Unsettlement brings about development in the classroom: Critical explorations with historical observations of light

ELIZABETH CAVICCHI
Edgerton Center, 4-405, MIT, Cambridge MA 02139 USA
ecavicch@mit.edu

The curiosity that light's properties provoked among historical observers has the educational potential to be re-expressed by students today. This paper narrates optical explorations of undergraduates in my laboratory classrooms, in response to historical observations by Shen Kua, Ibn al-Haytham, Leonardo, Galileo and others. My students' explorations included many "unsettlements" in which discrepant, unexpected findings encouraged students to revise their understandings of light's paths: a pinhole inverts an image; a mirror does not work like a picture window. To encourage this personal discovery, I apply critical exploration, the research pedagogy developed by Eleanor Duckworth from historical origins in the clinical interviewing of Jean Piaget and Bärbel Inhelder and the Elementary Science Study of the 1960s. In complimenting his extensive studies of children with analyses of historical science, Piaget concluded that in either case, what someone does in acting on the world brings about input that unsettles the interpretation held of it. Disturbance moves protagonists to reconstruct their outlook, integrating the unsettling with the familiar. In applying critical exploration, I provide conditions that support students in discovering their own unsettlements. Through engaging with unsettlement so as to take seriously such discrepant, unexpected findings as inverted pinhole images, students reconstruct their understandings of light's paths, but this reconstruction also allows them to look at the historical record – and even the educational process – through the lens of their own new insights. Through critical exploration, students and I both experience unsettlement and intellectual growth out of our prior assumptions about light, history, and education.

Introduction

Finding out that things are not as you assumed can be unsettling. Yet it's a feeling that moves us to reevaluate what we took for granted, to admit new evidence and rethink how we interpret what's around us. Its transformational power comes from the internal self-realization, as contrasted to some external determination of inadequacy. In doing science, it is productive to notice and follow through on unsettling hunches. Historical developments in science reflect this, where anomalies and ambiguities can set off a wide-ranging and generative response. This paper illustrates the productivity of unsettling experiences for learners in science classrooms where I was the teacher. In the examples that I'll describe, my students were exploring light using mirrors, holes, and lenses. Their own observations were beginnings for experiments and interpretations. My opening questions and interactions, along with historical readings and visits to instrument collections, broadened their experience. Previously unnoticed assumptions surfaced and reverberated against what students encountered investigatively. In engaging with this unsettlement, my students expanded their experimenting and reconstructed their beliefs about what is involved in learning and doing science.

Disequilibrium and Exploration in Piaget's Interpretation of Development

In this study, I apply analyses of development that Jean Piaget and his colleagues derived through extensive clinical studies with children (Piaget 1932, 1936, 1937, 1941, 1946; Piaget and Inhelder 1948, 1955). Piaget established that these developments do not proceed step-by-step, or according to a preformed sequence. Each child's development is uniquely transacted through personal agency in relation with the surroundings, while the mechanism of that development is in common across all children.

Children develop by interacting with the world through the use of whatever capacities and understandings they have already formed. Applying the term "structures" to these resident, yet always incomplete and evolving, capacities, Piaget identified two means by which internal structures mediate any interaction between child and world. When one means, termed "assimilation", is in effect, the child takes in and responds to something of the world by fitting it to the structures currently available. Or, if the child makes use of "accommodation", the structures undergo change and adaptation so as to take in and integrate that aspect of the world with the self. Assimilation and accommodation go on in fluid exchange across all experiences, whether these call for minor or major responses from the subject. Undergirding that fluidity is a process of equilibration, of making assimilative or accommodating adjustments that seek to balance the structural integrity of the self with regard to pressures, inputs and incursions from the world (Piaget 1936, 1937).

Piaget conceived the analogy of equilibration as a dynamic and ongoing mediating of self with environment. Changes in the self's structures organically draw upon the resources of the whole and affect it by restructuring what is there and adding in new elements or capacities. Nothing is torn down or cast off wholesale. The former structures and equilibrating practices are still there, having been stretched, reworked, adapted, extended or made to fit. This reuse of internal structures is in kind with biological development where the same tissue undergoes change, yet exceeds biology in the extent of novelty that can be generated. Occurring in the course of the self's seeking equilibrium with the world, it responds to disturbances that destabilize equilibrium (Piaget 1936, Piaget and Inhelder 1955). The experience of disequilibrium is thus an inducement to reorganize, redo, adapt and develop structures or capacities that engender more stability in the individual's relationship with something of the world.

Disequilibrium puts an individual into activity that brings disturbances into relation with that person's present (assimilative) and potential (accommodative) capacities for response. Piaget depicted this multifaceted means of response as a process of generating possibilities – possibilities for what can be: tried, understood, undertaken, manifested, evolved…:

> Disturbances function to drive transitions…possibility…constitutes simultaneously an instrument and the motor of reequilibration (Piaget 1981, v. 1, p. 153).

The more diverse and resilient the field of generated possibilities becomes, the more resourceful, robust and profound the developmental response of restructuring can be. The clinical researches of Piaget and his collaborators demonstrated that young children's capacities for generating possibilities are bounded and successively become more open and critical as they develop. Their development transpires across identifiable "stages", where the bounds of each are constituted by the operations then available to the child for initiating possibilities for action and thought (Piaget and Inhelder 1955).

