CHAPTER 9

Historical Science Instruments in Exploratory Teaching and Learning

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1. Introduction

Learners engage with historical science instruments in many of my presentations at Scientific Instrument Commission (SIC) Symposia.[1] The principal context for my educational studies is a university seminar that I have developed and taught for fifteen years at MIT's Edgerton Center, titled "Recreate Experiments from History: Inform the Future with the Past".[2] Sessions are evolving and open-ended, including observing outdoors and with materials; sharing observations; discussing questions and curiosities, responding to readings and historical resources, and collaborating with classmates. Field trips to museums, rare book library and other sites provide opportunities in which students examine historical materials directly, raising their own questions and insights. This seminar is offered for academic credit outside of any degree program or requirement. There is no prerequisite. Undergraduate and graduate students with any background may enroll, including cross-registering students from Harvard. The class size is intimate, typically fewer than seven, or even two members. Between sessions, students observe; keep a journal; do readings; and complete the course by writing a reflective paper. Assignments suggest diverse options for observing, reading and reflection; students may select and follow personal and collective interests. Potential for academic stress is lowered through building experiences together; my flexibility in

[1] This chapter expands upon the following presentations: Elizabeth Cavicchi, "Conflict and Balance: Classroom Explorations with Historical Instruments, Science, Geometry, and More", *XXXIV Scientific Instrument Symposium*, Turin, Italy, 7-11 September 2015; E. Cavicchi, "Old Instruments Give Rise to New Explorations in Learning and Teaching", *XXXIII Scientific Instrument Symposium*, Tartu, Estonia, 25-29 August 2014; E. Cavicchi, "Stepping into the Past to Understand Time: Explorations with Astrolabes, Clocks, and Observation", *XXXI Scientific Instrument Symposium*, Rio de Janeiro, Brazil, 8-14 October 2012; E. Cavicchi, "Telescopes and Telescopic Acts Bring Galileo into my Classroom", *XXIX Scientific Instrument Symposium*, Florence, Italy, 4-9 October 2010; E. Cavicchi, "Reconstructing the Camera Obscura Effect: Becoming Optical Experimenters", *XXVII Scientific Instrument Symposium*, Lisbon, Portugal, 16-21 September 2008; E. Cavicchi, "Recreating the Bead Lens of a Seventeenth Century Simple Microscope", *XXVI Scientific Instrument Symposium*, Cambridge (MA), USA, 6-11 September 2007.

[2] MIT OpenCourseware posts assignments, student work, and readings from the 2010 winter term of this seminar: https://ocw.mit.edu/courses/edgerton-center/ec-050-recreate-experiments-from-history-inform-the-future-from-the-past-galileo-january-iap-2010/ (accessed 13 Oct. 2020).

responding to where students are; and the course being half of the credits of standard offerings.

Being together, students and I form experiences: with the natural and social world, each other, historical figures, others of our time and in the future. Our lived experiences are openings to dialogue, experiment, question, and reflect. By taking action, such as observing the night sky or experimenting with lenses, students encounter something other, that may be intriguing and unknown for them, as it was for those in the past. Welcoming experience—however that evolves—is a mutual process of growing in respect, flexibility, spontaneity, and continuity. Understanding evolves; uncertainty abounds; creativity and new perspectives arise; evidence is produced and questioned; social concerns, history, reflection, and subjectivity are embraced. These qualities, inherent in our class experiences, are consonant with how many science educators today characterize the "nature of science".[3] Whereas those educators advocate for "explicit" instruction on each of these characterizations, my students directly access, discuss, and reflect upon the complex, contingent, and interactive relationships among each other, others, science, and the world.

As the teacher, I look to bring about experiences where students are explorers, and to sustain and extend their investigations.[4] In doing so, I play multiple roles—including researcher, participant, learner, advocate, and materials provider—throughout the experiences, practicing the pedagogy of "critical exploration in the classroom"[5] developed by Eleanor Duckworth from origins in the researches of Jean Piaget[6] and Bärbel Inhelder.[7] My observing, documenting, developing, and reflecting occurs alongside that of the students, and informs my thoughts for our further engagement with materials and questions. As an active participant in the evolving experience along with the students, I encourage class as a space where we all:

• Explore what is around us;
• Consider and try how others engaged with these things before us;
• Initiate experiments and understandings collaboratively with each other.

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[3] National Science Teacher Association, Nature of Science, 2020, https://www.nsta.org/nstas-official-positions/nature-science (accessed 13 Oct. 2020).

[4] See: E. Cavicchi, "Becoming curious science investigators through recreating with history and philosophy," in A. P.B. da Silva, B.A. Moura (eds.), *Objetivos Humanísticos, Conteúdos Científicos: Contribuções da História e da Filosofia da Sciência para o Ensino de Ciências*, Edupb, Campina Grande-PB (Brazil), 2019, pp. 265-284, http://eduepb.uepb.edu.br/e-books/ (accessed 13 Oct. 2020); E. Cavicchi, "Learning Science as Explorers: Historical Resonances, Inventive Instruments, Evolving Community", *Interchange* 45, 3 (2014), pp. 185-204; E. Cavicchi, "Opening Possibilities in Experimental Science and its History: Critical Explorations with Pendulums and Singing Tubes", *Interchange* 39 (2008), pp. 415-442; E. Cavicchi, "Historical Experiments in Students' Hands: Unfragmenting Science through Action and History", *Science and Education* 17, 7 (2008), pp. 717-749.

[5] Eleanor Duckworth, *"The having of wonderful ideas" and other essays on teaching and learning*, Teacher's College Press, New York, 1986/2006. For curricular materials, scholarly writing, and exploratory teachers' community, see https://cepress.org/ and https://criticalexplorers.org/ (accessed 13 Oct. 2020).

[6] Jean Piaget, *The child's conception of the world*, J. & A. Tomlinson, trans., Littlefield, Adams, Totowa (NJ), 1960/1926.

[7] B. Inhelder, H. Sinclair, M. Bovet, *Learning and the development of cognition* (trans. by S. Wedgwood), Harvard University Press, Cambridge (MA), 1974.

