her into Ptolemy's argument. Appreciation now came from classmates who had been put off by the austere texts and left that part of their homework undone. Through "wrapping [his] mind around" her construction, Jennimae's project partner Aaron attempted the assignment afterwards and invented another variation which also worked (Shaw, 2005).


**Figure 7.** Left: Jennimae's diagrams redoing Euclid's argument for equal angle reflection in flat and convex mirrors. In both, her eye is depicted at point *B*, looking at point *K* on the mirror at the reflection of object *D*. Angle *Z* is equal to angle *E* in both the case of the flat mirror *CKA* (top) and the curved mirror *CKA* (bottom, Cronan, 2005) Middle: Jennimae's replication of Ptolemy's apparatus has a mylar mirror sheet bent convex mounted on a circular disc like Ptolemy's, and uses a paperclip as a sighting aid. Right: Jennimae's mirror purse is cylindrical shaped, having the numbers 801 printed around its cylinder sides, and convex mirrors making up either end.

Whether by reading, constructing a model like Samatha's, or watching Jennimae's demonstration, the students' responses to Ptolemy drew on and stretched what they had begun noticing about the equal-angle reflecting of flat mirrors. They were flexibly changing their perspectives and not just following an ancient source. That active involvement shows in the eyes that Lucienne and Jennimae drew into their sketches (Figures 5 and 7). To gain the reciprocity of looking as if with someone else's eyes involved confusion, questions, and many possible placements of mylar, eye, and object. Each personal experience took a unique pathway by which understanding developed. Yet the students' many personal pathways integrated together by means of features shared in common: the consistency of light's reflection on any shape of mirror and the specific mirror construction of Ptolemy.

Not everyone tolerated the confusions and frustrations of Ptolemy, mirrors, or other class activities with the persistence and satisfaction of Samantha or Jennimae. One student having prominent academic skills became tangled in Ptolemy's diagram. Stress over a perceived lack of success led this student to drop the course. Citing schedule conflicts, others had already. The dwindling class size dismayed me. I doubted myself as a teacher of experiment, and my expectations for supporting and opening students' creativity through teaching.

My distress intensified when even fewer (a third of the original enrollment) were present for the next session. Although internally debating what to do, I still brought out supplies for the range of activities I had planned with pendulums, mirrors, prisms, and magnets. We started with pendulums, which the students had explored each prior week during class. Differing accounts arose about how pendulums interact, so the students proposed to set something up. Instead of many small groups, the class became one collaboration. A pair of interlinked pendulums

