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Teaching about the Nature of Science through Historical Experiments

Peter Heering and Elizabeth Cavicchi

Introduction

Having students experience historical experiments in the classroom is a powerful tool in teaching about the nature of science. Experiments performed by students support inquiry-based science instruction and have long provided an essential means of producing new scientific knowledge within science itself and throughout its history.

Students may be introduced to experiments by many instructional means. They may be asked to read and discuss written accounts of experiments (and experimenters) and historical publications based on experiments. Yet, such text-based instructional experiences do not engage students with procedural aspects of experimentation and related aspects of the nature of science (NOS). We argue that the procedure and process of science experimenting can only be conveyed through having students build their own experiences with experimenting and with reflecting on the nature of science.

Experiments from history manifest the full range of characteristics of nature of science, as discussed in the cases below. Just as there is not one scientific method, there is also not one experimental method. Along with probing natural phenomena, experimental work is usually theory laden and open to controversy and creative interpretation. While history of science is a resource for teaching the nature of science (Matthews 2000; Allchin 2013), the specific context of historical experiments augments historical accounts through the potentials of conducting experiments in classrooms (Kipnis 1996, Heering & Höttecke 2014). Performative aspects, such as how scientists stage experiments (and experimental reports), and material aspects (such as why particular materials were used, how the conceptual idea was materialized, what ascriptions applied to particular materials) elicit students' questions while they are initiating science experiments based on the history of science.

This chapter presents approaches by which historical experiments incorporated in science teaching bring about experiences and understanding of the nature of science for learners at differing stages in their education, from grade school to the graduate-level and practicing teachers.

School children build science instruments

Schools, particularly lower secondary schools, normally have no access to historical instruments. In response to this reality, we decided to loan (reconstructed) instruments to teachers for a limited time. After students examined and analysed these instruments, they drew on their findings, the students then build their own version of the instrument and performed experiments with these set-ups. Among the instruments that were built by the students were a camera obscura with a lens and a water prism according to Goethe (for a detailed account see Heering 2015). With the former device, students had two different options available (Figure 1), one large instrument originally built in the Augsburg workshop of Georg Friedrich Brander (1713 – 1783), the other being a much smaller instrument that was based on an instrument that had initially been in the possession of Johann Wolfgang Goethe.

Figure 1: Two reconstructed camera obscura, one from the possession of Goethe (left) and the other from the Brander workshop (right).

Both devices had a lens and a mirror that reflected the image on a horizontal semipermeable glass plate so that the observer saw an upright image. While taking the working principle from these models, students realized that the instrument's dimensions are undetermined. The most important element was to have an adequate ratio between the dimension of the camera and the focal length of the lens that they used. In analysing the instruments, students did not follow a step-by-step method. Rather, to be able to design their own version of the device, students had to understand its working principle. In developing their own analytical questions, as well as in making decisions on how to build their version of the device, students had to be creative. However, the intention of this approach lies not just in the reconstruction; students also should contextualize the instrument they build. Thus, in reflecting about the historical experiment together with the role of the device in that experiment which they also conducted, students are also enabled to reflect explicitly about physics.

From these activities, students realize that people with different skills and backgrounds are involved in scientific progress. In addition to the historical researchers mentioned in textbooks, people from diverse backgrounds, such as instrument makers, contribute to creating new scientific knowledge. While some are part of the academic culture, others are from cultures oriented around mechanical work and physical labor. Students come to understand that people from these different cultures participate in science. Through reconstructing the instruments, materials, experimental uses and principles in these projects, students recognize connections and distinctions between science and technology that figure in NOS studies.

Exchanges with Historical Experimenters and the Incomplete Story

For students' experimenting to be genuine research, they must be at liberty to develop their own questions and strategies. This liberty pertains to the nature of science characteristic that science and its history are not pre-determined and closed to questioning. To engage students with questioning in science, Metz, Klassen et al (2007) authored accessible narratives of historical science which put students in the position of asking questions and making inferences about these stories. In one classroom strategy, termed "interrupted storytelling", teacher narrates a historical science story that poses a predicament. After students predict what may happen next, the teacher resumes the story, introducing further complications. We suggest adapting this approach to historical science experiments, by putting students in positions of developing their own questions about historical experiments. After students investigate, the teacher may narrate further from the historical experiment. As students consider ideas of their own and of historical characters, they reflect on the process of knowledge production in science.

