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Citation: Cavicchi, Elizabeth. "Learning Science as Explorers: Historical Resonances, Inventive Instruments, Evolving Community." *Interchange* 45.3-4 (2014): 185-204.

As Published: <http://dx.doi.org/10.1007/s10780-015-9235-9>

Publisher: Springer Netherlands

Persistent URL: <http://hdl.handle.net/1721.1/103620>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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Learning Science as Explorers: Historical Resonances, Inventive Instruments, Evolving Community

ELIZABETH CAVICCHI

Massachusetts Institute of Technology, Cambridge, MA UNITED STATES

1. Introduction

Historical explorers set out into the unknown not knowing what they would find, took risks, wandered, discovered, had mishaps, and came back changed by their experiences. As dramatic and far-afield as their stories may seem, every life partakes in the unknown. We all share in, and can learn from, experiences of the explorers, their hazards and discoveries. While instruction is often framed in antithesis—that of leading students by established routes to well-known outcomes—actual processes of learning are as complex and divergent as are the ways of past explorers. This study draws on that commonality, by framing the science classroom as a safe space for engaging the unknown, where explorers of the past are colleagues whose steps and missteps often echo or serve as examples and inspiration for the steps and missteps of learners.

1.1 Critical Exploration in the Classroom

Creating a space that entwines the unknown with learning is an exploratory work of teacher and learners together. A beginning for that kind of exploration arose in the Elementary Science Study (ESS 1970) curriculum project of the 1960s. In children's hands, science materials came to such diverse uses as the swinging of single or multiple weights hung by strings differing in lengths or linkages. The teachers and curriculum developers observed how the children's curiosity moved them to wonder, investigate and question; the children were explorers in the world of science. One of these curriculum developers, Eleanor Duckworth, applied her training in the clinical interviewing method of Jean Piaget (1926/1960) and Bärbel Inhelder (1974) in interacting with the children. While engaging them with pendulums and other materials, she observed, asked neutral, non-leading questions, and wanted to know how they were expressing and understanding the materials and experiments. She discovered that her expression of curiosity regarding the children facilitated their own curiosity, activity and learning. In subsequent work, Duckworth (1987/2006a, 1991/2006b, 2005/2006c) developed these findings into the research pedagogy of "critical exploration in the classroom". Now expanded to all subject areas and in teacher education, critical exploration is practiced around the world, with the support of a website (Critical Explorers 2010).

The narratives in this paper express critical exploration in the context of a seminar course that I have developed and taught for nine years at MIT's Edgerton Center, titled "Recreate Historical Experiments: Inform the Future with the Past". The winter 2010 version, having a theme of Galileo, is published online as a website under MIT's Open Courseware Program (2002-2010) under Special Programs course number SP.713. That website includes assignments,

reading citations, activities, student work, photos from class sessions, and website links. Other past themes include: historical experiments (Cavicchi 2008a); periodic motions and sound (Cavicchi 2008b, 2011b, 2012); mirrors (Cavicchi 2007, 2009, 2011b); magnets; camera obscura; shadows (Cavicchi in press); time (Cavicchi 2011a); and space. Seminar activities extend from the lab to the outdoors, museums, rare book library, and beyond. Participants include MIT undergraduate and graduate students, and teachers engaged in graduate studies at Harvard. These teachers bring to the seminar their passion for learning and teaching with critical exploration in the classroom, the pedagogical method which underlies this seminar's explorations.

Teaching through critical exploration involves careful observation of the students and their relationships with each other and materials (Hawkins 1967/2002). I watch for tentative curiosity. I look for whatever stimulus—materials, questions, or silence—might sustain that incipient curiosity for just a moment further—and then for another moment, and another. I seek to encourage students to develop curiosity wherever it may go.

Another part of teaching through critical explorations is to provide an open and enticing environment that encourages curiosity to develop (Hawkins 1965/2002; Duckworth 1986/2001). At the beginning of each classroom session, I lay out plenty of enticing 'things' and tools within easy reach on our working tables: string, duct tape, balls, drawing compasses, tripods, lenses, cardboard, scissors, mirrors, clay, along with piles of historical books and picture books that grow across the course. Although I have ideas about how these items might support the students' curiosity and imminent explorations, I initially refrain from voicing them. Instead, I encourage students to pick up materials, huddle together some contraption, improvising with materials, instrumentation and ideas that will set them going as explorers. It is in constructing their own assortment of gear that they come to face the limits of their assumptions and envision unanticipated possibilities.

Recurringly across my teaching of this seminar, that potential comes to be realized in, and by means of, students' personal and collective experiences. These explorations, instigated by participants, impact them with a profundity relevant to their own vulnerabilities and capacities. Always, I am surprised by the specifics of students' inventiveness with materials, instruments and understanding. The recurrence of my surprise, in ever-new examples of their classroom studies, continually deepens my trust in the process of explorative learning that engages us all. So, the students' access to inventive work with instruments - where what constitutes an instrument can be very broadly interpreted—is foundational to the learning and community that develops.

As the substance of an engagement with materials begins, other voices come in. Most immediate, are voices of classmates that expand, swell, and diversify a tentative start. Classmates pose counter-prospects, alternative perspectives, and deep confusions. As their interactions generate new observations and puzzlements, classmates deepen in their relationships as co-explorers together. Often, I invite other voices near-at-hand, such as instructors, technicians, educators and curators. I introduce voices from the past, with readings and museum visits. Those historical voices lift off the page: their words, work and ideas are included in class debate, experimentation, and

wonderment. Students actively consult historical writings and speak aloud from the texts.