Historical science instruments, replicas and historical practices facilitate commencing experience where we act with something, find something unexpected, and create a further response. Through having historical instruments, or representations, in their hands, students frame relationships between their minds and bodies and things of the world in ways that are new for them. For example, measuring with a quadrant involves aligning one's eye with quadrant and distant object while a classmate notes where—within its arc—a weighted string hangs. Students' direct experience is inseparable from this measurement, unlike that of using many contemporary measurement devices.

One episode from a first day of a class illustrates how instruments from another time provide an entry to exploration. Often, on the first day of my class, we go outdoors and observe spatial relationships, sound and light. The weather was cold and clear and there was an auspicious circumstance: the class date coincided with a twice annual alignment of the setting Sun along the length of our building's hallway,[8] timed to occur in the final moments of our scheduled class. With this in mind, I chose to start with an activity that would lead us close to the sunset hallway. Being involved that day in reorganizing archaic apparatus kept on back shelves from a previous era, my colleague shared with me a strobe apparatus used by Harold Edgerton and originally designed for Albert A. Michaelson's speed of light experiment.[9] On the spot, I decided to accept his offer to borrow it for class, along with two other old instruments from his collection. To these, I added a replica brass astrolabe,[10] an instrument that would be a continuing focus that term in the course (see *Section 5*).

After our course introductions, I laid these four unidentified instruments on the classroom table. Questions and wonder abounded: "It spins!" "Does light shine through!?" "Have you ever seen anything like that plug? Not me." "Can we take it apart?" "They didn't have superglue back then. How is it connected?"[11]

Encouraged by me, students' curiosity moved their actions: turning dials of the astrolabe replica (*Fig. 9.1*, top left); disassembly of vacuum tube housing (*Fig. 9.1*, top right); shining cellphone light on the handgrip strobe; handling the revolving Sperry mirror unit (*Fig. 9.1*, bottom left); shining cellphone light at its revolving mirrors while seeking the reflection on a paper (*Fig. 9.1*, bottom right). Unfamiliar with these objects and their classmates, they became a team. Conjecturing, acting, and sharing, their investigations exemplify our course experiences. Their actions—taking initiative that may be more characteristic of nineteenth century science education[12] than

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[8] MIT Infinite Corridor Astronomy – MIT Henge, http://web.mit.edu/planning/www/mithenge.html (accessed 13 Oct. 2020).

[9] Sperry Gyroscope Company produced the apparatus for Michelson's speed of light experiments; this one came to Harold Edgerton. Thomas P. Hughes, "Science and the Instrument-maker: Michelson, Sperry, and the Speed of Light", *Smithsonian Studies in History and Technology* 37 (1976), pp. 1-18.

[10] Workshop of Norman Greene, Berkeley (CA); http://puzzlering.net/astrolabe.html (accessed 13 Oct. 2020).

[11] Quotes from "EC.090 Transcript", MIT, February 6, 2018, manuscript: MIT, Cambridge (MA), Author's Archive. EC.050 (undergraduate level) and EC.090 (graduate level) are the Edgerton Center course numbers for "Recreate Historical Experiments, Inform the Future from the Past".

[12] MIT's early lab text emphasizes student agency: Edward C. Pickering, *Elements of Physical Manipulations*, Hurd and Houghton, NY (1873), p. vi. See also: Peter Heering, Roland

subsequently—allowed students to take control of their learning in a situation where most contemporary learners are expected to accept authoritative claims.

***Fig. 9.1 – From top left to bottom right*: Students explore an astrolabe replica (at right); disassemble a vacuum tube housing; examine Sperry revolving mirror for Albert A. Michelson's speed of light experiments; and catch its reflections on paper.**

Through direct access to old instruments, as in this episode and in examples below, students related to objects present and past. For example, the act of sighting through a surveyor's level helped one student to realize its inadequacy for viewing indoors and to consider its historical use: "It was designed for large outdoor spaces […] I wonder how they chose a starting location?"[13] By handling an instrument, students synthesized experience and meaning in ways that go beyond what they inferred from class readings and videos.

As experiences with instruments are provocative for my students, I arrange for visits with historical science instruments in various settings: exhibits at university and local museums; study or store-rooms at local museums and libraries; university labs and historical buildings; and at a collector's home, club, or business.

MIT Museum hosts my class in a continuing relationship. Each term, MIT Museum curator Deborah Douglas and I brainstorm ideas for a class visit that involve

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Wittje (eds.), *Learning by Doing: Experiments and Instruments in the History of Science Teaching*, Franz Steiner Verlag, Stuttgart, 2011, pp. 152, 189, 193-195 and 258-261.

[13] Brian McCarthy, "Journal", EC.050, MIT, October 4, 2011, manuscript: MIT, Cambridge (MA), Author's Archive.

students with the instruments, materials, culture and technology of the past. We draw on specific holdings or exhibits of the museum, as these relate to ongoing student activities. Class visits may occur in a gallery, study room, off-site storage depot—or move among all three! With Douglas's guidance, students may touch, hold, and use instruments formerly used in teaching and research at MIT. Often Douglas puts students in a detective role, even in investigating the function of instruments of which she has incomplete information. She asks students to observe materials, examine markings, operate a handle, follow a connection, read articles, speculate about possible functionalities. Along the way, she tells fascinating stories about instruments, interweaving insights about materials, politics, people, and discoveries—including her own.

The next sections relate details of four principal ways that my students have engaged with historical science instruments:

• Viewing authentic instruments exhibited at MIT Museum; responding, and even replicating.
• Interacting with authentic historical instruments in the MIT Museum storeroom.
• Using a model instrument in class; interacting with the original in a collection.
• Initiating major personal projects inspired by historical instruments.

2. Museum Gallery Visit and Responses

When the MIT Museum exhibits relate to course themes, my class visits the gallery. Gallery visits accommodate learners' participation with historical instruments by other modes than direct handling. Activities that are supported in galleries include: drawing and diagramming; comparing instruments; photography; handling an analogue while viewing originals; discussion and questioning. In sessions following gallery visits, I invite students to share what piqued their interest and consider ways of continuing their curiosity in class.