In all cases, from infancy to maturity, the assimilatory and accommodating efforts are exploratory. As the intellect goes through the restructuring processes of development, the character of that exploration encompasses abstractive projections, holding multiple possibilities under consideration at once, reversible analyses and true experimentation. From its origins in such acts as an infant's groping for mother's breast, exploration becomes wide-ranging, not just over possibilities that are immediate and tangible, but as well over possibilities that can only be imagined or constructed in the mind. Given this diverse multidimensionality in process and possibility, the course of development cannot be faithfully mapped onto a linear sequence or plot.

Piaget did not view development as limited to individuals during their childhood years; he observed similar developmental mechanisms at work in the history of science or other personal and collective creative endeavors. Any new attainment in understanding the world came to be through restructuring and extension of previous understandings in equilibrations that are tentative, partially coherent, and responsive to further input (Piaget and Garcia 1983). Unforeseen possibilities come about not by exhaustive enumeration, but through acts of "liberation" from previously held factors that had limited the explorative potential (Piaget 1981, v 1, p. 148).

Piaget interpreted these findings as having import for education (1932, 1969). Active and cooperative experiences with others will offer more room for children to make use of their own capacities for developing intellectual and moral reasoning than do the transmission programs of conventional education. Taking the pedagogical implications further, Piaget's longtime collaborator Bärbel Inhelder adapted a method of researching learning from the interviewing and experimental activities by which Piaget originally established the processes of intellectual development (Inhelder, Sinclair, Bovet 1974). Using this method, which Inhelder named "critical exploration", she and her associates observed learning to happen while child subjects engaged with tasks that were provocative for them.

Critical Exploration in the Classroom

A former student of Piaget, Eleanor Duckworth extended the clinical method from the psychological investigations of Piaget and learning research of Inhelder into a classroom practice where learning, teaching and research are inseparable (Duckworth 1986/2006, 1991/2006, 2005/2006). The activities and educational understandings fostered in the 1960s Elementary Science Study (ESS 1970, Hawkins 1967/2002) inspired Duckworth's extension of clinical and research methods into everyday school classrooms. Critical exploration in the classroom relates students and teacher with the subject matter through their own active, spontaneous, and reflective responses. Surprise, delight, frustration, laughter and confusion sound openly there, valued as being integral to the depth of emotion, action and thought that wells up when people are truly being explorers. No single voice dominates; the teacher looking out for opportunities that encourage each in being heard, says little yet sets in motion much that is unresolved and evocative.

These classrooms are noisy and sometimes voluntarily silenced to assist hearing a faint chirp; full of stuff and occasionally emptied in a rush to sight the moon or a construction in the stairwell; dispersed while people hand-work differing or similar projects and gathered in a group as they reflect together. There is space and time for the unexpected, which may supplant the teacher's initial plan – to her delight --, bringing with it a tangle of questions, things needing to be tried, fresh and oblique perspectives. The possibilities waiting to be explored stack up, composing a reserve that is not forgotten by the student-inventors or by the teacher aware of the latent educational potential and wanting to see it expressed. Anyone, student or teacher, might take up some of these possibilities, sometimes rearranging, sorting out, retuning, and igniting them in action.

Where exploration is going on, any place for landing poses the risk of caving in, tipping, floating away, or having a seemingly impenetrable surface. The teacher and the others look out to provide conditions safe for taking these kinds of intellectual and emotional risks. In sensing instability or boundaries and working with that disturbance lie means not only for probing better what is there, but also for reorganizing and rethinking our own responses. Disequilibrium is an educational opportunity to be given real working space for testing out strategies and newly emerging possibilities, and not to be preemptively rectified, dismissed or passed over. It is central in the classroom researches of students and teacher.

To enable these exploratory experiences on the part of the students, the teacher researches what students are noticing, doing and wondering about, and intervenes in ways that support their tentative awareness of uncertainty and their trials at exploring what might be going on. Just as the students' curiosity drives their engagement with the subject, so the teacher's curiosity assists in connecting provocatively and supportively with students' thoughts and undertakings. Teaching through critical exploration makes different use of the teacher's knowledge and role, from that of conventional instruction, as Duckworth describes:

> Rather than being concerned with telling his students what he knows, then, a teacher involved in critical exploration must find something else to do with his knowledge. Just as a researcher's knowledge guides her further questioning, and gives rise to the next problem she asks them to consider, so a teacher, convinced that he cannot put his own understandings into the learners' heads, uses that understanding to help the learners take their own thoughts further. His own understanding determines what he sees and hears in the students' responses, and suggests further questions to ask, further resources to offer, further stories to tell. (Duckworth 2005/2006, p. 162).

To apply our knowledge, resources, and responses as openings to possibilities and inquiry, not as answers, takes continual observing, reflecting and rethinking, both in the classroom and outside it. Notes, recordings, photos, and student work assist a teacher in looking more deeply into a classroom experience, realizing its potential and aspects under development that passed unnoticed at the time. In communicating findings from ongoing and reflective analysis, practitioners of critical exploration build up a body of classroom narratives, curricular activities, reflective writing, teaching principles and theoretical perspectives (Duckworth 1986/2001, 2005/2006; Hsueh 1997, Mayer 2009). The subject matters of critical explorations span the whole range of school curriculum, including art (Chiu 2009), history (McKinney 2004), language (Gill 2007), mapping (Quintero 2001), math (Duckworth 1987), poetry (Schneier 2001), science (Julyan 1988, Cavicchi 1999, 2008a,b, 2009; Hughes-McDonnell 2000); and in teacher education (Magau 2001; McDonnell 2009; Rauchwerk 2009; Tai 2009).