To illustrate this strategy, we relate from three teachers' investigations of prisms, after reading Isaac Newton's letter (1671) on his prism experiments. In analogy to "interrupted storytelling", a follow-up activity could include asking participants to reconsider Newton's letter through their own experimental insights.

After discussing Newton's letter, each teacher took a glass prism (right-angled prisms; 6" long, 2" diagonal) and moved it in direct sunlight. Joy arose as they explored. Broad rainbows appeared on surrounding walls as the teachers rotated prisms (Figure 2, left). Prisms placed upright on the floor were stable but broad rainbows no longer appeared. Instead, narrow rainbows extended out from a prism apex light (Figure 2, middle left).

Figure 2. Left: Broad rainbow in bright patch on ceiling. **Middle Left:** Rainbows in lines exiting apex of upright prism. **Middle:** Multiple hands orient prism and screen. Photo: Arnfinn Christensen. **Middle Right:** Cardboard blocks light. **Right:** Block and two prisms.

Yang was startled by mirror-like behaviour of the prism; upon investigating the mirroring face, she found no light passed through. While Arnfinn employed science terms, "reflection" "refraction", and "total internal reflection"; upon becoming surprised by what the prism did to light, he observed "it is interesting, very complicated. I expected it would be simple." Those science terms were initially meaningless. Through experimenting, teachers gained grounds for meaning; describing the prism's mirror-behavior, its total internal reflection, Yang said "light is trapped".

The teachers questioned: “when do rainbows occur” and “what do light rays do, inside the prism, and coming out?” “Where does the rainbow come from?” “What about an equilateral prism, like Newton’s?” Collaboration arose spontaneously around these questions. Multiple hands positioned prisms and held screens to catch rainbows (Figure 2 middle). Growing awareness of spatial relationships showed as teachers lifted the prism off the floor. Seeking rainbows, the teachers eventually succeeded through re-orienting prisms in sunlight’s path.

Anne Kristine exclaimed “I don’t think Newton wrote down everything he did!”. Devising her own method of blocking light which enters and exits the prism in order to isolate part of a light ray, to investigate its path (Figure 2 middle right), Anne Kristine did not realize her blocking technique provides an analogue to how Newton selectively blocked light with a hole. The teachers introduced multiple prisms into their light paths (Figure 2 right). Excited by how such growing systematism expanded their experimenting, Anne Kristine proposed “we are better than Newton! Now! What would be his answer if we wrote him a letter!”

This session’s end interrupted their own ongoing story and its connection to Newton. The teachers initiated three experimental practices crucial to Newton’s experiment: working out relative orientations of light beam and prism that produce rainbows; devising methods for blocking parts of a beam; and adding another prism to analyze light exiting the first. Encouraged by Newton’s letter without grasping his procedure, and through being open in their own explorations, the teachers came into dialogue with Newton as capable coexperimenters. They experienced for themselves methods and creativity involved in experimenting with, and reasoning about, the lawlike behaviors of optics, aspects which are central in the nature of science.

Explorations with light in response to historical observations and experiments

In cases described above, historical materials are introduced before learners reconstruct instruments and experiments. An alternative strategy, where learners first investigate science phenomena for themselves, is illustrated here by an example from optics. The teacher opens with a question; what students notice, and become curious about, is the source of explorations that they initiate with science materials. Next, students read accounts of historical experiments with the same phenomena. In response to readings, students discuss, experiment, and reflect. Students’ personal experience with the science phenomena is their basis for questioning the historical experiments. Students act on these questions in experiments that they execute. In reflective writing, students’ personal experiences inform insights (excerpts appear below) that relate to the nature of science as elaborated by educators.

During each phase– observation and exploring, reading, discussion, inference, experimenting, and reflective writing — students confront science phenomena that they did not expect, and struggle with passages in historical texts. As students initiate science experiments that originate in their questions, they directly experience NOS methods of science including observation, inference, and interpretation. By doing science personally, and while working with others taking differing experimental paths, students experience first-hand how the process of science is not reducible to inexorable steps. Finding that historical readings carry descriptions and analyses that pertain today, students encounter the durable character of science. Confronting their tentative grasp of science phenomena, students discover that their questions, arising through subjective realization, are their means of building more robust understandings. Just as understanding in science is tentative, so too are the conclusions formed by students. By collaborating with classmates having differing perspectives, students discern diverse aspects of evidence. Students articulate multiple interpretations that facilitate collective questioning and discussions. In reflective writing, students realize themselves as participants in science, where classroom experience promotes understanding the nature of science.