For example, historical instruments were featured in the MIT Museum's 2006-2007 exhibit *Singular Beauty*, the first comprehensive public presentation of simple microscopes.[14] Drawn from Ray Giordano's collection, the instruments dated from seventeenth to nineteenth centuries; some elegantly crafted from precious materials; some by well-known optical makers; others by unknown artisans. Two of my classes visited this gallery. One student, Mingwei Gu, participated in the first visit. What emerged through his interest informed our teaching with the next class of eighteen students.

Douglas led Gu and myself on a stroll through the gallery, marveling at craft and designs (*Fig. 9.2*, top left). Douglas next directed us to one that did not stand out: a Leeuwenhoek copy.[15] Douglas amazed us with the wonders that Anton van Leeuwenhoek saw with his similar instruments. Knowing of our class activities in remaking historical effects with everyday materials, she suggested we make a bead lens.

Intrigued, we took up the project. The extended process of finding suitable glass, heating and shaping it into a sphere, and observing through the resulting bead immersed us in genuine exploratory work. With candle, alcohol lamp and Bunsen burner (*Fig. 9.2*, top right) as heat sources for blow-piping glass rods, Gu developed lung capacity and

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[14] Raymond Giordano, *Singular Beauty: Simple Microscopes from the Giordano Collection* (Catalogue of an exhibit at the MIT Museum, September 1, 2006 - June 30, 2007), MIT Museum, Cambridge (MA), 2006.

[15] Leeuwenhoek-type simple microscope, *Ibid.*, p. 13.

skill. Peter Houk, MIT's glass lab director, advised us on blowpipe technique. He made for us rods of soda lime glass, workable at lower temperature than the Pyrex we tried first. Gu produced several glass sphere magnifiers (*Fig. 9.2*, bottom left). He demonstrated his expertise at a bead-making activity held at the 2007 SIC meeting.[16] The participants steadied their breathing, shaping flame and glass together, yielding a few glass spheres (*Fig. 9.2*, bottom right).

***Fig. 9.2 - From top left to bottom right*: Microscope gallery visit at the MIT Museum; Mingwei Gu blow-piping with Bunsen burner; his glass spheres; blow-piping by participants of the *XXVI Scientific Instrument Symposium*, Cambridge (MA), USA, 6-11 September 2007.**

Months later, during the gallery visit of a class that I guest-taught at another school, Douglas invited students to draw a paper image of a microscope that interested them. A display of all drawings revealed diversity among the artifacts and in the observers' perceptions (*Fig. 9.3*). Students became invested in the instrument that they drew. One wrote: "I felt in love with one that stroked my imagination,[17] […] questions came into my mind […]. What is the story behind it? Was it used by common people?"[18] Feeling "confused" over how to sight through a compass microscope moved

[16] MIT Lab Tours, held on September 8, 2007, *XXVI Scientific Instrument Symposium*, Cambridge (MA), USA, 6-11 September 2007.

[17] The student refers to Hartsoeker screwbarrel microscope; see Giordano, *Op. cit.* (n. 14), p. 14.

[18] Gerald Koffi, "Microscope Writing Assignment", Honors Science 290, University of Massachusetts Boston, October 5, 2007, manuscript: MIT, Cambridge (MA), Author's Archive. Honors Science 290 is the number of the course that I taught during two fall semesters, at the request of the Honors Program.

one student to ask: “are the [historical] users careful and detail oriented people?”[19] Another student advocated: “I hope women as well!” were among the makers of microscopes.[20] Impressed by a rock crystal elegantly mounted like a gem,[21] her classmate imagined the scenario of its wealthy owner “whipping this out of his pocket” to show off at a party.[22] Students injected themselves into the historical context of the instruments, imagining what they would do with the instruments if they were the original owners.

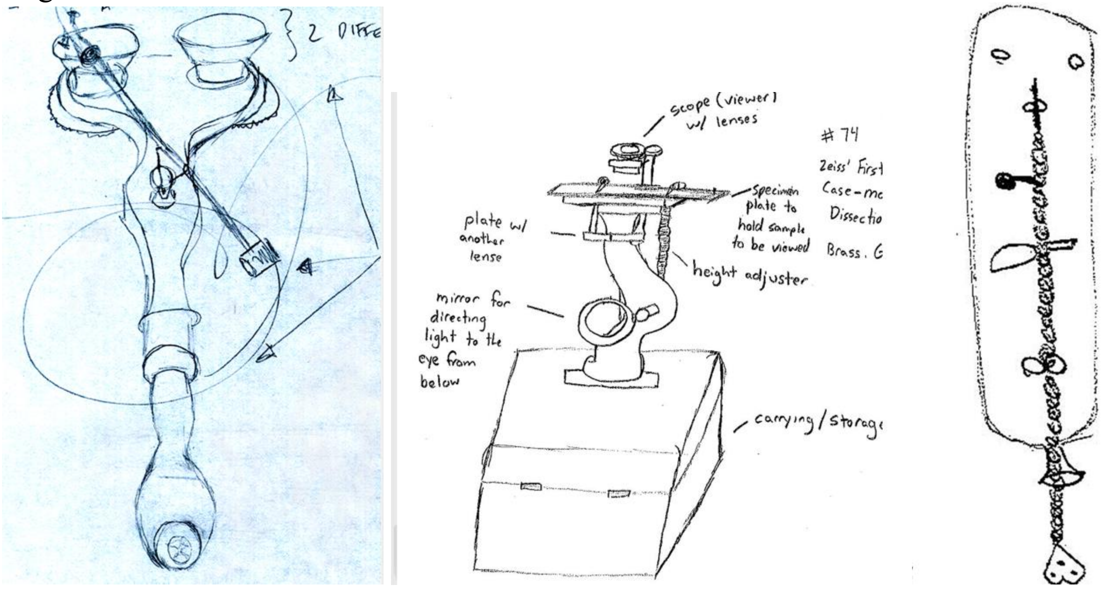

***Fig. 9.3* - Three microscope drawings by (*from left to right*) Gabriela Antunes, Sharon Kiley and Lillian Rodriguez (October 5, 2007).**

A week later, in the classroom where I was a visiting instructor, students responded to the microscope exhibit by following up on their personal interests. Some explored magnification by placing different shaped lenses over printed text. Analyzing and diagraming light’s path in differing microscopes, one student discerned three “completely different designs to capture light.” Intrigued, he asked: “what would the same object look like when viewed in different microscopes? Different? Similar?”[23] Drawing on the findings of Gu’s explorations, I provided materials that some students used in experimenting with shaping glass rods in a Bunsen burner flame.