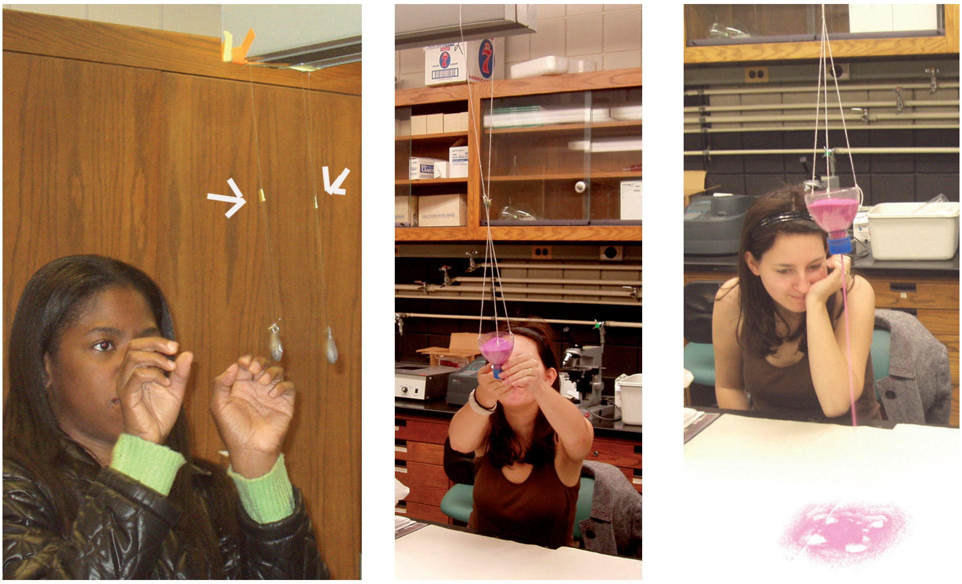

**Figure 8.** Left: Lucienne releases two pendulums together. The pendulums are interlinked by a horizontal thread (not visible) that is taped to their two vertical strings near the arrow heads. Middle: Samantha releases a pendulum supported by two long strings that cross midway and support a transparent cup of pink sand as the weight. Right: Samantha watches pink sand leak out of the swinging pendulum cup, producing overlapping figure eight patterns on the white paper below.

swung as everyone watched: in silence, in repetition, in discussion (Figure 8, left). Further modifications produced a pendulum whose two-string suspension joined at its midlength (Figure 8, middle), supporting a cup that leaked pink sand in figure-eight patterns while swinging (Figure 8, right).

I switched from pendulums to discuss the latest mirror homework, which involved finding the size of a mirror that is sufficient for a person to see their own whole face (Duckworth, 1990; Kipnis, 1993; Melchior-Bonnet, 2000). Lucienne said it made no sense. To Lucienne, depending on how far away it was, the mirror could be any size, even very "tiny." She said, "If you back away a lot you could see yourself... eventually you are going to get to a point where you are reflected in a mirror and you can see your feet." I asked how far back an image seen in the mirror, seemed to be from the object. Andrew proposed that the image was as far back into the mirror as the object was in front of it. Samantha had tried to estimate it and did not think the image was as far back in the mirror, as she was in front of it. However, in agreeing with Andrew, not Samantha, Jennimae explained how she used the image of her floor's tiling pattern to judge distance in the mirror.

Seeing that the mirror homework generated such discussion, I changed the plan that I had in mind to do for the day and decided to explore this question in detail. I presented the class with one notebook-sized mirror to work with. Taking

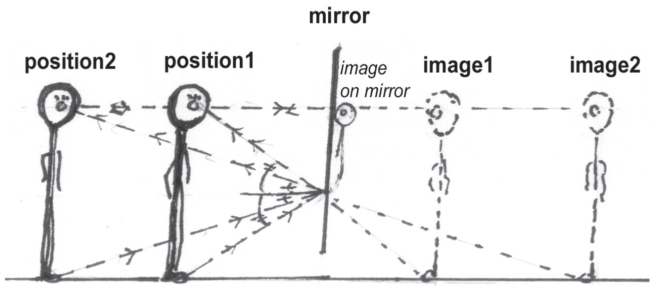


**Figure 9.** Left: Lucienne holds the mirror for Anna, who backs away from it, watching the size of her face's image. Right: Ray diagram for a person viewing their body in a mirror, at two positions. One ray passes from the person's foot, to the mirror, and reflects at equal angles to their eye. Another ray passes from the eye, to mirror, and straight back to the eye. The height occupied on the mirror, by the person's image, is the same at both positions.

turns in holding the mirror or being the looker, they checked out the size on the mirror occupied by the image of the looker's whole head when the looker stood at different distances from the mirror. It took practice, walking and holding, walking back and forth, to get where someone really saw their face throughout the whole time they backed up. Noticing something odd, Lucienne said "I don't think it [image] changes in size at all."

When Anna took her turn (Figure 9, left), Lucienne put tape onto the mirror around the outlines of Anna's imaged face. Anna backed up, in her words "believing that my face would obviously shrink in the mirror." (Tsui, 2005) While moving, her surprise at what she saw deepened with some realization that things seen in mirrors are not quite what one might expect:

> … my face…if I keep like…It's weird. It still fits between the lines!

An effort to measure both head and its taped image was inconclusive; not quite a ratio of 2/1. Peter tried it too. Insightfully, he linked the outcome of a constant image size with the shift from the viewer's perspective to that of the mirror plane which had eluded the others and left them with flawed expectations. Peter said:

> [At] a different distance, it [the image] looks like a different size because you are further away. So you look smaller *to you*, but in the mirror, you are still the same… size.