Everyday materials accommodate provocative explorations which are accessible in any classroom. Light has boundless potential for classroom investigation, yet is seldom observed closely. Light, shadows and reflections are evidenced with: daylight, cardboard, mirrors, shiny mylar, paper, tape, string, scissors, and a darkened room. Observations of light occur in diverse ancient cultures, affording multiple entries, examples, and applications of law-like behavior in optics.

Through witnessing properties such as reflection, and working out laws of optics, students encounter the remarkable consistencies of physics. In my (EC) example, light's equal angled reflection figured in diverse settings. Students observed that law in context, not as severed from the world. Recognizing that lawlike behaviors are evident within the natural world is foundational to understanding the nature of science.

An example from a science class illustrates this approach, where students explore mirrors, read about mirrors and their use in ancient times, and discuss, experiments and engage in friendly arguments about things they encountered during this class study.

Students were first asked to explore by working in groups of 2-3 for over half an hour on the question, "where do you have to stand, so as to look in a small mirror taped to the wall and see in it someone standing at a different place from you?" (This activity was inspired by Hawkins 1985; Duckworth 1990; Cavicchi 2009). Provided with tape, a small mirror, and string, groups dispersed. After taping their mirror to a wall, students immediately found it disorienting to position themselves so they could view in it anything specific.

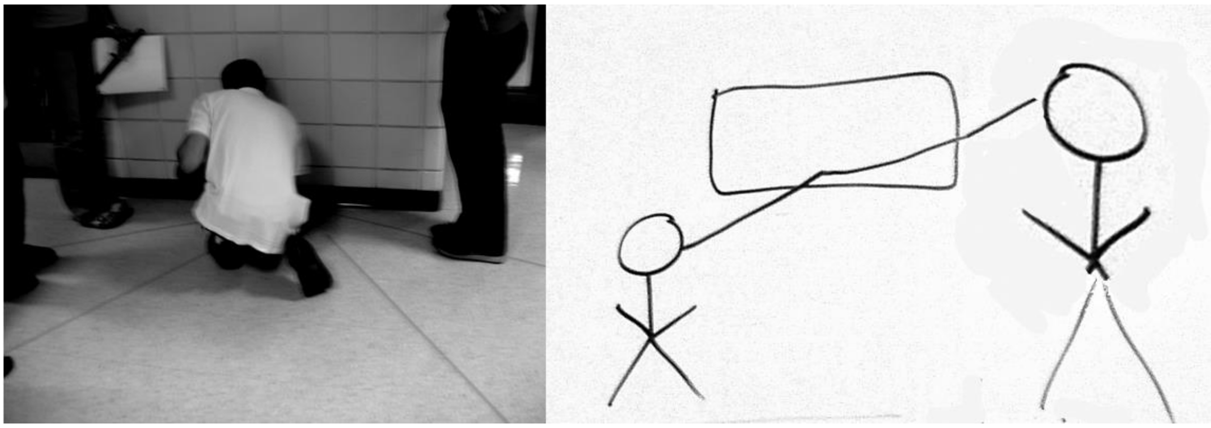

Figure 3. Left: Student Peter Tusi (center) tapes lines on the floor. A mirror is above his head [not shown]. A student walking along the line to his right, while looking in that mirror, sees someone on the line to his left. **Right:** Samantha's drawing depicting herself [left figure] viewing taller Andrew [right figure] in the mirror [rectangle].

We find that confusion, such as about where to position themselves to see something specific in the mirror, intersperses with occasional success, which might first manifest as seeing any recognizable object in the mirror. Having first sighted something seemingly random, by iteratively readjusting position, the student eventually sees the intended target in the mirror. Students express confusion while experimenting; we encourage teachers to support their seemingly divergent conjectures and activities without speaking; to observe without directing; to keep open the space which the students need in order for their thinking and observations to evolve. In doing so, the teacher demonstrates to students, trust in the nature and process of science. That trust of the teacher will make possible trust in the students, who come to form robust understandings about science and realize they are participants in science.