These gallery visits create space where students contemplate historical instruments through personal observing and drawing, and by hearing stories. Students’ connectedness to microscopes—initiated in the gallery—was extended in classroom explorations in diverse ways, as suggested above. These personal experiences sparked students’ sense of dialogue among past, present and future humans doing science—

[19] John Kerpan, “Journal”, Honors Science 290, University of Massachusetts Boston, October 5, 2007, manuscript: MIT, Cambridge (MA), Author’s Archive.

[20] Carolina Gomez, “The Microscope Activity”, Honors Science 290, University of Massachusetts Boston, October 12, 2007, manuscript: MIT, Cambridge (MA), Author’s Archive.

[21] See: Giordano, *Op. cit.* (n. 14), p. 62.

[22] Renata De Carvalho, “Journal”, Honors Science 290, University of Massachusetts Boston, October 5, 2007, manuscript: MIT, Cambridge (MA), Author’s Archive.

[23] Noam Shabani, “Journal”, Honors Science 290, University of Massachusetts Boston, October 11, 2007, manuscript: MIT, Cambridge (MA), Author’s Archive.

including themselves. That students live deep qualities associated with "nature of science" is conveyed in one student's reflection:

> The fact that [historical people] made these microscopes speaks volumes of their curiosity […] to observe the small worlds that exist among us and yet escape our natural eyes […]. The human curiosity of wanting to know what is beyond one's own backyard, across the ocean […] or even outside of space is the same with that of wanting to see the smallest details. […] [Microscopy] has tremendous impact in our lives! I wonder what the makers of these early microscopes would think of today's super advanced microscopes.[24]

3. Hands-On Storeroom Activities

MIT Museum's off-site storage accommodates experiences where students encounter historical instruments that are not behind glass. Just to enter the vast warehouse is amazing (*Fig. 9.4*, top left). Amid towering shelves, packed with artifacts, old research apparatus and sculptures, with a human-powered plane hung from rafters, students identify with the fictional character Indiana Jones![25] Douglas invites them to wander and select something to explore together. Scaling a ladder, a student brought down what resembled a violin case, an instrument he plays. When opened, a classmate recognized a historical Chinese balance, and demonstrated how her parents used one (*Fig. 9.4*, top right). Gary Stilwell (see *Section 5*), an advanced study fellow, gathered us around a model of the sailing ship *Maltese Falcon* built in 2006. He had seen the actual square-sailed ship close-up while crewing on the tall ship SV *Tenacious*.[26] He asked: "What's unique about it?"[27] Looking closely, classmates pondered sailing in the past and on the ropeless yacht. Drawn by aesthetics and personal experience, students engaged each other in questioning and in understanding historical instruments.

[24] Gomez, *cit.* (n. 20).
[25] *Raiders of the Lost Ark*, 1981, directed by Steven Spielberg.
[26] https://sailtraininginternational.org/vessel/tenacious/ (accessed 13 Oct. 2020).
[27] Quote from "EC.090 Transcript", MIT, April 6, 2018, manuscript: MIT, Cambridge (MA), Author's Archive, fol. 4.

***Fig. 9.4* - Students visit MIT Museum's off-site storage. *From top left to bottom right*: Museum storeroom; testing historical Chinese balance; opening boxes of surveying instruments; adjusting an instrument.**

For the bulk of each more than two-hour visit, Douglas prepares hands-on activities around themes of mutual interest. On a worktable, she places historical instruments that are unknown to the students. Gloves are distributed. Tools are available to assist in opening or testing instruments. Partway in, she may provide manuals, news articles, photos, and other materials from the historical time. Students discuss with her and each other while investigating instruments' materials, culture and uses.

One winter, our class visit to MIT Museum occurred after students had developed considerable experience observing the night sky. Every clear evening, we went to the Charles River Bridge, watching sunset, waiting for Venus to appear, noticing birds, waves, ice and other wonders. Along with viewing by naked eye and a portable refracting telescope, students estimated these bodies' elevation with: a training model sextant, a quadrant that students improvised from a protractor, and a laser-cut Galileo compass (see *Section 4*). They related these practices to readings on African American astronomer Benjamin Banneker[28] and James Ferguson's eighteenth century astronomy manual.[29]

At that term's end, we went to MIT Museum's off-site storage. In light of Banneker's role in surveying Washington DC, Douglas chose to share nineteenth-

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[28] Silvio Bedini, *The Life of Benjamin Banneker*, Maryland Historical Society, Baltimore MD, 1999.

[29] James Ferguson, *Astronomy Explained upon Sir Isaac Newton's Principles*, James Ferguson, London, 1756.

century instruments used in training MIT's civil engineers. When we arrived, eight wood boxes lay closed on the table. Douglas encouraged students to walk about, open boxes, examine each, and select one for personal study (*Fig. 9.4*, bottom left). On first impression, students identified the instruments as like telescopes; one was labeled for surveying. Speaking on his choice, Jais Brohinsky said: "I have the least idea of what it did". Raul Largaespada, an aspiring aero/astro engineer, said he was drawn to one that most "looked like a telescope".[30]

Fig. 9.5 **- Students visit MIT Museum's off-site storage. *Left*: Handling an instrument; *Right*: sighting with optical level.**

Wearing gloves, students were encouraged to remove instruments from the boxes and explore whatever they could by viewing and manipulating (*Fig. 9.4*, bottom right). Douglas provided a printed sheet for writing inferences, such as about materials, function, and era. Students were engrossed with what was before them, trying out the range of available motions (*Fig. 9*.5, left), sighting through lenses, and writing notes. A half hour in, Douglas passed out historical civil engineering texts and manuals. On finding these instruments depicted, students applied the texts in handling the optical levels and theodolites. These pursuits absorbed them as Douglas told stories about how surveying advanced Western empires.