At the board, I sketched the ray diagram (Figure 9, right) for someone viewing their own reflection at two distances, applying in it what the class previously worked out about equal-angle reflection. But I soon became aware that my synthesis was not in contact with theirs and felt bad about it. Later, I realized that in its failure lay clues to differences between students' outlook on light, and mine, that I had not yet appreciated.


**Figure 10.** Left: Students seek a relation between mirror, sunlight, and paper. Right: Sunlight reflected off a concave mirror focuses as a bright spot on newspaper that Peter holds, below where it is already burning.

Next, I passed out right-angle prisms, whose startlingly distinct reflections Anna described as "just as good as a mirror". Grouping around one lamp that stood on the labtable, students played with their prisms in its light. Someone asked for a curved mirror to put in the lamp's path. As they put cardboard in the path of light coming from that concave mirror, I watched and realized that the students were attempting to recreate the ancient Chinese practice of "burning mirrors" described in our reading about an optical text of the late Han dynasty (206 BC-220 AD, Needham et al., 1962). My students kept checking the cardboard, feeling it with their hands to see if it would burn up!

After silently allowing some time for this test to fail, I asked whether they would like to try the curved mirror outdoors. We reconvened on a plaza in full noon sunlight. Anna started by holding a curved mirror aimed low, toward the horizon. Peter waved a sheet of paper nearby, but not in front of the mirror. Perhaps he was trying to put the paper at an angle suggested by the class' equal angle reflection diagrams. The two kept up moving mirror and paper with each other, gradually coordinating them and involving the sun. When the paper came more along the mirror's central axis, a bright defined spot appeared. What amazement when the paper smoked!

With this achievement, they now had instant feedback to every move and could repeatedly find, and even measure with a ruler, the position of the mirror's focal point. Spontaneously improvising, Peter started to burn a hole, stopped it by moving the paper away from the mirror and reignited it by replacing it again (Figure 10). They discovered newspaper lit faster than notebook paper. It was their idea to use two mirrors at once, differently angled toward the same paper. This doubled effect scorched a hole through the entire school newspaper. It went up in flames!! With experience, ideas, and flame feeding on each other, the experiment evolved in ways no one could have predicted. (On returning to our classroom, there was still time to float a lodestone on a little boat in water, find north, and perturb it with magnets.)

When the students left that day, bits of experiments were strewn around the room: pendulums still hanging, a pile of pink sand, another of iron filings, mirrors, lamps, prisms, and spilt water. Anguished by the precipitous drop in class size, I could not yet take in what transpired during the session. Dismayed with myself, I felt "I had not engaged well with the students" (Cavicchi, 2005c). I had said little, missed opportunities to encourage certain observations to go further, put up a ray diagram that meant little, and forgotten to bring out relevant items (like having a bucket of water on hand when the newspaper burned up).

The next day, on writing up my notes and records from the class, I came to see that mirrors, prisms, pendulums—even the reading!—had engaged the students, even if I had not. Students' experiments developed through what they did, and what they did disclosed their emerging awareness of mirrors and other materials. An entire newspaper burned, after an initial failed attempt to singe cardboard under a lamp. That development was what I hoped for in teaching, even if it happened mostly without me. And what the six students present that day forged in relationships with materials and each other fueled exploration across the term for them and the three others who had missed class that day for various reasons and who did rejoin the class.

## ANXIETIES WITH INVESTIGATION PROJECTS

Attendance was up the next time, and no further attrition ensued. With encouragement from the Honors program, I initiated a conversation about the class. The anxiety that my students voiced was over the investigative project assignment (other concerns appear in journals, such as the view that our "simple" experiments were beneath Honors students, and discomfort with a course not centered on exams). One student asked to be assigned something to do.

In contrast to a prespecified task, my project instead asked students to further explore something from our class activities that they were personally curious about. I suggested trying something out, watching what happens, generating questions and ideas, just as we did in class. I described the project as "starting on a journey" where experience gained along the way was the project, and the research paper that I assigned was their record and reflection on that process. During this discussion, I learned that students identified research with searching online databases. Research in the context of my assignment was defined differently. I said "your database is your notebook, readings, class discussions, activities".