Students, teacher, and historical investigators are all explorers (Cavicchi et al. 2009). For explorers, pitfalls, disorientations and confusions go on alongside discoveries and wonderments of all kinds. The experiences and vulnerabilities shared among participants in my classroom modulate our sensitivity to hear a doubt, to re-examine what we've done, and to propose alternatives. All contribute in providing the respect, trust and safety that sustains such interactions. Students' process in building that grounding is just as interlaced with partial communications—while also hosting emergent possibilities—as is their process of building understandings of science and history. The relational processes that negotiate trust are inseparable from the intellectual processes that initiate experimenting. In that concurrence, we experience teaching and learning as the evolving of community that embraces those in the past and is woven throughout the exploratory journeys of all.

By describing what happens across these explorations as historical resonance, I observe and portray a relation between classroom experiences and the historical materials we encounter together. As students deepen in their curiosity for natural behaviors and historical observations of these behaviors, they initiate responses in relation to the historical explorations. This relation might emerge intuitively, hardly evident, and yet come to so pervade the classroom environment that it is shared, felt and actively sustained by all. That confluence between learners of today and the past, in their seeking, uncertainty and struggle, initiates and cements the relation.

Across my efforts as a teacher to imagine, observe and further extend what could and does happen as students engage with materials and each other, I look to evolve a space of safety for exploring among all participants. That space is formed through qualities which are subtle and difficult to accurately describe, such as mutual respect, openness and sensitivity. To hold open the potential for that space – especially during passages where I and others fail in hearing and respecting what might be emerging, or where we act so as to close off an opportunity for curiosity – requires the teacher to seek a delicate, often faltering, balance. For bewilderment, hardly-articulate ideas, self-critical realizations, collaborative constructions with stuff on hand – and extended silences – to surge and ebb with spontaneity among students, a teacher must maintain a presence in ways that are unlike the roles that teachers and students are inured to expect. Yet in the fluidity of students' engagement, with its flows, dips and crests, students learn how to share and create knowledge in ways that are absent from typical science curricula.

1.2 Historical Materials in Science Teaching

In integrating science history with science learning, my students and I participate in an educational community whose work spans the rift that ordinarily distances science instruction from its past and cultural contexts. As they rediscover the science through its circumstances, these educators and students find the science of their studies being expressed through people's lives and works; convoluted paths of experiment, invention and analysis, and the instruments and materials that were in use.

Through science history re-expressed as stories, science learners encounter science through its human expressions in settings ranging from classical science (Piliouris et al 2011; Aduriz-Bravo 2011) to Newton's prism (McMillan 2007). Arguing that a story engages science learners in making meaning while interpreting it, and in integrating that meaning into their longterm memory (Klassen 2010), Klassen and colleagues craft stories that infuse the science with enduring human qualities. Their recent study compared a control group that did lessons on electricity with an experiment group that also discussed their story about Nicolai Tesla, and were shown to outperform the others on science tests (Hadzigeorgiou et al. 2012). Experimental group students listened enthusiastically; journals they kept up to a month after discussing the story reveal wonderment about electricity and "romantic" understandings of Tesla and his heroism. Tesla's combative resistance to authority emboldened one student toward applying it in personal life:

Tesla...went against everything. His father, his teachers, and the American system. ...you need guts [to do that]. It is not easy. Many times I want to disagree with my father and my teacher but in the end I agree with them. (Hadzigeorgiou et al. 2012, p. 1136)

This student's affinity with Tesla through resistance resonates across history and in classrooms including mine, where new ideas struggle unsupported (Harouni 2011b).

In redoing experiments of historical science with replicated instruments and materials, students of Peter Heering (2000, 2007) face unknowns in how they understand science phenomena and in the practices and thinking of history. Classroom activities – adapted from the public demonstrations of electricity performed by eighteenth-century traveling lecturers – provoke particularly responsive participation on students' parts (Heering 2007). Whatever they try meets with immediate feedback from the shocks and sparks of electrical discharges, motivating students to devise new experimental tests. Finding themselves confounded by what electricity does, students discuss it with others in their group and instructors. In the process, their interpretations of electricity become more robust and explanatory than what they retained from previous, formal instruction. Emphasizing the educational value of investigation and critical thinking, Chang (2011) advocates posing historical experiments to students where outcomes remain unresolved, contested or anomalous, where there are no established explanations.

That investigative quality of dealing in the unknown also emerges as students interact with historical instruments of science through artifacts, replications and other resources. During a workshop at the Canada Science and Technology Museum, educators examined a seemingly inscrutable apparatus, deduced its functions and chronicled its travels from Hungary to Canada (Anderson et al. 2011). Informed by this experience, they undertook to puzzle their own students with actual mystery objects, encouraging drawing as one means of attending to details, dissecting the parts and following how parts interrelate. Drawing as a process of calculation proved new, and productive in exposing inadequacies in interpretations of spatial relations, for students who "critically replicated" early modern astrolabes in Alistair Kwan's (2008) undergraduate course. Through following their

curiosity about the astrolabe's technical aspects and trying it in open-ended activities, students struggled with, and came to understand, the observational acts that underlie both cultural and abstract depictions of the night sky.