"Using the apparatus, how tall is that shelf?" Douglas's direct question was met with silence. Her follow-up questions elicited tension. Unlike the activity of exploring instruments which engaged everyone, these questions aimed at right answers. Teacher education student Brohinsky reflected: "it made me not want to interact […] the tension was where the potential for real learning lay in that session".[31]

A story eased mutual strain. Largaespada shared a legendary fraternity prank. MIT freshman Oliver Smoot's body was lain end-to-end across the Bridge's length. Each placement was marked in paint. The "smoot" is now a unit of length in Google convertor![32] A student exclaimed: a wall-sized photo in the storeroom depicts the

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[30] Quotes from "EC.050 Transcript", MIT, January 27, 2017, manuscript: MIT, Cambridge (MA), Author's Archive, fol. 1.

[31] Jais Brohinsky, "Two very curious wonderings from MIT Museum warehouse", EC.090, MIT, January 30, 2017, manuscript: MIT, Cambridge (MA), Author's Archive.

[32] Patrick Gillooly, "Smoot reflects on his measurement", *MIT News* (September 24, 2008), https://news.mit.edu/2008/smoot-tt0924 (accessed 13 Oct. 2020).

original 1958 hack! While observing on the bridge, we often walked over the colorfully painted "smoot" marks without notice. Now those marks attracted interest. This discussion uncovered history's evidences, previously unseen around us.

Lacking Smoot, Douglas handed a historical steel tape to the group. Using it to measure the floor entailed unexpected set-backs. The tape kinked, curled and did not stay taut. Its divisions did not start at "0"; part had broken off long ago. After measuring a horizontal distance along the floor with the tape, each took a turn at looking through the optical level to read vertical height on a surveyor's target (*Fig. 9.5*, right). Collaborating made the group aware of the back-and-forth inherent to forming science understanding.

This museum storage activity, which in Largaespada's words "helped familiarize us with the surveying tools and techniques Banneker would have used while surveying the land that would become Washington D.C.", interleaved supportively with our ongoing class activities. Direct experiences with telescopes, sextants, and other instruments pervaded those activities, from the first session's sighting of Venus, to personal observing with portable refracting telescopes, to our tour at MIT's Wallace Astrophysical Observatory on a clear night.[33] In Raul's regard, "our extensive class use of telescopes was a great boon in our quest to understand what Galilei and Banneker saw and calculated".[34]

In hands-on activities in the museum storeroom, like those described here, personal experience engages historical experience through physical actions with instruments and interpretive discussion. The learning goes beyond working out how instruments were formerly used. It encompasses fun and surprise; insights about how pedagogy shapes an experience and how differing perspectives coordinate in collaboration. For example, along with questioning tension arising between "holder of knowledge and petitioners", doing the museum surveying activity stirred Brohinsky to propose an activity where young people would use ratio relations, based on their own bodies, to measure heights and distances.[35] He developed this idea into a lesson that he later taught in a summer camp.

4. Galileo Compass: Model and Original

Themes of Galileo Galilei, his instruments and experiments recur in my seminar.[36] A typical science classroom may have physical materials for interpreting some Galilean era instruments—pendulum, ramp, telescope. Introducing other historical instruments, such as the astrolabe and Galileo's geometrical compass, in a classroom calls for constructing analogues having specific features. Initially, I addressed this circumstance with cardboard models. I assembled geometrical compasses from templates at Museo Galileo website;[37] James Morrison produced two card astrolabes for the class.[38] On

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[33] http://web.mit.edu/wallace/ (accessed 13 Oct. 2020).

[34] Raul Largaespada, "Across Generations: Curiosity as a Unifying Force in EC.050", EC.050, MIT, February 7, 2017, manuscript: MIT, Cambridge (MA), Author's Archive.

[35] Brohinsky, *cit.* (n. 31).

[36] Philip Morrison, my teacher, inspired my passion for Galileo's instruments. I assisted him as researcher for Philip Morrison, Phylis Morrison, *The Ring of Truth*, Random House, New York, 1987; and the TV documentary *The Ring of Truth*, part 1: "Looking", 1987, available at www.youtube.com/watch?v=bQ4Oz2Xk2Ws (accessed 13 Oct. 2020).

[37] "How to Make Galileo's Compass", Museo Galileo: Institute and Museum of the History of Science, Florence,

seeing my students struggle with these flimsy devices, my Edgerton Center colleague Ed Moriarty organized a student team to convert the templates to CAD as input to a laser cutter. After multiple iterations, they produced several laser-cut models in birch, of the geometrical compass at twice the original scale, and one enlarged astrolabe (40 cm diameter).

In opening a session with Galileo's compass, I distribute to each student pair: Galileo's manual,[39] a laser-cut geometrical compass, 12" (ca. 30 cm) long dividers, pencils and large paper.

Like cellphones, the geometrical compass is multipurpose. Often students' first use is estimating a star's angle, then dialing that value into our large astrolabe. Other opening exercises in Galileo's manual include: finding a tower's height (see Douglas's question above), dividing a line in equal parts, and constructing polygons.

Without first reading Galileo's method, three engineering students set out in snow to measure a Boston skyscraper's height. Having sighted its angle with the laser-cut compass from two spots and paced a few steps between, they derived their own equations for the building's height. "Plugging in" their values and calculating by cellphone yielded an absurd value: 14 feet! The group devoted several sessions to track down errors. Redoing the experiment (*Fig. 9.6*, left) brought attention to selecting locations for perceptible difference in the plumb line's fall along the divided arc. A plausible height resulted when they applied Galileo's scales, which by encoding trigonometry of the students' (revised) equations, reduces the calculation to ratios. The wood model proved more reliable than the cellphone: one student, YouYou Li, discovered reproducible malfunction in her cellphone's calculator.

***Fig. 9.6* - Sighting (*left*) and calculating (*right*) with laser-cut Galileo compass.**

Indoors, now trusting Galileo's manual as a guide, the group drew geometrical shapes using scales on the model compass to compute the length of a side (*Fig. 9.6*,

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https://brunelleschi.imss.fi.it/esplora/compasso/dswmedia/risorse/ecostruire_compasso.pdf (accessed 13 Oct. 2020).

[38] James Morrison, *The Personal Astrolabe*, James Morrison, Rehoboth Beach (DE), 2010.