Setting

The teaching examples that I describe below come from two undergraduate courses where I have been developing critical explorations that involve students with physical phenomena and history, in a variety of science areas including: electricity, magnetism, water, sound, optics, and microscope observing. My first example describes a science class at U Mass Boston; my next are taken from a small lab seminar at MIT. Beyond what I excerpt here, each course included other activities, phenomena, assignments, historical materials, museum and library visits, and guest speakers. Each week, I developed activities in response to what students were doing, that challenged them to go further, observe by new perspectives, listen to each other. A unique story of exploration, discovery, and curriculum development arises in each course (Cavicchi 2007, 2008a, b, 2009).

The students in these classes lack experience in looking at things in the world, wondering about what goes on, and inventing an investigatory response on their own. Most science they've done before emphasized getting answers, or perhaps solving well-specified problems. These students might be curious about science history or have heard a few names, but not have engaged history as an ongoing process of learning and exploring in a past time, and again for them now. Not being told directions or having recourse to answers is a disconcerting aspect of the course for them.

Yet in doing the class activities, something occurs that is not what they expected. Seemingly simple physical phenomena show behaviors that go beyond the answers students never really had or got. A disequilibrium experienced in the context of science phenomena perhaps sets off sympathetic and interlinked disequilibrium in students' impressions and outlook about what it is to learn. The historical work alongside weaves into the enriching of students' questions and ideas for possible experiments.

Looking in Mirrors

I started the first activity by asking the class where they could stand, so as to see someone else in a small mirror on the wall (Hawkins 1985; Duckworth 1990; Cavicchi 2009). Confusion interspersed with success in sighting a classmate. “Was one success the answer?”[1] asked two who represented it this way (Figure 1, left); I encouraged more looking. One group taped walking lines to the floor, along which a pair advancing or receding could see each other. They disagreed about whether the walkers had to be at the same distance from the mirror, or not (Figure 1, right). During the next class’ discussion, someone drew on the board a line from object to viewer that bounced off the mirror, with a dotted line going through it. This diagram raised provocative questions about relationships among objects linked by the mirror. Seeing these questions as productive possibilities, I reintroduced the mirrors. The students improvised. One group held a quarter back from the mirror, and moved a dime closer, getting the dime image to overlap the quarter’s, looking the same size. On exploring reflections of print, another exclaimed “It’s making me think more than before”. They identified relevant factors: objects’ angles, mirror position, the observer’s height.

Figure 1. Left: One student’s first attempt to depict the experiment of sighting someone else in a mirror (rectangle at top) (Tsui 2005). Right: Students put tape lines on the floor, indicating where two people can stand and walk while sighting each other in a mirror taped to the wall.

Subsequent homeworks asked students to read classical texts (Smith 1999, Kheirandish 1999) and descriptions of how ancient mirrors were made (Melchoir-Bonnet 1994; Needham and Ling 1962; Pigott 1992) and to try out the classical demonstrations. The historical language was unfamiliar; some students left their homework undone. Samantha gave herself space for the dissonance of Ptolemy’s demonstration of the equal angle property of reflection using flat, concave and convex mirrors (Smith 1999). She started by writing down questions about the set-up that Ptolemy used (Figure 2, left):

> [are mirrors] placed flat on ground?
> Leave all three mirrors up simultaneously?
> Or look @ object in each one at a time?
> Simultaneously—how would you be able to see past first mirror to the other two?
> Is the ‘plaque necessary to expiriment?...
> Exactly how are the mirrors supposed to be set up?... (Pitchel 2005)

Although Samantha considered that these questions left her “unable to fully recreate the experiment”, in fact the rethinking of generating them was her opening to continue.

---

[1] All quotes without a textual reference are taken from transcripts and teaching records of the courses.

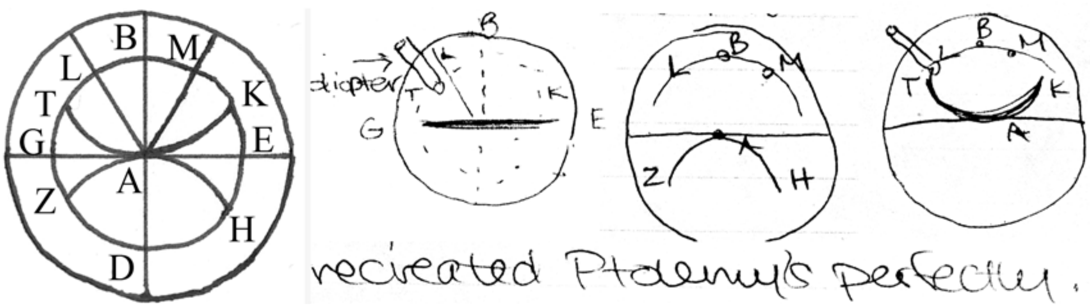

Figure 2. Left: Ptolemy's top-view diagram of a set-up to demonstrate the equal angle property of reflection through a mirror. The observer sights a marker M by looking through a movable tube LA at the flat mirror GAE, concave mirror TAK, and convex mirror ZAH. Next three circles: Samantha's diagrams of her efforts to redo Ptolemy's demonstration using a flat mirror, convex mirror, and concave mirror (last circle) (Pitchel 2005).