In this example, upon finding arrangements by which two students mutually sighted each other, the student Peter marked those positions on the floor with tape. Eventually, Peter's group taped lines on the floor (Figure 3 left): walking along these lines, a pair of students could see each other in it. These students disagreed about whether the walkers had to be at the same [perpendicular] distance from the mirror, in the same way that scientists would have to interpret evidence.

In the next class, discussion was lively. Lucienne, in Peter's group, said "you could see someone at the same angle as you, you could walk back and forth on that line and still see; distance didn't matter, but angle did." One classmate asked "Can a short person see a tall person?" The class' shortest student, Samantha, who had paired with Andrew, the tallest, drew on the board. Her diagram, with a line bouncing between a tall and short person (Figure 3 right), expressed the law of the mirror in a new context, not yet considered by others. Further discussion raised questions about the image seen in the mirror.

Seeing these questions as productive, the teacher provided students with mirrors again. Improvising, they extended their observations. For example, coming upon the inverted reflections of print, Lucienne exclaimed "It's making me think more than before". This session ended with students listing relevant factors: angles of objects, mirror positions, and heights of observers.

In preparation for the next class, students were asked to read excerpts about optics from ancient classical texts (see Smith 1999 or Kheirandish 1999 for examples) and descriptions of how ancient mirrors were made (Melchoir-Bonnet 1994; Needham and Ling 1962; Pigott 1992). Along with these readings, the assignment asked students to try the classical demonstrations. While historical language baffled some students, others found their way to a plausible interpretation. Composed of short historical readings, this assignment accommodated differing interests and comprehension. Samantha responded to Ptolemy (Figure 4). Lucienne reacted to Roman artisan practice in initiating the class investigation of the size of one's face when viewed at differing distances from a mirror, as described below, after Samantha's personal study.

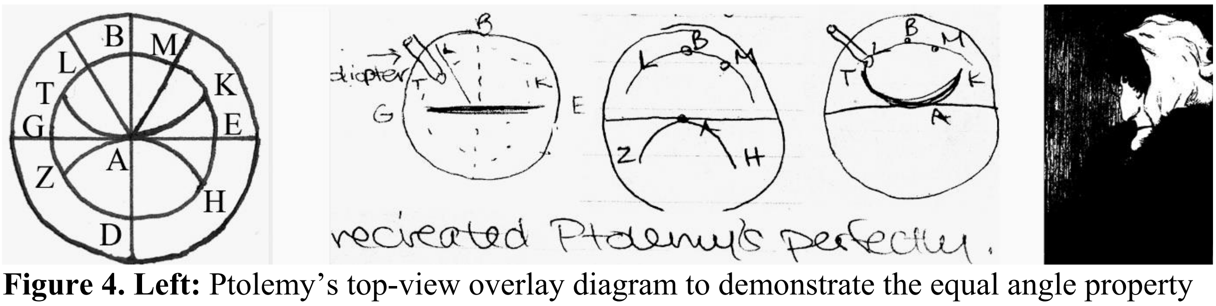

Figure 4. Left: Ptolemy's top-view overlay diagram to demonstrate the equal angle property of a mirror. The observer sights object M looking through movable tube LA at: flat mirror GAE; concave mirror TAK; convex mirror ZAH. **Middle -Next three circles**: Samantha's diagrams apply Ptolemy's demonstration to: flat mirror, convex mirror, and concave mirror

(last circle) (Pitchel 2005). **Right:** The drawing simultaneously portrays a young woman and an old woman (Hill 1915).

With its top-view diagram [Figure 4 left], Ptolemy's demonstration of the equal angle property of reflection as a common property of flat, concave and convex mirrors (Smith 1999) seemed inexplicable to Samantha. In representing all three cases as overlaid on the same diagram, the diagram emphasized the consistency of the law of equal angled reflection for all shapes of mirrors, but it was unserviceable as a guide to conducting the experiment in three dimensions with any one mirror. Thus the paradigm underlying the diagram's construction was disjoint from the outlook of Samantha seeking to perform the experiment. She moved in her thinking so as to reconstruct the experiment and to comprehend the paradigm that the diagram represents. In doing so, she experienced for herself the process by which science expands our understanding by means of multiple concurrent paradigms – in this case coordinating a theory-directed representation with an experimentally-oriented one. Classmate Lucienne described attaining similar reversibility in perspectives through moving out of her "box-like" fixation on the young woman in Hill's cartoon (Figure 4 right), when classmate Devin supported her in tracing its lines to discover the old woman there too.