[39] Galileo Galilei, *Operations of the Geometric and Military Compass*, Stillman Drake (trans.), 1977; available at https://brunelleschi.imss.fi.it/esplora/compasso/dswmedia/risorse/eleoperazioni.pdf (accessed 13 Oct. 2020). Also see the website simulation videos.

right). We found that our model lacked reference marks that Galileo describes as key to constructing a square having the area equal to that of a section of a circle.[40]

Spurred by these students' extensive involvement with Galileo's geometrical compass[41] and discovery of the template's omission, I arranged a class visit to see an original: the fine instrument that Galileo presented to the Duke of Mantua, now at Harvard (*Fig. 9.7*, top left).[42] Being removed from display for our visit, curator Jean-François Gauvin put it in Li's gloved hands. She spied a fingerprint—was it Galileo's!? As mechanical engineering students, she and C.J. Munroe were impressed by how the compass arms' design conceals its joinery, making it appear all one piece. In a crack that showed on one arm's side, not the other, they detected evidence of multipart makeup. Side-by-side, they compared division markings on Galileo's instrument with those on the laser-cut model (*Fig. 9.7*, top right). Discerning divisions, as Galileo's pupils would need to do, is difficult: "its lines are so close […] faint". Li exclaimed that one dent "really dug in!" likely made by a user's divider point.[43]

This instrument was configured as a quadrant, with an exquisite acorn-shaped weight suspended from its hinge. Its removable arc screwed onto the movable arms, fixing them at a right angle. In this configuration, the instrument cannot be used for calculation—as Li explained and demonstrated, with our model (*Fig. 9.7*, bottom left), to the curator who was unfamiliar with that aspect. The arc's flange was tightly screwed over where we expected to find the reference mark that was missing from our laser-cut model (*Fig. 9.7*, bottom right). Although that mark's position was unresolved by our hands-on examination, a new question arose as we considered the logistics of undoing the screw. How practical was it for a soldier in the field to sight with Galileo's instrument, then unscrew and calculate with it?

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[40] *Ibid.*, pp. 77-78. These marks were omitted on the Museo Galileo template. After my inquiry, the template is now corrected.

[41] The team created an educational music video featuring the cellphone, sextant, and astrolabe, *Science Enhances Romance*, posted under Entries 2014 at http://sciex.mit.edu/videos-all/ (accessed 26 Oct. 2020).

[42] Galileo's geometrical and military compass, Padua, c. 1604, Harvard Collection of Historical Scientific Instruments, Boston (MA), inv. No. DW0950; http://waywiser.fas.harvard.edu/objects/3608/galileos-geometrical-and-military-compass?ctx=433cfbdd-853c-4c19-9b4c-fa5682e40921&idx=0 (accessed 13 Oct. 2020).

[43] Quotes from "EC.050 Transcript", MIT, April 1, 2014, manuscript: MIT, Cambridge (MA), Author's Archive, fol. 9.

***Fig. 9.7 - From top left to bottom right*: Galileo's geometrical and military compass, Padua, c. 1604 (Harvard Collection of Historical Scientific Instruments, Cambridge, MA, inv. no. DW0950); comparing laser-cut model to original; orienting for use as quadrant; flange covers mark.**

By exploring with the model compass outdoors and indoors, these engineers confronted failings in the modern tools and analysis they rely on, and gained respect for Galileo and skill with his instrument. Bringing this experience to the original instrument enabled them to comprehend the maker's design and discern marks, dents and attributes of how it was used. Personal experience with both model and original grounded the students' interactive questioning and vision of the instrument's role in historical hands.

5. Student-initiated Projects Inspired by Historical Instruments

I encourage students to act on their curiosity in developing explorations. Some projects extend beyond my course. Here I summarize two such projects—one inspired by the other—where students' passion for historical instruments creates new experiences for us all.

For architect Francesca Liuni, who entered my seminar intent to reinterpret Islamic science, our class activities with astrolabes struck a chord of lasting resonance. While discussing SIC's 2015 theme "Instruments in Conflict" with classmate Ronald Heisser in relation to their poster proposals,[44] Liuni voiced her emergent vision for a radically interactive museum. It would be an immersion in the astrolabe: using it, being

[44] Francesca Liuni, "Balancing the Astrolabe between Art and Science"; Francesca Liuni and Ronald Heisser, "Conflict and Balance: Archimedean Conflicts"; Ronald Heisser, "Methodical Conflict in Past and Present Fluid Mechanics Research: An Alternative Investigation"; posters presented at *XXXIV Scientific Instrument Symposium*, Turin, Italy, 7-11 September 2015.

in its space, and with historical astrolabes displayed. When shared with her advisor, he reacted "you are crazy!"[45]

Liuni was undeterred. Her first model, puts museum-goers amid windows incised with the astrolabe's grid projection of the celestial sphere's azimuthal lines and altitude circles, so as to cast their shadow arcs within the interior space.[46] SIC members' feedback fueled her next version: an award-winning master's thesis uniting art and science in engaging the public with the astrolabe.[47]

Becoming immersed in geometrical thinking of Islamic science, Liuni discovered its architectural potential. Responding to Walter Benjamin's vision,[48] where past and present meet in recreating historical experience, she converted the axiomatic system underlying the astrolabe into architectural structures through which today's viewers encounter its constraints and possibilities. Her intricate hand-crafted thesis models and architectural drawings place the viewer within a celestial sphere, bounded yet open, and wandering among geometrical relationships of angles in space (*Fig. 9.8*). Architecture, she reflected, integrates "the abstraction and intuitive language of Art with the exactitude and practicality of Science".[49]