Taking up the mirror shapes one by one, she set the flat one erect and put a marker in front of it. Looking at the mirror through a tube, she moved the tube until the marker showed. Samantha found the relative positions of tube, marker and mirror were "exactly like Ptolemy's", both for that placement and others that she tried (Figure 2 right, first circle. She went on to see if these results were different for a curved mirror. Unable to sight the marker in a mirror sheet bent in, she wrote more questions. Flexing the mirror outward, she found it easy to sight the marker (Figure 2 right, middle circle). This confirmation of Ptolemy with the convex encouraged Samantha to redo the concave test. Now matching his findings with it too, she realized she had "recreated Ptolemy perfectly" (Figure 2 rightmost circle and caption, Pitchel 2005).

Samantha could not follow Ptolemy's text literally. By working with her sense of disequilibrium about that and revisiting it on each next failure, she recreated not only arrangements of the things, but also the analysis of relationships that underlay the demonstration. Tracing her confusion along the way to reconstructing her interpretation, Samantha's notebook entry was instructive for me as the teacher watching her develop as an experimenter, and for her as the learner. She wrote:

> "[The historical] experiments had to be tried often, and with many subtle variations, in order to gain … understanding … …In taking my notes, I was sure to record every detail, so I could go back to a certain piece and know how it was done and why. (Pitchel 2005).

Mirrors were not so simple as they seemed. One disequilibrating moment shared by the class built from a discussion about how Roman artisans (Melchoir-Bonnet 1994) conserved metal by making the smallest mirror that showed a whole face or body. Lucienne articulated why this was nonsense:

> If I used a little mirror, and set it up…and I backed away really really far, I bet that I could eventually see my whole body in that little mirror …(Pierre 2005)

Those who'd tried this at home saw their body diminish. However some detected more nuance, providing initial grounds for reexamining their assumptions. Bringing out a notebook-sized mirror, I suggested that using it in exploring a face's view. One student held it vertically, at her waist; another backed off. They found that the mirror had to be at face level. It took many iterations before someone viewed their face throughout their displacement (Figure 3, left). Then, it was one student's idea to put tape on the mirror around face. Now, the persistence in backing up evenly from the mirror gave way to surprise over what was seen, in the spontaneous exclamation

> My face…It's weird it still fits between the lines!

And response from another

> yeah it stays the same.

I asked what measurement might show. A ruler put to the viewer's head and to the taped mirror segment gave almost a ratio of ½. Sketches that I made on the board, even the standard ray diagram, did not gain students' full assent (Figure 3, right). They were amazed.

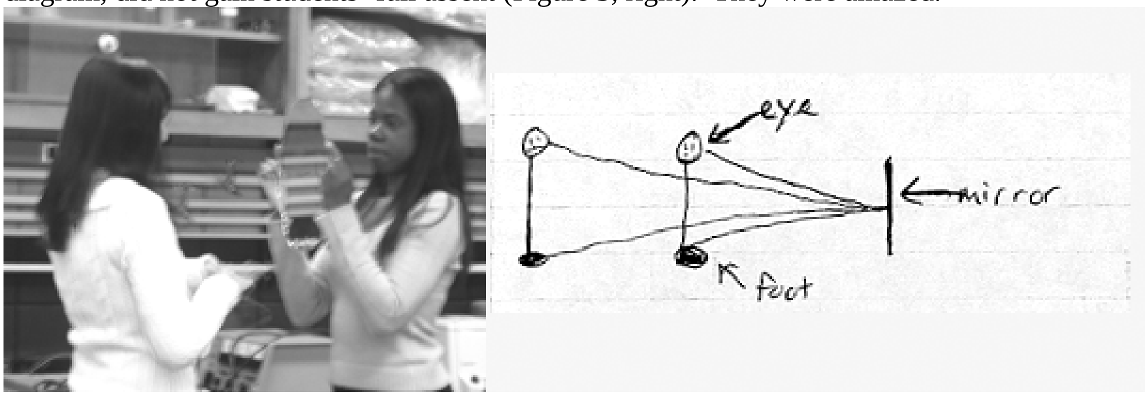

Figure 3. Left: One student holds a mirror while another backs away from it while watching the image of her face. Right: A student's diagram made during class discussion about the constant size occupied in the mirror by the image of a viewer who has moved (Tusi 2005).