Samantha started by writing questions about Ptolemy's demonstration:

> [are mirrors] placed flat on ground?
> Leave all three mirrors up simultaneously?
> Or look at the object in each [mirror] one at a time?
> [if] simultaneously—how would you be able to see past first mirror to the other two?
> Exactly how are the mirrors 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 decode his text and "recreate Ptolemy perfectly" in a series of separate setups, one with each shape of mirror (Pitchel 2005, Figure 4 middle). Similarly, teachers in the preceding example did not discern Newton's procedures from his letter, yet they reproduced key components of his experiment.

Samantha could not follow Ptolemy's text literally. By working with her sense of uncertainty and revisiting it on each next failure, she recreated not only arrangements of the mirror and objects, but also the analysis of relationships that underlay the demonstration. Tracing her confusion along the way to reconstructing her interpretation, Samantha's notebook charts her process as an investigator reconstructing methods of science. In reflective writing, 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).

A 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. Lucienne articulated why this historical practice 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)

Jenniemae and Samantha, who tried this exercise at home, reported seeing their body appear further away, but disagreed about its apparent size. In that uncertainty, the teacher perceived a basis for inviting the class to experiment. Imagining that further experimenting carried potential that students might re-examine such assumptions as underlie Lucienne’s response to the Roman mirror, the teacher brought out a notebook-sized mirror and suggested using it in exploring a face’s view.

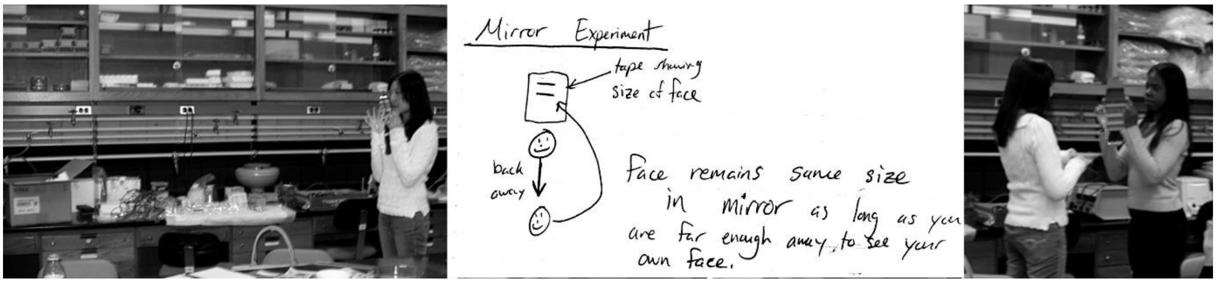

Figure 5. Left: Anna (right) holds the mirror at her face level, while a classmate (not shown) views her face in it while walking left. **Middle:** Peter’s diagram of of tape on the mirror, around upper and lower outlines of the viewer’s head (Tusi 2005). **Right:** Lucienne holds the mirror for Anna (left) who discovers, with the aid of the tape markers, that the size of her face does not change in the mirror reflection she sees.

The experiment began with Anna holding the mirror vertically, at her waist, while others took turns backing off (Figure 5, left). This arrangement proved unworkable. Anna was asked to hold the mirror higher and higher - until it was at the viewer’s face level. Just as Samantha had encountered in responding to Ptolemy, many iterations were required before someone viewed their face throughout their entire displacement backing away from it. Samantha then proposed to put tape on the mirror around the viewer’s face (Figure 5, middle). Now, the persistence students had invested in backing up evenly gave way to astonishment. Having traded roles (Figure 5, left), it was Anna viewing her face in the mirror who first observed and expressed the startling consistency. Speaking at first in tentative disbelief, her conviction grew in spontaneous exclamation:

> My face…It’s weird. It still fits between the lines!

One after another, every student put themselves in the role of being the viewer and witnessing the same outcome. Even Lucienne, upon observing her face in the mirror, now affirmed the opposite of her original claim:

> Yeah. It stays the same.

The concurring observation of each student brought stability and coherence to the surprise that all felt – a surprise that carried awareness of inadequacy in their assumptions about the mirror.