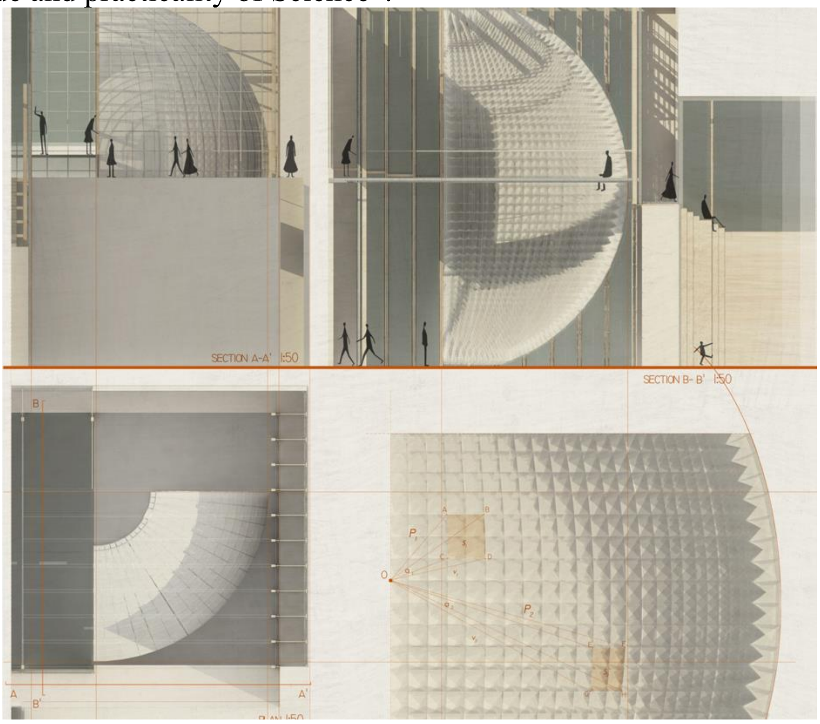

Fig. 9.8 **- Francesca Liuni's section architectural drawing of her astrolabe museum (Liuni, *Experiencing Mathematical Proves: Syntax of an Astrolabe*, Master of Science in Architecture Studies Thesis, MIT, Cambridge, MA, 2016, pp. 66-68).**

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45 Quote from "EC.050 Transcript", MIT, March 12, 2015, manuscript: MIT, Cambridge (MA), Author's Archive, fol. 11.

46 Liuni, *Op. cit.* (n. 44).

47 F. Liuni, *Experiencing Mathematical Proves: Syntax of an Astrolabe*, Master's Thesis, MIT, Cambridge (MA), 2016; https://chsi.harvard.edu/files/chsi/files/967222067-mit.pdf (accessed 13 Oct. 2020).

48 Walter Benjamin, "Theses on the Philosophy of History", in Hannah Arendt (ed.), *Illuminations*, Fontana-Collins, [London], 1973, pp. 255-266.

49 Liuni, *Op. cit.* (n. 47), p. 51.

Fig. 9.9 **- Francesca Liuni explains her exhibit, *Syntax of an Astrolabe*, Foyer Gallery, Harvard (Cambridge, MA), 2017.**

Liuni's next project (*Fig. 9.9*) echoes her original dream. In a gallery at Harvard, she created and built a walk-in spatial rendering of the divided sphere.[50] Posters depicting her artistic renderings of the astrolabe's projections lined the walls, while an authentic seventeenth-century Persian astrolabe was exhibited within.

I invited Liuni to share her astrolabe work in my next year's seminar. Never having seen an astrolabe before, yet trained with the sextant, Gary Stilwell (see *Section 3*) scrutinized our laser-cut astrolabe (*Fig. 9.10*, above), eventually identifying the North Star. With breath-taking realization, a classmate exclaimed: "when they invented the astrolabe, they thought the Sun moved and Earth does not! Wow!" Stilwell extended that perspective-taking to the entire solar system: "What if we made eight astrolabes, one for each planet!?"[51] Stilwell developed understanding for acting on this idea by constructing astrolabe geometry by hand on paper with guidance from Alistair Kwan's manual.[52] Our class was awed by Stilwell's term project. He coded, designed and printed on paper, an astrolabe tympanum for each planet in our solar system. The base location for each planetary tympanum corresponds to the latitude of Cambridge Massachusetts, on that planet (*Fig. 9.10*, below).[53] My subsequent students are inspired

[50] F. Liuni, *Syntax of an Astrolabe*, Foyer Gallery, Harvard, 2017; https://chsi.harvard.edu/syntax-astrolabe (accessed 13 Oct. 2020).

[51] Quotes from "EC.090 Transcript", MIT, February 15, 2018, manuscript: MIT, Cambridge (MA), Author's Archive, fol. 10.

[52] Alistair Kwan, *Introduction to Astrolabe Construction and Application*, 2007, MS.; A. Kwan, "Determining Historical Practices through Critical Replication: A Classroom Trial" *Rittenhouse* 22, 2 (2008), pp. 132-151.

[53] Gary Stilwell, "Le Voyage Dans Les Planets", EC.090, MIT, May 2018, manuscript: MIT, Cambridge (MA), Author's Archive.

by viewing Stilwell's exhibits of his planetary astrolabes, printed in crisp lines on titanium, copper, glass and paper.[54]