The rethinking educed for them by the unexpected face and mirror observation went deeper than I supposed. One student astutely expressed the disruptive shift that was involved:

> …it 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

Looking at a mirror is not like looking through a picture window. That their own actions were the means of bringing about that disequilibrating realization was significant to the students. It put them in the place of the original investigators, as one later reflected:

> … our small, seemingly insignificant comments … in class over…a simple beam of light are important steps in the explorations of science. (Tsui 2005)

Explorations with Light Through a Hole

In my second example, two students, Julia and Cecily, explored light going through a hole and the historical camera obscura. At home, Julia tried to replicate a reading I'd assigned by Chinese philosopher Shen Kua:

> When a bird flies in the air, its shadow moves along the ground in the same direction. But if its image is collected… through a small hole in a window, then the shadow moves in the direction opposite to that of the bird. (Needham 1962, v. 4, p. 97)

Julia thought she'd seen something similar – while moving her hand past a pinhole, its shadow went opposite. In the lab, she tried to redo that. Setting this up took so much improvisation that Julia exclaimed: "oh man I thought this was going to be so easy .. now I'm not going to finish!" She kept on. Next trials gave rise to new experimental issues. Julia doubted her past findings, saying "Maybe I've been making it up all along. Now I don't know." Cecily was absent that day. The next class, when Julia tried to tell Cecily about this experiment, it was not straightforward to explain. Cecily was skeptical that Julia had really observed inversion in the shadow's motion. So Cecily proposed a game: "You would not tell me which direction [you moved the object] and I would have to guess! Which direction!" [the shadow goes]

Figure 4. Left: at the back of the students' cardboard box, light from a hole at its front projects as a bright spot. Right: The student moves a scissors upward past a hole in the front of the box, while looking at the projection of the scissors' shadow inside the box. The shadow moves downward.

Julia and Cecily began the experiment, but Julia had to leave. Now it was Cecily who made a surprising "cool" observation on her own. Between the lamp and hole, she moved a scissors, while watching its shadow on the screen (Figure 4). She said "if I am moving the scissors up, the shadow is moving down." Later, she wrote about her "bias" that the shadow would not move opposite the scissors. This bias held her back. When Cecily did the experiment, the shadow moved *not* as she'd expected. That unsettled her understanding both of the phenomena of light, and of herself as an experimenter.

The next week, I took the class to Harvard's instrument collection, to see an 18th century camera obscura by Benjamin Martin (Figure 5, left). The display, having an artist's paper under a box, suggested to Julia that it could project an image. She really wanted to see an image, but none was there. We flashed a light near the camera's hole; it showed on the paper as a circle. No motion, no form. Cecily doubted it could make an image. We visited it again on two more occasions, noticing more.

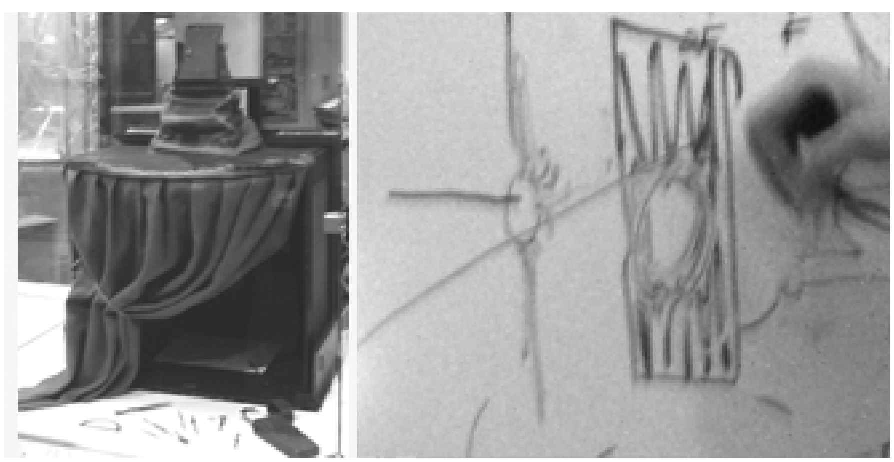

Figure 5. Left: An artist's camera obscura, made by Benjamin Martin of London and exhibited at the Harvard Collection of Historical Scientific Instruments (Camera obscura in the shape of a large book, inventory: 0010). Right: Julia's diagram where the diagonal light from left to right shows light passing through a hole (vertical line with circle in it) to a screen (rectangle with circle on it).

In lab, Cecily and Julia recreated the reversal in shadow motion that Cecily saw with the scissors. Later Julia and Cecily took time to discuss that reversal. It didn't make sense to Cecily; she'd believed you need a lens to invert. On the board, Julia diagrammed object, screen and hole, to work out what could make the inversion (Figure 5, right). Cecily's queries assisted Julia in articulating her idea: " Model: A perfect point pinhole. You have objects moving this way, shadows moving that way" She invented the idea that the hole selects, out of all the rays of light, only those that get through. The process of articulating her emergent idea brought Julia to a new unsettlement. If the hole wasn't there and light rays go in every possible direction, there should be no shadows at all! Julia took her model so seriously that she met up with its intrinsic limitation, even in the midst of expressing it.

Their next experiments involved testing Julia's ray model using color laser pointers, baby powder and the hole (Figure 6, left). They raised new questions that brought them back to wondering if it was possible to get an image by projecting light through a hole. In the rare book library, we looked at facsimilies of da Vinci's optical diagrams with holes (Leonardo 1973). In the lab, Cecily and Julia renewed their ambition to produce an image. Still skeptical, Cecily shone a bright light at her ID photo, tilted over a box's hole (Figure 6, right). Julia watched beneath the hole. Amazingly, Cecily's face showed up, vague, upsidedown and in COLOR!!!