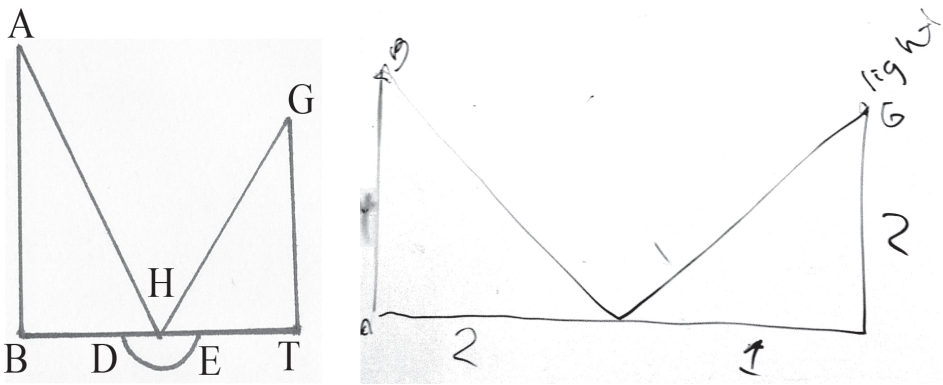


**Figure 11.** Left: In Euclid's diagram, a mirror is on the ground at *DE*. An observer whose eye level is at *G*, views unknown height *A* in the mirror via reflection at *H*. Sides *GT*, *HT*, and *BH* are known, and *AB* is calculated. Right: Blackboard version of the same diagram; Peter assigned values 2 and 1 to the height and base of the observer's triangle, and 4 and 2 to the respectives sides of the triangle containing the unknown.

Our discussion exposed disparity between educational practices familiar to students, and those that I sought to facilitate exploratively. We each incurred risks by departing from conventional roles. Having demonstrated success in executing prescribed tasks, these Honors students risked not succeeding when the activity was up to their own curiosity and observation. As their teacher, I risked failing to elicit class explorations that were sufficiently evocative to enable students to go on to pursue others at home. Would I receive final reports that correspond to the usual research project expectations, or would students' work reflect personal observing, wondering, and analysis?

## RECREATING EUCLID'S PROPOSITION 20

The next week, the class viewed treasures of historical science and technology such as the first printing of Euclid's *Elements* (Euclid, 1482) and a display of early light bulbs during a visit to the Burndy Library, then located in Cambridge Massachusetts.[5] Scholar Elaheh Kheirandish met the class. She described trends in historical optics, from the geometrical emphasis of the Greeks Euclid and Ptolemy to the "revolutionary" integration of experiment and perception in the optics of Ibn al-Haytham during the medieval period in the Islamic world. Jennimae demonstrated her construction of Ptolemy's three mirrors, and Elaheh responded:

> You are very fortunate to have a nontextual element to your studies, it is very rare. I'm sure you are aware of that.. I was very fascinated by the way you are doing this...

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[5] **The former Burndy Library collection is now held at The Huntington Library, San Marino, CA.**

Elaheh contributed further by giving us her own English translation of proposition 20 from the ninth century AD (ca. 170/786–218/833) translation into Arabic of Euclid's Greek *Optics* (Kheirandish, 1999, vol. 1, p. xix, 58–61).

A week later in our classroom, everyone read Elaheh's translation. In the proposition, Euclid used similar triangles to argue that an unknown height *A* could be determined if it was viewed by reflection in a mirror located at a known distance from both object and observer, and where the observer's height *G* was also known (Figure 10, left). Devin protested the whole passage, saying: "I don't get it." She sketched on the board two triangles having a common point (at the mirror).

Peter, who grasped the geometry, went to the board. Without redrawing Devin's triangles, he assigned hypothetical values to their sides in illustration of Euclid's argument but without being scaled to her pre-existing diagram (Figure 11, right). Starting in each case with a length value on the observer's triangle and following that with the corresponding side of the object triangle, Peter proposed "say that base is one, that [base] is two. So if you know that height is two, this [height] would have to be four."