The teacher raised the issue of making measurements. A ruler put to Anna’s head, and to the taped mirror segment, gave almost a ratio of ½. When the teacher asked if the reference point on Anna’s head was the same for taping and measuring, Lucienne averred it was not. Peter astutely expressed the disruptive shift in understanding involved in this experiment:

> …it[face in mirror] 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

Classmates were amazed. Looking at a mirror is not like looking through a picture window. That their own actions were the means of bringing about that disequilibrating and self-correcting realization was significant to the students. It put students in the role of the original investigators, as Anna – discoverer of the reflection's property in this class– expressed in reflective writing:

> Science does not come from textbooks, it is an extension of our inherent curiosity and will to learn…When we are on our own and pondering [our experiments] we are indeed following the footsteps [of historical science] . . . our small, seemingly insignificant comments … in class over…a simple beam of light are important steps in the explorations of science. (Tsui 2005)

Having evolved a new understanding of light through experimenting grounded in her own questions and those of people in history, Anna reflected on what is involved in doing science first-hand. This personal experience grounded her eloquence in describing the nature of science, its methods, use of evidence, and creative insights.

The experience of being shown up, by the outcomes of experiments that he had initiated under expectations that came to be invalidated by his own evidence, was powerful for Peter. In contemplating this experience reflectively, Peter gained for himself the nature of science function of applying science experimenting as a tool in exposing false assumptions and facilitating self-correcting:

> Each unique experiment yielded something new…Some [classmates] … and I myself thought that I knew exactly what would happen. Needless to say… all of us, myself included, were dazzled when experiments had not gone as we had expected… it was the seemingly simple experiments that seemed to stun everyone the most when their basic assumptions proved false….
>
> Working through problems in a systematic way as we did a multitude of times, is an intriguing process… This critical problem solving, and self-correcting capacity is quite a useful tool. (Tusi 2005)

Having taken the risk of disputing the Roman mirror-makers, Lucienne brought herself and classmates into dialogue with nature, where nature's response took the form of evidence, revealed in how "the chips fall down":

> We were [in class] to learn about nature, history, and ourselves…in the most unexpected ways, letting the chips fall down where they may, and, if we could manage to pull ourselves away from the action long enough, note our observations…I felt like we were gaining the skills to be great innovators and investigators of the world around us. (Pierre 2005)

The dissonance between learners' assumptions and historical accounts of experiments, provided openings for investigations initiated through learners' own questioning. Along with unearthing inadequacies in their assumptions, the students developed as practitioners of science, experiencing for themselves the nature of its experimental, theory building, reflective, and humanly interactive character.

At the same time that these students learned how science works and its nature through their first-hand experiments informed by history, they also expanded in awareness of what science is not, so as to recognize that science has limits. At the end of the course, in reflecting on the class' experimenting with the pendulum in response to Galileo's pendulum investigations (see also Cavicchi 2007, 2008, 2011, 2012), Lucienne acknowledged that initially, she had sought to “connect science with spirituality…a pendulum is like karma”. After having done experiments establishing the law associating the length of pendulum string to its period, she no longer regarded pendulums as potentially bearing spirituality; “I don’t know the answer to that question…pendulums are easier to understand than karma” (Pierre 2005). In the particularity of experiments she had formed with string and weights, bearing out the law that Galileo understood, Lucienne came to see science as provisional and dynamic, accessible through sense and reasoning in a community including classmates and scientists across history.

Teaching university students about NOS through historical experiments

Historical experiments are conducted by first year students who intend to be physics teachers at Europa-Universität Flensburg during their compulsory course on history of physics. Here, the students build a gnomon and take measurements with it, work with Galileo’s inclined plane; carry out 18th century electrostatic experiments; and perform electromagnetic experiments inspired by Oersted and Ampère. Likewise, historical experimenting was part of the education for teacher-students at the Carl-von-Ossietzky Universität Oldenburg (Heering 2003, Heering 2009, Riess 1995, Riess 2000). Historical instruments which these teacher students used to experiment include: Coulomb’s electrical torsion balance; Ohm’s electromagnetic torsion balance; magnetic apparatus of Gauss and Weber; Thomas Young’s optical eriometer; and Count Rumford’s experiments on radiant heat. Additionally, these students made experiences with 18th century electrostatic experiments. Before each experiment, students read instructional materials (20 pages) on physics and historical background, with outlines covering advance preparations. The section below details how some experiments relate to understanding the nature of science.