Figure 6. Left: A red and a green laser pointer (outside the view, to the left) are aimed crosswise at a hole (vertical support in middle). Baby powder sprinkled from a bottle above reveals the light's paths beyond the hole. Right: Cecily directs a light at her ID card tipped above a hole in a box, while looking for its image on the white paper below.

Pervading the students' discussions and experiments were their expectations about optics and experimental learning. On being put to a test, the optical phenomena, the instruments, and students' ideas functioned differently from what they expected. That dissonance was unsettling. As many times as they observed the reversal of light that has passed through a hole, the behavior remained in question. New doubts and old convictions alike unsettled each finding. In the process, the students integrated emergent actions and ideas with ones they'd already used and even found inadequate. Cecily's conviction that a hole can't invert what light does and Julia's inclination to doubt her findings persisted alongside their accumulating alternatives. Insights from history such as Shen Kua's passage, Martin's eighteenth century camera obscura and Leonardo's drawings were so fecund as to sustain revisits, where students' response to history deepened in connection with their lab work.

Julia's intellectual reorganizations were encompassing. Disturbances incited her to rethink her outlook: "It is the unexpected occurrences … that perhaps have most influenced how I think about light. " (Kingsdale 2008) Yet as compelling as her next analyses seemed, she then risked being limited by her own ideas. For Cecily, it was a development to have the experience of taking her own ideas seriously enough to follow them:

… I learned how to follow through with my curiosities …. not only did I realize how complex it is to study light but I also realized how complex the possible paths we can take in the study of any curiosity we have... (Lopes 2008)

What is a Telescope?

My last example involves explorations with lenses along with resources related to Galileo and his telescope. The students determined to make a telescope. But what is a telescope? They weren't sure. Laura expressed it operationally: "It makes something far away and tiny appear larger … Think of a ship on the horizon. Take a tiny part of the ship and make it our whole field of view…" (Figure 7, left) Among the class' assorted lenses, Sara was drawn to the magnifiers. She observed: "our magnifier makes distant things smaller, and upsidedown. A magnifier raises questions. Can it be a telescope? " Laura and Sara explored magnifiers in combinations, both by shining a laser pointer's image through, and by using their lenses to view a lit sign far down the hall. Laura described the sign as "inverted, clear, and maybe a little bigger".

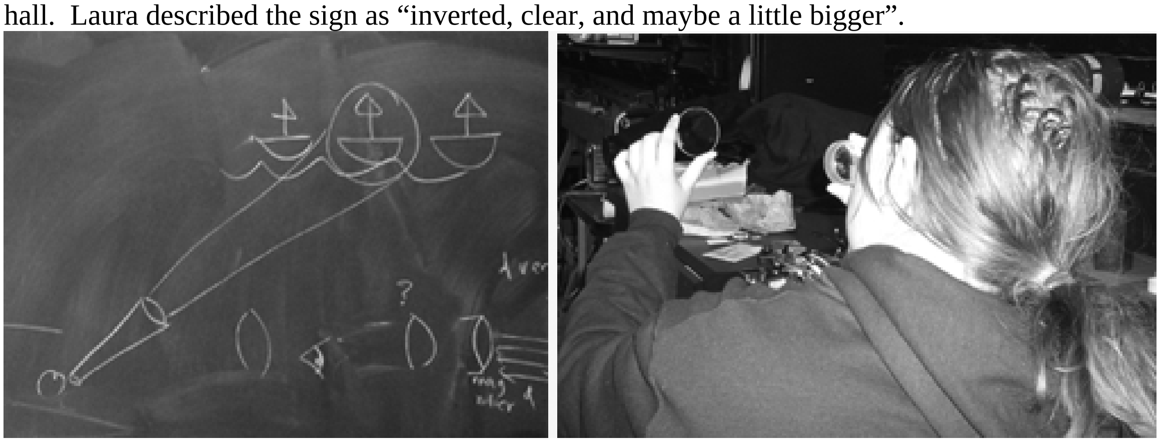

Figure 7. Left: Laura's blackboard diagram of a ship as viewed by a telescope. Right: Sara looks through two lenses held in her hands, and reads magnified print from across the room.

In later sessions, Laura and Sara investigated shapes of lenses. After reading that Galileo used a planar convex and planar concave lens, they gave up on two magnifiers and tried unsuccessfully to emulate his. In the process, the search space narrowed. Visiting historical collections and working observatories, the class viewed a variety of telescopes. That diversity did not of itself release the untapped possibilities for optical combinations in the lab. When we resumed with lenses, Sara started afresh, widening the options and again producing an inverted view. Further exploration brought her to something more striking: upright, clear magnification (Figure 7, right). Exclaiming "Wow", she used her new construction to read out fine print from across the room. For Sara, intrinsic with the unsettlement of the magnified image was a realization about her inventive process and inhibitions. She wrote:

"My determination to get the results shown by previous experimenters led me to ignore many other paths which later turned out to be successful."