2. Explorations with Euclidean Geometry

As an opening to exploring spatial relationships, a theme in my teaching, I convened my seminar in a space so newly erected that no one had been there before: MIT's 2010 Porter Management building. Into its polished floors with oddly canted steps and surfaces, everyone dispersed with the assignment to observe. After filling their journals, observers paired up. Amanda, a graduate student in education, and Nolan, a senior in chemistry, sat together. Sensing themselves poised on a brink of time to come – and long since passed—they portrayed a gulf in intervening times.

Amanda asked: In 50 years, what will people see out this window?

Nolan: There'd be more bicycles, more grass.

Amanda: What it was like 50 years ago here?

In contrast with these feelings where our present is disparate from historical time, relationships of more immediacy with the past would eventually emerge. I assigned a reading of the first five propositions in the *Elements* of the classical Greek geometer Euclid – without the proofs! – from the *Bones* edition of St. John's College (Euclid 2002). I sent everyone home with a straight edge and a drawing compass – along with encouragement to play!

Starting by redrawing Euclid's diagrams, Nolan worked out the first proposition's symmetry (Figure 1, left).¹ Nolan's sense of realization shows in how he recorded it: "Wow! I just chose an arbitrary length AB and the resulting intersection... equilateral triangle". Nolan extended his construction into a "complex pattern" (Figure 1, right). In class, his drawings drew awe. Euclid's diagram originally seemed static; by acting upon it, he discerned its *operative* power to construct new, repeating forms. Nolan had become an explorer in the space of his notebook page, using means that the ancient source had incited him to discover by acts of his own mind.

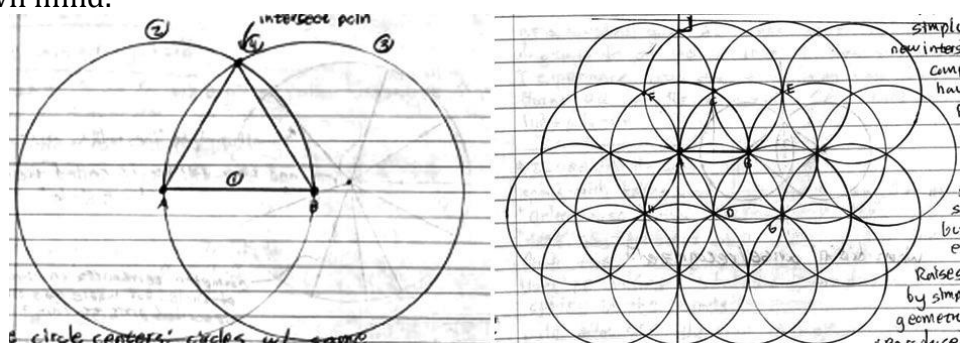


Figure 1. Left: Nolan's construction of an equilateral triangle. Right: Nolan's "Complex pattern" construction, inspired by Euclid (McCarthy 2011a).

¹"On a given finite straight line, to construct an equilateral triangle." (Euclid 2002, p. 4).

Babak, a doctoral student in education, also shared his diagram. It depicted a line whose division was indicated by the crossing of arcs made by a compass whose point was set at each endpoint (Figure 2, left). The line's division looked equal, but was it? How could we know? As the diagram came to be redrawn large on the board (Figure 2, middle), it became a quandary adopted by the class as a whole. The adventure of it occupied the rest of that period, and weeks beyond. As the teacher, I welcomed the investigation, although it was unclear what might become of it. The question—how to bisect a line – appears as the 10th Euclidean proposition – yet the reading I had assigned only went to proposition 5! Resonating with historical geometry, Babak's notebook thrust us further into its structure! My assigned reading included no proofs, and yet the class experiences yielded a proof that all could check, revise and re-examine!

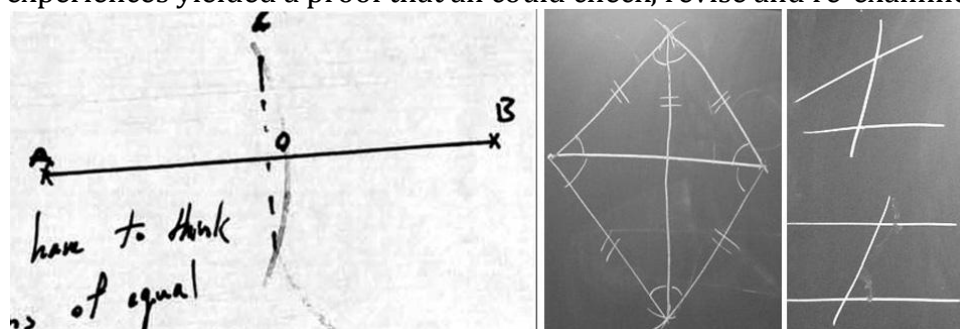


Figure 2. Left: Babak's notebook drawing bisects a line using compass arcs originating at either end of the line (Harouni 2011a). Middle: blackboard diagram working out the line's bisection by means of triangles. Right: how a line intersects two lines that are converging [top] and parallel [bottom].

Some gathered at the board; others apart. Mac, a masters' student in engineering education, convened one conversation by saying: "I am still confused: We separate [angles] into degrees... How do I [as Euclid] measure that?" Yang supposed Euclid didn't have "degrees"; Babak asserted there was a different degree. Zengxu, an engineer, observed "they don't care about numbers"; Yang offered: "they can compare whether something is the same or not."