The class debated. Could Euclid work this out without measuring any angles with a protractor? Insisting that "he doesn't need to know the angle", Peter described the proportionality between the two triangles—in his case a factor of two—as all that was needed to work out the unknown height:

> He [Euclid] knows it's proportional. He knows the height and base on the right [observer] triangle...And that it is going to be the same ratio as on the other one [object triangle]. He knows the base on the left one... he knows the ratio is like one to two..

In reworking the argument for herself, Lucienne made no use of Peter's numerical values. Instead, picturing the triangles imposed on a realizable arrangement of observer and objects, Lucienne reasoned:

> You put the... the flashlight where the eye is at point G. Put the mirror on the floor...so that it [reflected light?] hits the top of point A. You know equal angles... OK I see what Peter is saying....

To Lucienne's imagined set-up, Devin reintroduced Peter's values. By differing routes, they concurred in retracing Euclid's argument with their minds.

A pause ensued. I was uncertain whether students who had not spoken, had engaged with these analyses. Mentioning that Elaheh described this proposition as optics applied to surveying, I wondered if anyone could imagine a situation where it might be used. Peter said it could give a building's height. Lucienne, whose understanding of the proposition came through visualizing it in practice, proposed that we try it out.

Lucienne's proposal came as a surprise to me. I was thinking that the blackboard discussion sufficiently clarified Euclid's text. Early in the discussion, Peter had asserted there is nothing new in it, and I had agreed. We had already explored the equal angle reflection of mirrors.

At once, the experiment began to happen, all coordinated by the class. I watched, fetched any tools they asked for, checked their calculation, and marveled. Aaron wanted to be the unknown height. To make it more of a challenge, he stood on a lab table. Peter would be the known height, and a flat mirror went on the floor between them. Lucienne and Jennimae knelt on the floor with a tape measure. Others made suggestions, recorded data, and calculated results.

Problems immediately arose. Peter shone a flashlight at the mirror, but no one could see where its reflection went! This was perplexing. Soon the room lights were switched off, a transforming intervention. Still, it took a while adjusting Peter's light and the mirror before, amazingly, Aaron's face caught the reflected glow! Euclid's effect worked—but what about the measurement?

New problems surfaced. The flashlight's reflected bounce was too wide to measure; Peter switched to a laser pointer. The bounced path was beautiful to see in red: grazing Jenniemae's hair, hitting one spot on mirror, Aaron's head, the ceiling. Measurements followed for: the laser's height from the floor, the length from Peter's feet to the mirror, from mirror to the lab bench. With these read aloud measurements, everyone next concentrated on calculating our unknown—Aaron's height—either by long-division or cellphone keypad. There was consensus: the number was too far off. Someone noticed that Aaron's shoes were set back from the table's edge. Adding in his shoe's length did not make up the needed difference. Someone said "This can't be right." The experiment had to be redone.

It was redone many times, accompanied by lovely and teasing interactions among the students. Before anyone went on to a next attempt, they always waited until everyone was done calculating the last one. Into these discussions came a need to, as Devin said, "try controlling variables". For example, instead of being in Peter's hand, the laser was mounted on a table, "so we can measure an exact height". Even our unknown came into question. Devin observed "we had guessed Aaron's height the whole time—Finally we measured it" (Bramhill, 2005).

Jenniemae's prior physics course came to her aid; she remembered to calculate percent error. The last result was within 5% of Aaron's true height. She did not win everyone's consent to conclude the experiment. Aaron, reluctant to step down before the experiment *really* worked, said "We didn't break anything except our pride", while Peter took an engineer's stance: 5% wouldn't do "if it was a bridge or a dam in Taunton…so I say FAILURE" (Tusi, 2005).[6] Another student said that if we were going to do this another time, we should chose a fixed point that isn't moving around like Aaron, such as a point on a wall, have a mirror on the floor, and another light on another wall. Talking about how they liked seeing the experiment

[6] **A major news item that week involved the imminent failure of a dam threatening to flood downtown Taunton, Massachusetts.**

develop in successive trials, Devin and Jennimae asked me: was it alright that it happened that way?