Disequilibrium and Development

Light's unexpected behaviors in transiting mirrors, holes and lenses evoked surprise and wonder from my students. Yet the disequilibrium of such effects or their explanations does not in itself accomplish the internal restructuring of old thoughts and impressions with new and disturbing findings. It was through taking that disequilibrium seriously enough to respond, that they generated the conjectures and experimental tests by which their understandings of light and learning developed in yet further unexpected and destabilizing ways. In the process of adaptively dealing with the unknown through what they knew and observed, they were becoming optical experimenters like the historical investigators Ptolemy, Martin and Galileo. To do this meant recognizing and critiquing limiting assumptions, not only about light, but also about learning. They discovered the roots of learning in their own emergent curiosity.

Acknowledgments

I am happy to thank the students: Laura Boyton, Devin Bramhill, Jennimae Cronan, Julia Kingsdale, Cecily Lopes, Andrew Lix, Ana Malagon, Lucienne Pierre, Samantha Pitchel, Aaron Shaw, Anna Tsui, and Peter Tusi. For the opportunity to develop and teach these experimental courses, I thank Dick Cluster, Joyce Morrissey and Rajini Srikanth at University of Massachusetts Honors Program, and James Bales and the Edgerton Center staff at MIT. I acknowledge support of lab activities by: James Bales, Paul Foster, Markos Hankin, Edward Moriarty, Wolfgang Rueckner, William Sanford, and Yvonne Vaillencourt. Field trips were hosted by Anne Battis, Steve Beckwith, Mark Belanger, Gil Cooke, Philip Cronenwett, Deborah Douglas, Peter Houk, Elaheh Kheirandish, Joe Peidle, Martha Richardson, Wolfgang Rueckner, and Scott Sewell. Guests and speakers included Elaheh Kheirandish, Paula Labbe, Zuraya Monroy-Nasr, Edvin Østergaard, and Wenjun Zhang. I acknowledge encouragement for teaching with historical materials from: Peter Heering, Elaheh Kheirandish, Alistair Kwan, Ben Marsden, Alythea McKinney, David Pantalony, Tom Settle, and Ryan Tweney. I learned from discussing exploratory teaching with James Bales, Fiona McDonnell, Lisa Schneier, and Bonnie Tai. Eleanor Duckworth's teaching inspires my study. This work honors the memory of Philip Morrison.

REFERENCES

Cavicchi, E. (1999). Experimenting with Wires, Batteries, Bulbs and the Induction Coil: Narratives of Teaching and Learning Physics in the Electrical Investigations of Laura, David, Jamie, Myself and the Nineteenth Century Experimenters – Our Developments and Instruments, Dissertation, Harvard University, Cambridge MA.

Cavicchi, E. (2006). Faraday and Piaget: Experimenting in Relation with the World, *Perspectives on Science*, 14(1), 66-96.

Cavicchi, E. (2007). "Mirrors, swinging weights, lightbulbs…: Simple experiments and history help a class become a community", 47-63, in *Constructing Scientific Understanding through Contextual Teaching*, Peter Heering and Daniel Osewold, eds., Frank & Timme, Berlin.

Cavicchi, E. (2008a). Historical Experiments in Students' Hands: Unfragmenting Science through Action and History, *Science and Education*, **17** (7), 2008, 717-749.

Cavicchi, E. (2008 b). Opening Possibilities in Experimental Science and its History: Critical Explorations with Pendulums and Singing Tubes, *Interchange*, 39, 2008, 415-442.

Cavicchi, E. (2009). "Exploring Mirrors, Recreating Science and History, Becoming a Class Community", *New Educator*.

Cavicchi, E., Chiu, S-M., McDonnell, F. (2009). "Introductory Paper on Critical Explorations in Teaching Art, Science and Teacher Education", *New Educator*.

Chiu, S-M. (2009). "The Ancient Master Painted Like me", *New Educator*.

Duckworth, E. (1973/2006) The Having of Wonderful Ideas in *"The Having of Wonderful Ideas" and other essays on Teaching and Learning*, NY: Teacher's College Press, 1986/2006.

Duckworth, E. (1979/2006). Learning with Breadth and Depth in *"The Having of Wonderful Ideas" and other essays on Teaching and Learning*, NY: Teacher's College Press, 1986/2006.

Duckworth, E. (1986/2001) Inventing Density, in *"Tell Me More": Listening to Learners Explain*, NY: Teacher's College Press, 2001.

Duckworth, E. (1986/2006). Teaching as Research, in *"The Having of Wonderful Ideas" and other essays on Teaching and Learning*, NY: Teacher's College Press, 1986/ 2006.

Duckworth, E.R. (1987). Some depths and perplexities of elementary arithmetic. *Journal of Mathematical Behavior*, 6, 43–94.