In voicing confusion, Mac brought us to a crucial threshold: that of realizing a way that our reliance on numerical values diverges from classical work. Thinking by comparison, *by relation*, was unfamiliar to us. The class took up that challenge, but actually implementing it placed them on uncertain ground. On engaging with the diagram's *triangles*, Zengxu noted that Euclid did not provide a crucial property: "We have to prove the interior angles of the triangle are 180 degrees, two right angles. I think we can use the postulate about parallel lines." (Figure 2, right) Mac was doubtful "I am not sure you can prove it", as was Amanda who did not see how parallel lines could be any help. Intense debate ensued. Mac again revealed how numbers present a barrier. He said: "the idea of having a sum of two angles, is an idea that you have to have numbers [for]." Babak countered "I don't think so" and Amanda observed that Euclid "uses right angles like a quantifying measure?"

Rereading Euclid yet again, passages were noticed, read aloud, restated and adapted into the lengthening chalkboard argument. For example, Babak announced "I bring to your attention! Euclid says 'things

which are equal to the same thing are equal to one another.” (Euclid 2002, p. 4) Now, with a means of transitivity along with Amanda’s observation that the right angle works like a measure and with Zengxu’s diagrammed equivalences, they gained means for drawing the kinds of comparisons that Yang proposed earlier. Mac came to see geometry as a means of computation *without* numbers, in saying “so there is the notion of addition and subtraction and remainders.” Babak cheered “YEE HA!” Zengxu produced the finding that the divisor line in their diagram makes a right angle with the line it divides (Figure 3). Mac celebrated it: “BAM!” Skeptical, Yang worked it out anew. [Interestingly, Euclid’s proofs, which I provided to them later, proceed in the opposite sense by demonstrating equality first, then perpendicularity.]

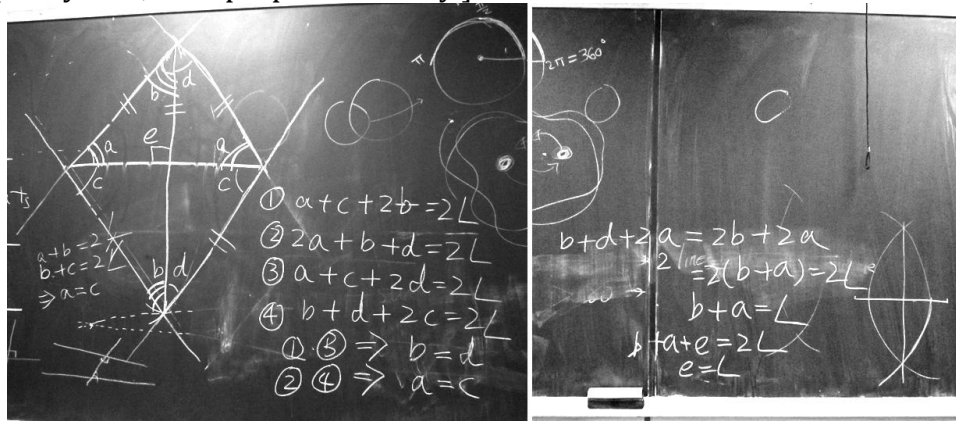


Figure 3. The class proof establishing the line’s bisection. The letters a, b, c, \dots indicate the angles noted on the diagram on the left. The symbol $2L$ represents 2 right angles; L represents one right angle.

During this development, Mac became further invested through realizing that the divisor line’s perpendicularity signifies equality in the divided segments. Yet Yang and Babak protested, saying

Yang: Wait, how do you know that?

Babak: We haven’t got there yet

Such peer challenges threaded so fluently across our discussions as to merit a label:

Who are the Euclidean Police, those fearsome enforcers of what makes sense? They are us. If someone claimed something and it wasn’t obvious ... other classmates would immediately question” [McCarthy 2011b]

In acting as Euclidean Police, classmates ensured the authenticity and accessibility of each other’s work. They were faithful both to Euclid and themselves as learners, building understandings that robustly derived from what they knew or worked out.

This exploration spawned the class project of creating a playful educational video on Euclidean geometry for a middle-school audience. That video is now online on MIT Video (2011) website: *Playball: The House that Euclid Built*. For the video, the class brought Euclid to life – as Babak in costume and with a facsimile 19th century edition of Euclid! (Byrne 1847/2010) Euclid demonstrated--without numbers--the geometrical construction of a baseball diamond having true right-angle corners, that saves the day for a beleaguered ball team (Figure 4, left). The finding of the video’s fictional students, that instruments—a protractor and a GPS—fail to produce a true square at the scale of a ballfield, parallels the

actual students' realization that their dependence on numbers impedes geometrical understanding.

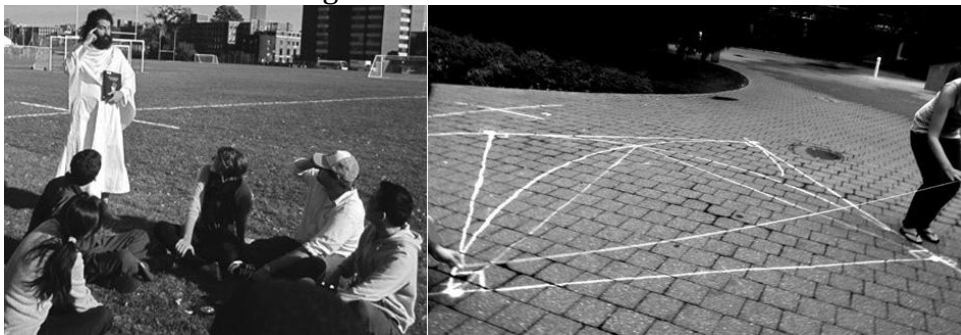


Figure 4. Left: A scene from the class' Playball video, where Euclid shows how to make a baseball diamond. Right: The large constructed square does not **look** square.