To me, the self-generating experiment, with all the joy and fun of it, was exactly their learning. In the first weeks, creativity and questioning were personally expressed and individual results never quite correlated across the class. This experiment was different. Igniting newspaper took physical and observational coordination. But to recreate Euclid encompassed interpreting an ancient text, intellectual debate, confusion and invention, light's reflection, bodily motion and nonmotion, measurement, and calculation, in cycling critiques. In doing this, the class became a community that made, disputed, and shared understanding in common. That understanding was not just the value of Aaron's height, but the creative process itself. Watching this evolve in the darkened room, I observed the development of what Hughes-McDonnell (2009, this issue) describes as trust.

## INVESTIGATIVE PROJECTS OPEN NEW CLASS EXPLORATIONS

During our last meetings, explorations arose as each student took a turn in sharing their investigative project with the others. Project activities included: making paper from diverse fibers (Bramhill, 2005; Pitchel, 2005); dissecting flourescent and incandescent light bulbs (Shaw, 2005); hooking bulbs and flashlight batteries together (Cronan, 2005); sounding guitar strings (Pierre, 2005); guitar strings viewed under strobe light (Tusi, 2005); optical illusions (Lix, 2005). Optics resumed through Anna's aspiration to "reveal the rays of light" (Tsui, 2005). By treating light rays as a subject of investigation, Anna brought me to recognize that the ray representation of light is not obvious. I then appreciated the obscurity, for students, of the ray diagram I had drawn on the board after the head-in-mirror activity.

Jello—both homemade and prepackaged—showed best the linear path that Anna recalled from her childhood memory of a shaft of light revealed in a dusty classroom. At uneven jello surfaces—where classmates' spoons had gouged it—the laser beam showed "very cool" effects. In contrast with the jello, Anna dosed so much cream into a water-filled fishtank that flashlights and laser pointers directed into it did not make it to the tank's other side. The liquid became "a light ray death trap" (Tsui, 2005). Next, Anna wanted to explore "how light reacts to smoke and vapors" (Tsui, 2005). We put a cup of liquid nitrogen in another fishtank. In the forming vapor, the laser's path appeared with a surrounding glow.

Anna incited a new challenge: mixing cream and sugar with liquid nitrogen. Would it make ice cream?! Several students ran down four flights of stairs to collect free creamers and sugar at the school cafe. Crushed wintergreen candies, remaining from a previous experiment (Cavicchi, 2008a), provided flavoring. Aaron stirred cream and liquid nitrogen together, Peter taste-tested, and Andrew supplied "liquid N" from the large and formidable dewer. It took a lot of liquid nitrogen to freeze the cream. We all had some, encouraged by Aaron and Andrew: "it's good, it's good." Relishing the last spoonfuls, Peter rejoiced in the ice cream: "fantastic...the first thing we made that didn't explode!" to which Jennimae rejoined "or catch on fire". Wonderful questions—such as were we eating "liquid N" itself?—were genuinely evoked. Some were pursued on the spot, while others remained as the course concluded.

## EXPLORATIONS WITH MIRRORS AND COMMUNITY

This upwelling of questions and the capacity to be in their midst, generating more, without easy answers in sight, signals what developed among these students and their teacher. Something about the world opened up. Things that students had previously passed by without noticing, now held them for a closer look which could set them off doing something more, observing, talking—together. Being together, through relationships among people and things, was integral in the developing experience. Those relationships sustained experimentation with physical materials, and with the nature of teaching and learning.

Learning and teaching were becoming community work where individuals poignantly expanded each others' experiences and understandings. Samantha and Andrew's gap in height raised others' consideration of reflection in a vertical plane; her shopwindow story widened their outlook on the complexity of viewed images. Just as Lucienne helped Anna find constancy in her imaged face size by taping the mirror around it, so on another occasion Devin "literally made [Lucienne] see" the old woman in the young/old woman illusion by drawing over it (Boring, 1930; Pierre, 2005).