The eriometer (George & Guarino 1973) has simple components: a candle, a screen pierced with one central hole with additional holes circumferentially arranged around the central hole, a device to hold the sample, and a ruler scale (Figure 6). Passing through the central hole, light traverses a sample, such as wool. The (wool) structures diffract light, producing a diffraction pattern observed by the viewer. The size of particles (typically several µm) determines the pattern’s diameter. The distance between the the sample and the screen is adjusted so that the observational angle of the circular ring of holes in the screen corresponds to the one of the (also circular) diffraction pattern. From the distance of the sample to the screen, the diameter of the particles in the sample can be inferred.

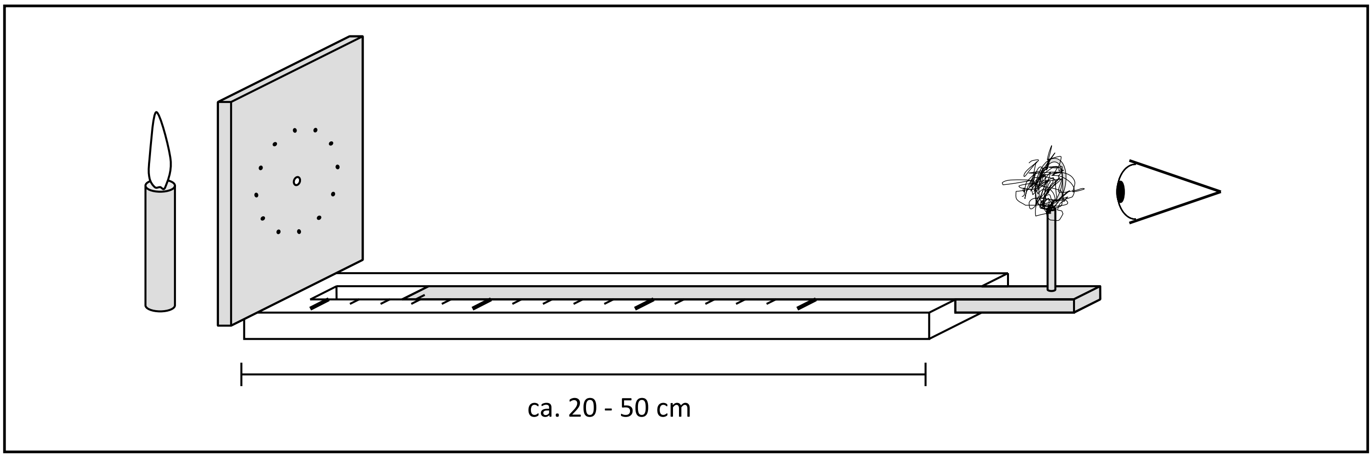

Figure 6. Working principle of the eriometer

Thomas Young published papers on the eriometer, arguing for its applications in medicine and commerce. Neither contemporary scientists nor practitioners adopted it. Such thorough rejection might be attributable to an unreliable instrument. Making measurements with it, students obtained good results. The conceptual basis of the instrument provides clues to its rejection by contemporaries. Only a wave model of light can account for a diffraction pattern. In the early 19th century, Young advocated this theory. Influenced by Newton's particle model of light, the British scientific community dismissed evidence of light as a wave. Young's explanation, and his instrument, were rejected.

This example illustrates how science and technology impact each other and how observations are theory-laden. As is typical for historical experiments, the experiment alone does not yield these insights. Observational experiences with the instrument, combined with historical contextualisation, enable students in forming these NOS understandings. In retrospect, students reflect on their process. Initially, students cannot discern the diffraction patterns. Only through observational practice, and personal experience, do students develop the skills to see these patterns and make measurements. No explanation can short-circuit this process.

Learning to work with an eriometer bears similarities to working with a microscope. Both involve an image which cannot be projected; the image is formed in the observer's eye: one must learn to see the image. Students hardly can learn this NOS aspect through other means than personal experimenting and respective reflection upon processes involved. It is necessary for students to develop skills; students must be afforded time in order to develop those skills.

Under a naïve picture of experimenting, the experimenter approaches apparatus, performs the experiment and produces results. Looking closer at experimental practices (either through practice or based on lab notes) quickly reveals that this image is completely misleading.

This issue of experience also applies to Galileo's inclined plane. When working with this device, students try to determine the position of the rolling ball in equal time intervals. Initially, this is challenging. With practice, students manage, getting reasonable positions for the balls. In discussion with each other, students come to agree that the time intervals are equal – thus it is not an individual confidence that is developed but a collective one as is characteristic of science.