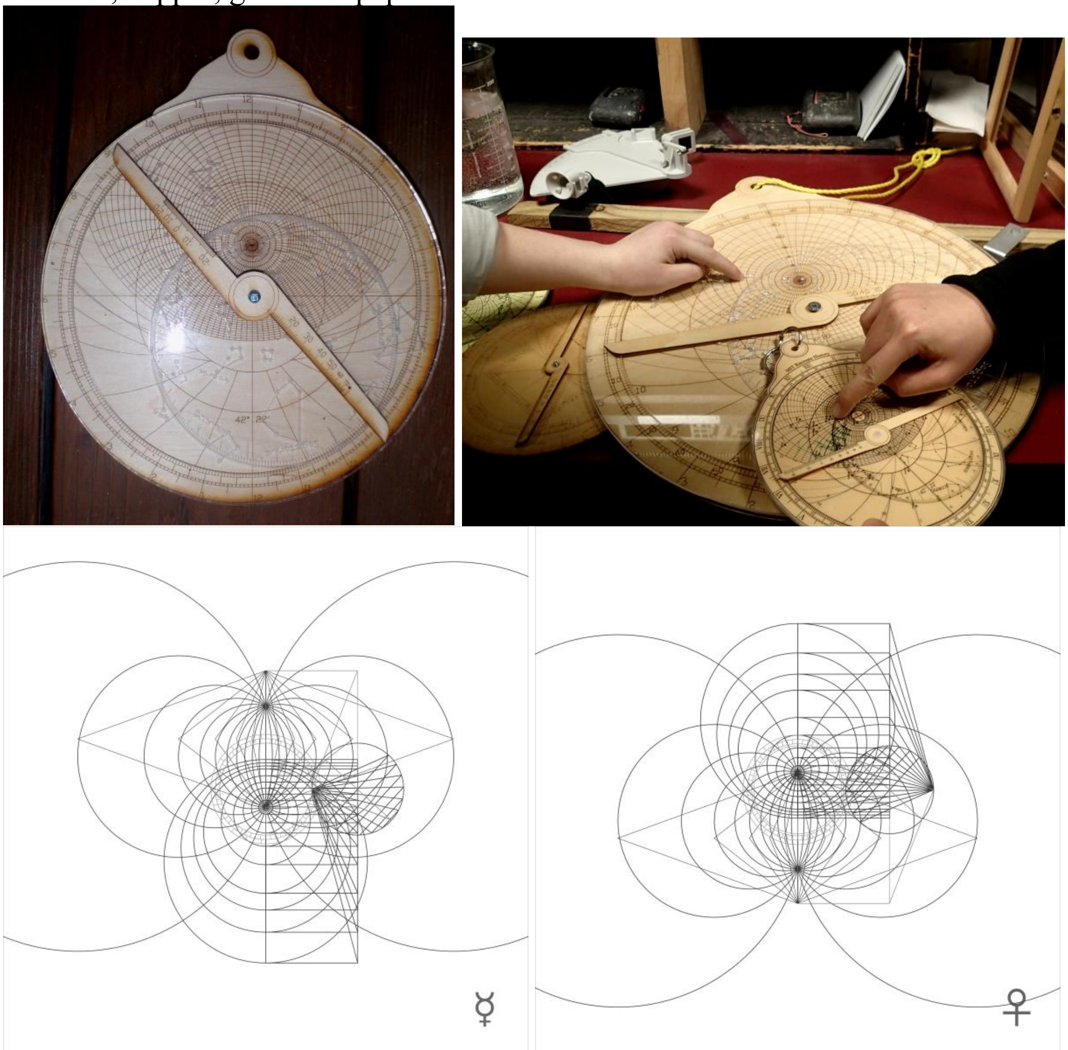

***Fig. 9.10* - *Above*: Laser-cut astrolabe in class: incised acrylic rete, 40 cm diameter; *Below*: Gary Stilwell's line drawings with stereographic projections corresponding to astrolabe plates for the planets Mercury and Venus, for an observer at 40° north latitude on each planet.**

The projects of Liuni and Stilwell were generated and shaped through their own questions: "How can I create an historical experience?" "What if we made eight astrolabes?" Personal curiosity shaped the iterative and evolving routes by which each delved into the astrolabe's mathematics, geometry, design, history, and astronomy. Drawing by hand with paper and pencil, they sketched and constructed its geometries anew for themselves. Each transformed their vision of the astrolabe into digital media: Liuni by architectural and spatial renderings; Stilwell by *JavaScript* coding, taking into account each planet's orientation. Having traversed mathematical, constructive, abstract and digital realms, each project brings the viewer to new physical experience with the astrolabe: Liuni's through architectural space; Stilwell's through lines inscribed on

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[54] G. Stilwell, *Where is Here? Astrolabes for Future Use on Mercury, Venus, Mars, Jupiter… and even Pluto*, Wiesner Student Art Gallery, MIT, Cambridge (MA), December 2018; and ProjXpo MIT, Cambridge (MA), January 31, 2020.

polished metals and glass, helping future travelers find their way in outer space with a historically inspired instrument.

6. Reflections on Historical Instruments in Exploratory Education

Thrill is palpable among learners engaging with authentic historical scientific instruments, as illustrated here. That depth in responsiveness arises in diverse forms of interaction: whether with an instrument on display ("I felt in love with one"), or held in a gloved hand ("Is that Galileo's fingerprint?"),[55] or in active use (sighting a surveyor's target through an optical level "I think I see the circle!").[56] Emotion, aesthetics, bemusement and action with historical instruments figure in how learners bring themselves into relation with the past, its people and science.

Where historical instruments are not museum quality, the opportunities widen for students to handle and trial uses, enhancing their participation with historical materials and questions, as in this chapter's first example. Models of historical instruments, such as the blowpipe and laser-cut Galileo compass and astrolabe, afford multiple and distinct interactions over time, as was needed for Mingwei Gu to develop blow-piping expertise, and for YouYou Li and her team to work through their uncertainties in observation methods and analysis, eventually finding a building's height with a model of Galileo's geometrical compass. Practical skill with the instrument, discovering all its functions and adapting to its limits, such as they gained, requires more than a single museum visit to attain. Through activities such as observing Venus from the Charles River Bridge and working hot glass, students meet first-hand the phenomena that historical instruments address.

Awe for the antiquity of human observing and awareness of taking part in it now, opens dialogue among students and their predecessors. That relation invites students to put their own past and future into relief. Such perspective-taking is especially poignant where predecessors were students like them: Galileo's pupils using the geometrical compass; MIT civil engineering students working with the same surveying instruments; and Oliver Smoot, marks of whose body's measure still remain on the Bridge where they walk now. Sharing her personal transformation arising through exploratory experiences with science and history, one student reflected: "This class opened my eyes, mind, and thoughts to explore things that I never thought I would. Now when I step, I see a lot more and now I question things, like Galileo did".[57]

Student's relation with the past, its science, instruments, and the relief it sets upon today's context, is stirred by *experiences* that put them in the role of detective, investigator, observer, surveyor. In the sessions described here, education is inherent to experiences of exploring in the unknown among learners together with teachers and others of the past. Historically, instruments were made and used by those going into the unknown. Those same instruments can open to further unknowns today, where students' experience with them is an unknown by which they evolve and learn—about historical instruments and what matters in their present world. To the extent that students have and take agency to explore, question and act, the experiences they live and create will widen all our understanding.

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[55] "EC.050 Transcript", *cit.* (n. 45), fol. 6.

[56] "EC.050 Transcript", *cit.* (n. 30), fol. 5.

[57] Renata De Carvalho, "Reflection Paper", Honors Science 290, University of Massachusetts Boston, December 20, 2007, manuscript: MIT, Cambridge (MA), Author's Archive.

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