While the group effort to bisect a line involved geometry at the board, our next activities engaged complexities of *physical* space. The class collaborated to apply Euclidean methods on a plaza, using sidewalk chalk and rope. Their first undertaking, suggested by my activity sheet and elaborated by a subset of the class, was to produce a very large square. When that square was completed, it didn't look square at all! (Figure 4, right) Dismayed and intrigued, the students checked whether their square's corner obeyed a 3-4-5 ratio (Figure 5, left). It did.



Figure 5. Left: Does the square's corner make a right angle? Students check whether the sides of a triangle formed from it obey the 3-4-5 ratio. Right: the observer of the outdoor square [left of photo] uses a tube to view it.

Babak later depicted his part in the outdoor making of a square as one of resistance: "I did not want to do it. It seemed there would be no surprises in it for me." [Harouni 2011b] Yet something did surprise him. As Babak voiced what provoked his mind, Mac listened intently:

Babak: Let's say we draw something on the ground that looks like a square if you look at it from a certain spot. It won't be a real square, right?

Mac: Go on.

Babak: But what *will* it be?

Mac: Are you talking about reversing perspective?

Babak: Whoa! Is that what I'm saying? Yes! That's what I'm saying. [Harouni 2012]



Figure 6. Left: A cardboard square is mounted on a pole. Right: An observer, viewing the square against the pavement, directs others about where to place strings so as to line up with the square's edges. Photos by Paula Labbe.

The class exploded with curiosity to make a square that *looked* square. Across several sessions, the students improvised instrumental assists. Viewer location mattered. Marking it, students took turns occupying it, and even provided their viewer with a viewing tube (Figure 5, right). While the viewer directed, others placed string and poles so as to produce the *appearance* of a square. Even so, the viewer was found to consent to configurations that the “Euclidean Police” showed were not square!!



Figure 7. Left: the resulting figure is elongated. Right: for an observer at ground level, the string figure appears square. Photos by Paula Labbe.

In response to this discovery—that an observer could be fooled to suppose that the constructed figure's sides were parallel and of equal length, when another viewer found that not to be so—the students devised a view-guide. This view-guide was a cardboard square mounted on a vertical pole intervening between viewer and the construction (Figure 6, left). It was held upright between the viewer and the area on the ground where classmates again tried to construct a square, under the guidance of the viewer (Figure 6, right). The ground crew tried

to align string and chalk with the cardboard squares' edges, as seen by the viewer. The resulting figure was elongated (Figure 7, left) as seen from anywhere other than ground level! (Figure 7, right).

Into these experiences, I assigned readings such as Ames' Distorted Room [Ittleson, 1952]. When I projected my photos from the San Francisco Exploratorium's (1995) Ames Room, the class expressed awe: "Wow!" Babak exclaimed "To build something like this, required them to do the explorations we are doing!" The students observed historical collaborators to be engaged in a curiosity that they too had constructed and discussed.

3. Explorations invent Bodily 'Orreries' to uncover the Heavens' dance

These perspective explorations connected us to the endlessly multiple perspectives on spatial relationships that Aristarchus (1981), Copernicus (1543/2002), Galileo (1632/1967) and others had worked out for Earth, Sun and heavens. Along the way, students observed the sky and used historical instruments including the quadrant and astrolabe. My next example excerpts from class activities where orreries – instruments for depicting relative positions and motions of heavenly bodies—came to be invented in bodily dance as students researched their ideas and observations of the night sky.

A reading from Archimedes (2002) on Aristarchus evoked confusion, careful re-readings and exploratory constructions, at once demanding and stretching our Euclidean experience. What did these ancients mean by the circle of the zodiac? Babak pondered further "What did Archimedes mean by describing the sun as $1/720$ part of the zodiac?" Yang interpreted that ratio geometrically: "I think it is the size of the sun! You are standing on the earth; the sun forms an angle (Figure 8, left). Nolan –who had already ruined his binoculars by projecting sunspots-- considered the instrumental portent of Yang's proposal "How do they measure that?; without blinding themselves?" Amanda so immersed herself in the ancient outlook as to express a realization that unseats our present thinking, analogous to the impact of the class' prior realizations that Euclid didn't need numbers. She exclaimed: "They didn't think the earth was moving at all!" Her tentative hold on this idea shows in her next question: "Did they even think it was rotating? The earth?"