Even last names could hold mutual discovery. Near the course's end, Anna noted the one-letter transposition between hers (Tsui) and Peter's (Tusi):

> *Anna* Pete is your last name Tusi? [mine] is Tsui. People always pronounce it Tusi
>
> *Peter* I think my greatgrandfather changed it! It used to be some long crazy Italian name.

Anna reported the next week that she had researched Peter's name with an Italian friend who said it should be "Tuzi". Peter disputed her claim and others joined in:

> *Devin* Yours is what?
> *Anna* Tsui T S U I
> *Peter* Tusi T U S I
> *Aaron* And my name's Shaw!

Analogous to this play with last names, students' diverse participations were both cooperative and critical. This combination of cooperative and critical interactions produced experiments and experimental knowledge. For example, multiple revisions in redoing Euclid's proposition depended on cooperation in envisioning and producing the set-up and on critique of the measurements and experimental design. Spontaneous observation and thoughtful reevaluation motored the transitions in these cycles. This whole process struck Peter as "amazing"—that it was possible to "come up with new ideas" from inadequate starting premises (Tusi, 2005). Experiments with everyday things were key in precipitating critical review:

> it was the seemingly simple [experiments] that seemed to stun everyone the most when their basic assumptions proved false (Tusi, 2005).

Shared outcomes included new optical effects, substances such as ice cream, and understandings of light's paths and of developing as an experimental "team" (Pierre, 2005). While shared, the body of this knowledge was no uniform "answer" that anyone could summarize or repeat, and each participant apprehended it by different means. The class's body and process of knowledge correlated with science laws, like the equal angle reflection of mirrors, and science history, such as operating Ptolemy's curved mirror device. This knowledge was not static; something in science or history might provoke students to further thought. After the burning mirror activity, Lucienne pondered out for herself the distinction between real and virtual images that is often instructionally presented via vocabulary:

> the image of the sun on the paper was real somehow, though it was a reflection. It was the sun's power focused at one point...not like an image in the mirror that you can't touch or feel; it had a real consequence." (Pierre, 2005)

Like Peter's appreciation of "seemingly simple" experiments, Anna perceived the large in the small while realizing that original historical experiences:

> of awe and puzzlement are similar to our own …[O]ur seemingly insignificant comments … in class over… a simple beam of light are important steps in the exploration of science. (Tsui, 2005)

Seemingly transitory experiences like newspaper ignited by redirected sunlight carried "real consequence" that grew large in my awareness of what contributed to developing students' understanding, and of what I might look for and support as a teacher of exploration. I documented sessions to help me and my students see critical explorations develop, whose transient yet formative features we may miss while being involved. Part of what developed for me lay in my actions and thinking of teaching, as well as of what students did with light and mirrors.

I continually dealt with evidence of what students had not noticed or reconsidered and implicit, unseen boundaries, set both by them and me, to what could happen next. Assumptions in my teaching, such as what might be involved in learning mirrors exploratively, or the self-evidence of the ray representation of light, underwent change. Teacher as well as students struggled with doubt about the work, sensed its departure from practices that assure a recognizable success, and adapted themselves to interact with things and each other in ways that increasingly opened up exploratory actions and insights. Initially students hardly tapped into the potential that I conceived for the lab materials and activities. Eventually they generated a momentum in looking and learning. I assisted while privately continuing to imagine yet further activities.

The mirror's reflection of light seems at the surface to be simple, but the process of discovering its possibilities—and the reflective thought that accompanies that process—unsettles familiar patterns of knowing and relations. Mirrors seem to be simple in the tightly framed demonstrations of textbooks, but a new complexity emerges when students and teacher depart from rigid demonstrations to explore personal questions. Our critical explorations exposed both constancy and diversity in the interplay between light and mirror, raised things to do and notice, and accommodated enthusiasm, wonder, and critical analysis. Constancy in equal-angle reflecting of mirrors, whether flat glass, curved mylar, or dimpled jello, and diversity in mirror applications, such as burning paper or estimating unknown heights, were present in everything we did with mirrors. This combination of constancy and diversity engaged us in making the connections between our explorations and everyday experience that give depth to learning.

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