Duckworth, E. (1990). Opening the World, in *Science Education: A Minds-On Approach for the Elementary Years*, E. Duckworth, J. Easley, D. Hawkins, A. Hentriques, eds., Hillsdale NJ: Lawrence Erlbaum Ass.
Duckworth, E. (1991/2006). Twenty-Four, Forty-Two and I Love You: Keeping it Complex, in *"The Having of Wonderful Ideas" and other essays on Teaching and Learning,* NY: Teacher's College Press, 1986/2006.
Duckworth, E. (2001). Teaching/Learning Research, in *"Tell Me More": Listening to Learners Explain,* NY: Teacher's College Press, 2001.
Duckworth, E. (2005/2006). Critical Exploration in the Classroom, in *"The Having of Wonderful Ideas" and other essays on Teaching and Learning,* NY: Teacher's College Press, 1986/2006.
E.S.S. (1970). *The ESS Reader*, Educational Development Center, Newton, MA.
Gill, K. B. (2007). Toward authentic communication: analyzing discourse in adult ESOL instruction in an art museum, Dissertation, Harvard University.
Hawkins, D. (1967/2002). *The Informed Vision: Essays on Learning and Human Nature*, Algora NY.
Hawkins, D. 1985, "Critical Barriers to Science Learning", *Critical barriers phenomenon in elementary science* , eds. Maja Apelman, David Hawkins, Philip Morrison., North Dakota Study Group on Evaluation, Center for Teaching and Learning, Grand Forks, N.D.
Hughes-McDonnell, F. J. (2000). 'Circuits and Pathways of Understanding: "I can't believe we're actually figuring out some of this stuff"', Dissertation, Harvard University, Cambridge MA.
Hsueh, Y. (1997). *Jean Piaget, spontaneous development and constructivist teaching.* Dissertation, Harvard University.
Inhelder, B., Sinclair H., and Bovet, M. (1974). *Learning and the Development of Cognition.* Cambridge, MA: Harvard University Press.
Julyan, C. L. (1988). Understanding trees: five case studies. Dissertation, Harvard University.
Kheirandish, E. (1999). *The Arabic Version of Euclid's Optics, Edited and Translated with Historical Introduction and Commentary*, 2 volumes, NY: Springer-Verlag: Sources in the History of Mathematics and Physical Sciences, ed. G.J. Toomer, no. 16.
Leonardo da Vinci (1973-1975). *Il codice atlantico. Edizione in facsimile dopo il restauro dell'originale conservato nella Biblioteca ambrosiana di Milano*. Florence: Giunti-Barbèra.
Magau, N. (2001). Looking at Learning to Understand Teaching: A South African Study, in *"Tell Me More": Listening to Learners Explain*, NY: Teacher's College Press.
Mayer, S. J. (2009). "From Clinical Method to Critical Exploration: A Methodological Genealogy", paper at Jean Piaget Society, Park City, Utah, June 6, 2009.
McDonnell, F. (2009). "*I wonder how this little seed can have so much potential*": Critical Exploration Develops Pre-service Teachers' Potential as Researchers and Teachers of Science, *New Educator*.
McKinney, A. W. (2004). Shaping history: Five students, three artifacts, and the material, social and economic lives of late nineteenth-century butter-makers, Dissertation, Harvard University, Cambridge MA.
Melchior-Bonnet, S. (1994). *The Mirror: A History*, K H Jewett, trans., NY: Routledge.
Needham, J., and Ling, W. (1962), *Science and Civilization in China,* v 4, Cambridge UK: Cambridge University Press.
Piaget, J. (1932) 1965. *The Moral Judgment of the Child*. London: Routledge & Kegan Paul Ltd.
Piaget, J. (1936), *Origins of intelligence in the child,* M. Cook, Trans., NY: International Universities Press, Inc., 1952.
Piaget, J. (1937) 1964. *The Construction of Reality in the Child.* New York NY: Basic Books.
Piaget, J. (1941) 1965. *The Child's Conception of Number*. New York NY: W. W. Norton & Co.
Piaget, J. (1946) 1970. *The Child's Conception of Time*. New York NY: Basic Books.
Piaget, J. and Inhelder, B. (1948) 1967. *The Child's Conception of Space*. New York NY: Norton.
Piaget, J. and Inhelder, B. (1955), *Growth of logical thinking,* A. Parsons and S., Milgram, Trans., NY: Basic Books, 1958.
Piaget, Jean (1969) 1972. *Science of Education and the Psychology of the Child*. New York NY: Viking.
Piaget, J. (1981), *Possibility and necessity,* 2 Vols, Minneapolis: University of Minnesota Press, 1987.
Piaget, J. and Garcia, R. (1983), *Psychogenesis and the history of science,* New York: Columbia University Press, 1989.
Pierre, L. (2005). Assignments and notebook for Honors 290F, University of Massachusetts Boston.
Pigott, V. (1992). Ancient Metal-Mirror Making in South India: Analyzing a Mysterious Alloy, *Journal of Metallurgy (JOM)*, 38-40.

Pitchel, S. (2005). Assignments and notebook for Honors 290F, University of Massachusetts Boston.
Quintero, I. M. (2001), "Children Map Their Neighborhoods", In *"Tell Me More": Listening to Learners Explain*, NY: Teacher's College Press.
Rauchwerk, S. (2009). "Critical Exploration with Typical and Atypical Learners", paper at Jean Piaget Society, Park City, Utah, June 6, 2009.
Smith, A. M. (1999). *Ptolemy and the Foundations of Ancient Mathematical Optics: A Source Based Guided Study*, Philadelphia PA: American Philosophical Society.
Schneier, L. (2001). Apprehending Poetry, in *"Tell Me More": Listening to Learners Explain*, NY: Teacher's College Press.
Tai, B. (2009). **"**Developing Teachers Learning to Embrace the Atypical", paper at Jean Piaget Society, Park City, Utah, June 6, 2009.
Tsui, A. (2005). Assignments and notebook for Honors 290F, University of Massachusetts Boston.