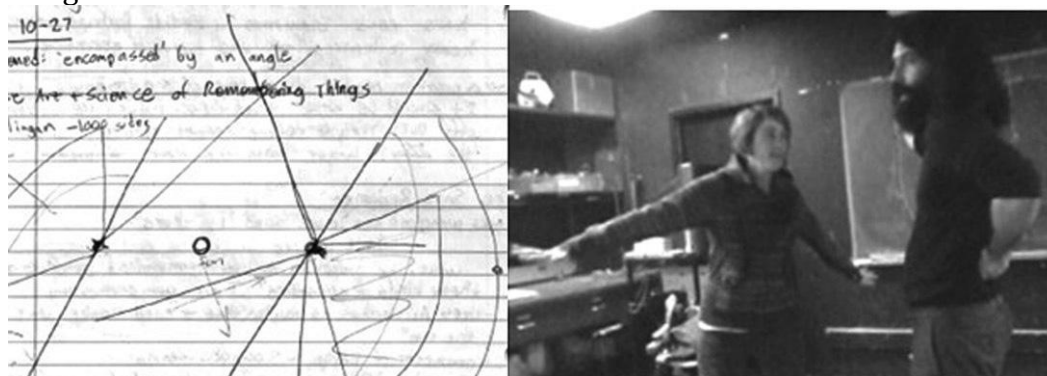


Figure 8. Left: Diagram made to understand how the sun occupies an angle of the zodiac. Right: Amanda dances as the sun around Babak as a stationary Earth.

Quickly words, text and diagrams became inadequate to the task. Already up from their seats, students began creating and exploring a geocentric universe in the classroom! They had to actually be in space, moving through it with their bodies, seeing with their eyes. Babak posed as Earth – yet, trying to work out

how it could be that what he sees is always different, he moved! Into my expressed confusion about that, Amanda proposed that Babak be a standing-still Earth; she danced around him as the Sun, arms stretched out like sunbeams (Figure 8, right). When Babak remained perturbed about how the whole sky's motion, Amanda invited Yang to be all the Stars and to stroll about him at a slightly different pace from hers. Taking a turn as Earth-observer, Yang formed a role for Nolan as the moon– only to be astounded by complexities of rendering its motions.

Like the heavenly bodies they reenacted, their universe model arose through each student's integral and diverse participation. Yang exclaimed: "To understand what we are doing, I have to understand every word that everyone is saying. Fascinating!" That co-creation equally enthralled the others, melding them as an investigative body that often functioned beyond the need for words while retaining and drawing on the unique perspective and understanding of each. Gathered about a ball, which in the context of Aristarchus and their own wonderings became Earth, they pondered how daily light and dark play out on a sphere (Figure 9, left). Since overhead lights left the ball's light and dark boundaries ambiguous, someone switched those off and produced a spotlight sun.



Figure 9. *Left: students consider the half-lit ball in Babak's hand as an analogue to the Moon. Right: a white hemisphere with markers at Boston and North Pole.*

New investigations percolated. A half-sphere, basketball-sized, became Earth (Figure 9, right). Amanda pioneered a technique of aligning one's eye tangent with it to simulate an Earth observer's view. The small ball figured as the moon, whose illuminations at various relative positions were sighted from the Earth (Figure 10, left) at its differing orientations of day, night and the seasons. The observer sought to identify moonrise and correlate it with the Earth's illumination. Extending this work, Amanda later devised a testable interpretation linking the moon's changing appearance with its height across the year.

All of this exploration went on through a grace of bodily motion. Together the class accomplished an understanding of a whole in which nothing could be left out, from the Euclidean ball-field, to perspective square discoveries, to the celestial dance. In speaking about this experience later at a physics teachers' conference, Amanda affirmed: "everything we had done led up to our [understanding]".



Figure 10. Left: Amanda lines her head with the white half-sphere Earth and views the crescent lighting of the Moon, the small ball held in Yang's hand to the right. The sun [spotlight] is off to the right, out of the photograph. Right: At the blackboard, Amanda diagrams a hot air balloon and other modern analogues to Galileo's ship.

4. Multiple Perspectives Emerge in Recreating Galileo's Motions

In the next term, exploration came to foster community with new and continuing seminar participants, each bringing their own curiosities, confusion and inventiveness. Our theme of Galileo wove across such varied activities as observing the night sky with eyes and telescopes or experimenting with balance recreations of Galileo's hydrostatic Little Balance (1586). A passage in Galileo's *Dialogue* (1632/1967) about the path of a cannon-ball dropped from a moving ship's mast set off an investigation by which the students—to their own astonishment—made evident two concurrent perspectives on the ball's motion. The exquisite physics education photos made by Berenice Abbott in 1960s, which we had viewed in the MIT Museum (2008), evoked a historical resonance crucial to this undertaking.

Speaking for Galileo, Salviati posed a question to interlocutors Simplicio (holding the Aristotelean outlook), Sagredo (curious and open-minded) – and to our class:

SALVATI: Now tell me: If the stone dropped from the top of the mast when the ship was sailing rapidly fell in exactly the same place on the ship to which it fell when the ship was standing still, what use could you make of this falling with regard to determining whether the vessel stood still or moved?

SIMPLICIO: Absolutely none...

SALVATI: Very good. Now, have you ever made this experiment of the ship?

SIMPLICIO: I have never made it, but I certainly believe that the authorities who adduced it had carefully observed it... there is no room for doubt. (Galilei, 1632/1967, p. 144)



Figure 11. *Left: Yang sits on a moving cart and drops a ball. Right: the class attaches a yardstick to the cart to provide a vertical reference for the falling ball.*

In debating the passage, students sought out analogues to the ship: subway, airplane, hot air balloon or car (Figure 10, right). Real uncertainty arose about what the released object would do. Yang sought to demonstrate by running and tossing a ball upright, but others, acting as Euclidean Police of this next seminar, did not accept her analogy. They suspected that she, as a human catcher, might be contriving to retrieve the ball. Determining that the ball had to be dropped, Yang's classmates pushed her on a cart and watched for the ball's fall after she released it (Figure 11, left).



Figure 12. *Left: releasing a ball from the moving cart while filming it. Right: students examine Abbott's photo.*

As ambiguities continued to manifest, the group revised their instrumentation, sturdily affixing a yardstick to the cart, then designing a place above it for the ball's consistent release (Figure 11, right). Uncertain about what they saw, they used a cellphone to record the ball's fall. That video's coarse framing omitted too much. Seeking to follow the motion more closely, the class asked to use a high-speed camera. In adapting their experiment for the view of the high speed camera, the students further refined it. One classmate pushed the cart, another walked beside it to release the ball, while others observed and

coordinated the videotaping of its fall. (Figure 12, left). The resulting high speed video showed the steel ball fell straight along the yardstick of the moving cart.

When the class reviewed their video, the straightness of that path came into question! Jason, an engineer, imagined doing the experiment in a vacuum to eliminate air friction. That stirred Leslie, an education student, to think in ways she hadn't conceived before. She queried: "so if you drop it out of a car in a vacuum, it would fall next to car? I am still confused. ... even though your hand was moving it at 60mph and when your hand releases, there is nothing moving [the ball]!?" When Jason proposed checking this out through more observations, Leslie exposed the conflicting uncertainty inside her mind, saying: "The videos are proof for me. I can see it. But in my mind, I can't come to accept it." Yet as Leslie elaborated, her thinking moved. And she elicited confused wonderment from classmate Madhu, another education student, who asked "So what we are seeing [in our video] is not really a straight line?" Leslie replied "No. [the ball] is moving forward.. I was thinking it was going straight down; Jason helped me frame that [other view]."

Amanda envisaged a trenchant synthesis: "It's like a projectile. Where is that photo?!!! Abbott! The train and the ball!" The Abbott photo that Amanda sought was a strobe photo of a toy train that shot a toy cannonball upright as it moved forward (Figure 13; Abbott, 1958-1961). On seeing its reproduction (O'Neal 1968, p. 6-7, Abbott 2012, p. 31), Yang gasped "Oh my God!" (Figure 14, right) For Leslie, the historical photo evoked a capacity to see two perspectives at once, akin to what the previous term's students experienced in doing Euclidean constructions. Leslie said "when you step back and look...you can see the [ball's] movement (Figure 13, left). If you are on that train, you might think of it very differently." Amanda's supportive question "what would you see?" facilitated Leslie's insight "you would see the ball above the train. .. just hanging out."

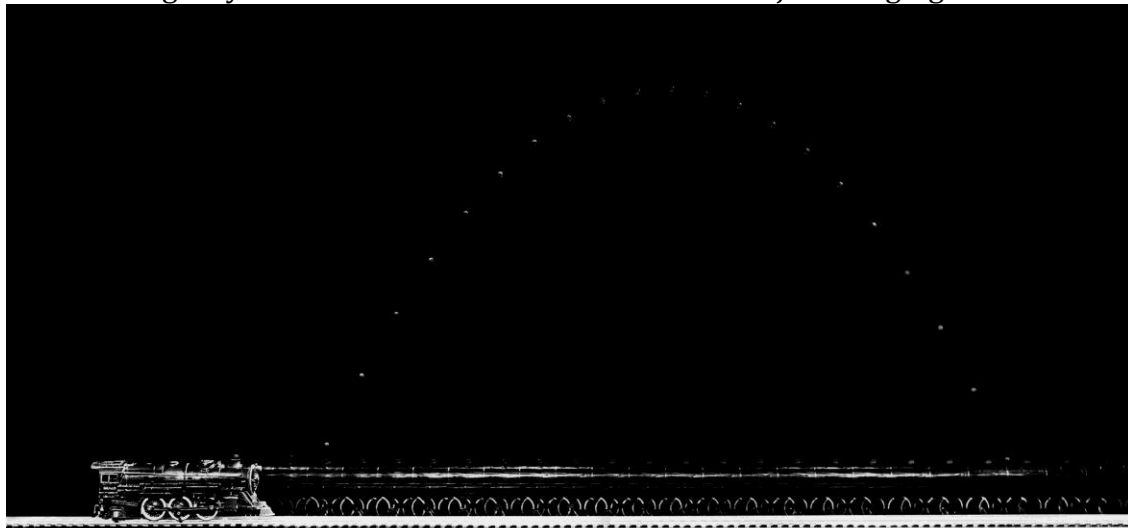


Figure 13. *Berenice Abbott's photo ,Multiple exposure showing the path of a steel ball ejected vertically from a moving object, Cambridge MA, 1958-61'. Berenice Abbott/Masters/GettyImages.*

How could our ball's forward motion be made evident? We projected the video onto the blackboard in the darkened room. Stepping through the video, frame by frame, we marked with chalk on the board only the ball's location in each frame, along with the frame number (Figure 14, right). When room lights came on, successive marks of the ball's location were staggered forward [leftward] in

the direction of the cart's motion! Madhu was amazed! "I just assumed it was falling in a straight line!" The multiple and yet concurrent paths uncovered in our video data resonated for Yang with Galileo's actual innovative process: "like Galileo; he had to respond to all objections in his mind before he took Copernicus' view." Amanda invited us to ponder what it might be like inside that mind, in saying "Galileo believes multiple conflicting things at once."

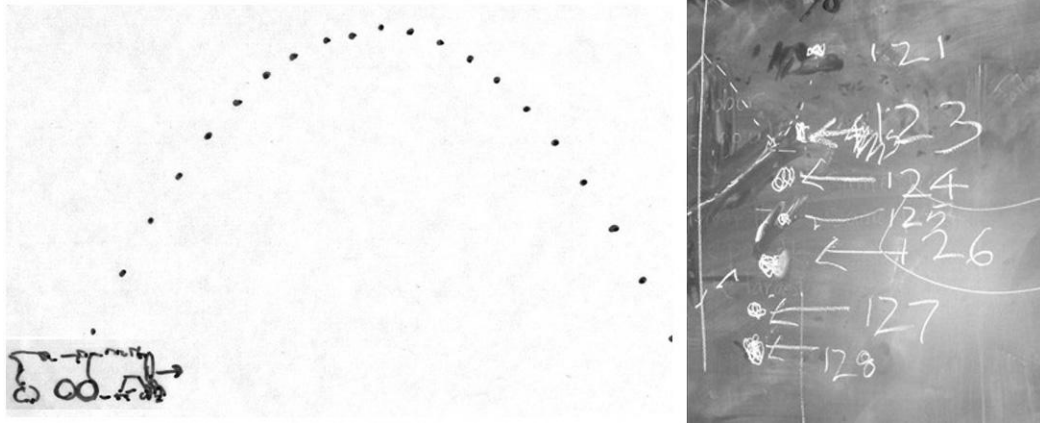


Figure 14. Left: Diagram based on Berenice Abbott's photo: a toy train moves horizontally; a ball shot vertically out of its smokestack, executes a parabolic path; black dots represent the ball's position at equal time intervals. Right: Each frame of the class' high speed video of the ball falling from a moving cart was projected directly onto the blackboard. The position of the falling ball at each successive frame is marked with a white hand-drawn dot and labeled with a frame number [121, 123, 124...]. Each dot is displaced to the left of the one above it; the ball was released from a cart that was moving from right to left.

5. Uncertainty and Doubt in Explorative Learning

To hold "multiple conflicting things at once" also entails not conforming to any one view. In discussing Galileo's struggle with the church (Milton 1644; Brecht 1980/2008; Sobel 1999), students identified with uncertainty and doubt, a core in Galileo's experience (Drake 1978, 1990; Settle 1996), and their own:

Amanda: Being uncertain, rather than being certain about being in opposition to an idea.

Madhu: The space to doubt.

Jason: Faith and doubt are inextricably linked. Doubt can reinforce faith, have you reevaluate when your faith is unfounded.

Further, that uncertainty, expressed so fluently by these students yet experienced and pioneered by Galileo under duress, is for them a grounding of their being in community as explorative learners. Theirs is a community grounded by the openness to be in doubt, not in conformity, where 'Euclidean Police' unhitch the confinements and limitations in participants' understandings.

In their final papers, the students attributed their depth in learning to their own explorative endeavors of going into the unknown together with others – companions in the classroom and in history.

During ...our exploration .. I walked away with a much deeper sense of what I had learned [than in a conventional classroom]. Key here was the freedom to act as a member of the Euclidean Police. [McCarthy 2011]

I have reached this understanding by following my own thinking as it developed through my encounters with the materials by and on Galileo. These are not questions or answers that were given to me explicitly, but ones that I arrived at through our individual and collective explorations. [Anatharajan 2012]

It was not until after our discussion and subsequent experimentation that I truly understood Galileo's words. ... The knowledge we created together through our own experiments is much more profound precisely because it was created for us and by us. [Pillsbury 2012]

Galileo extricated his mind from the authoritative prescriptions of his time. With resonance to historical examples, as the students experimentally and collectively generated multiple concurrent, conflicting perspectives, they also diverged from the goal-directed curricula of most schools today. They learned something that cannot be learned from structured curricula: how to observe; how to question; how to communicate; how to determine what is reasonable and what is not; how to create and share knowledge rather than just accepting it.

Acknowledgements

I am happy to thank the students: Yan Yang, Madhu Anantharajan, Houman Harouni, Mac Hird, Brian McCarthy, Amanda Pillsbury, Stephen Ray, Laura Sher and Zengxu Yang. Course experiences were supported by: Jim Bales, Edgerton Center, Rebecca Fearing, Debbie Douglas, James Capobiano, Akiko Yamagata, Bethany Mulimbi, Ed Moriarty, Adrian Tanner, Jackie Sly, Charles Guan, Alex Shvonski, Gary Van Zante, Peter Houk, Sara Schechner, James Capobianco, Wallace Observatory, Larry Ford. Alva Couch, Eleanor Duckworth, Houman Harouni, Yan Yang, and Janet Youkeles responded to drafts of this paper. Past classes of EC.050/090 and SP 713/726 extended my trust and understanding. I thank Peter Heering for his creative teaching with historical experiments and encouragement. I am grateful to Peter Heering and his colleagues at the University of Flensburg for the opportunity to participate in this ICHSSE meeting. Eleanor Duckworth and Alva Couch sustain my teaching. This work honors the memory of Philip Morrison, Alanna Connors and my father.

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