The crown of cups is an electrical device described by Volta, similar to his Voltaic pile. Metallic strips are terminated at one end with copper plate, at the other end with zinc plate. A cup filled with salty water receives one end of the strip, the strip's other end is immersed in the next cup. Cups, connected through metal strips, form a series of galvanic cells (Figure 7).

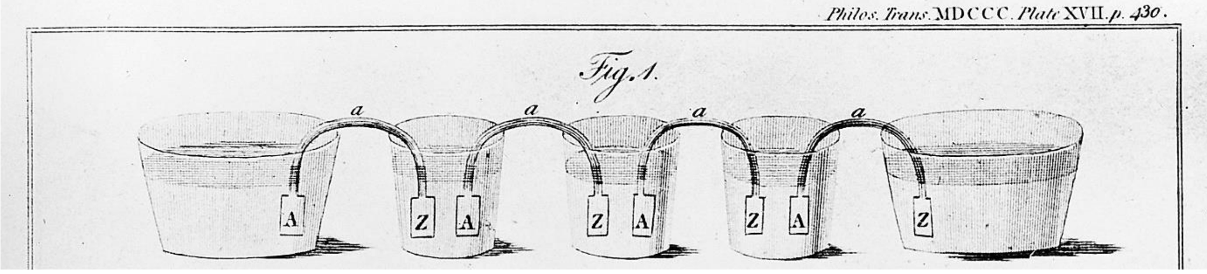

Figure 7. Volta's 'crown of cups' from the Philosophical Transactions in which Volta's letter to Joseph Banks was published. The letter was dated 20 March 1800. Credit: Wellcome Library, London M0014526

Students can “feel” electricity by immersing fingers in cups, closing the electrical circuit. Student experiences differ. Some students are very sensitive to the shock and take only a few cells in series before stopping. At this point, others feel nothing and are able to stand the shock of more cells. Students notice that the human body is not that reliable in making statements about the strength of electricity – at least in making objective statements. Most students claim they have the impression of getting more sensitive in the course of the experience. Yet, what is crucial in these experiences is that practical interaction with the instrument forms a reason for discoursing. In this discoursing about their experiences, students develop insights in the nature of science. Their discussions consider whether this is electricity and how this phenomenon relates to static electricity (where everything has to be kept dry). This makes it evident that definitions in a field are tentative, and that classifications are humanly constructed.

Lab activities based on electromagnetic experiments of Oersted and Ampère provide teacher education students with a different direction. A particular challenge in analysing and describing the interaction between a magnet and a current in a wire (or currents in two wires) is the discussion of the orientation of the wires and the currents, the poles etc. Ampère used spirals and coils to analyse these phenomena, and in doing so he employed an approach that Steinle describes in terms of exploratory experimentation (which is largely unconstrained by theoretical predictions, yet still systematic, see Steinle 2016). At the end, a different type of experimentation is established based significantly on the theoretical understanding that has been developed. In this session students come to understand that there are different ways of experimenting: not only is there no universal method in the sciences; even in experimenting, different methods are employed.

One of us (PH) employs this NOS theme in a course at the Europa-Universität Flensburg that begins with the gnomon, a device originating 3000 years ago. During the last session, students visit a modern research lab with a clean room and helium ion microscope. Experiencing differences between historical and modern experimentation, students realize that scientific methods change over time.

In combining two sessions, one on the electrostatic experiments on discharges (Heering 2000) and the other enabling experiences with the torsion balance, the students immediately realized that the criteria for scientific experimentation change significantly over time. The discharging experiments are qualitative, phenomenon oriented, and address a lay audience. This emphasis on the electrical phenomenon results both in a non-mathematical outcome of the experiments as well as a robustness of the experiments that were performed before audiences, or with audience participation. Coulomb’s experiments are based on precision measurements, consequently the instrument is error-sensitive, which requires the exclusion of audiences. Lay-persons are excluded through the results: a few quantitative data demonstrate a general mathematical relation. In contrasting these experiments, students realize immediately such significant differences as to conclude that there is not one experimental method.

Using the Historical Approach to Encourage Students’ Own Research Projects

Another more individual approach relies on students being able to carry out their own research project. This project could be a BA or MA thesis, or a smaller undertaking. These students try to develop an understanding of how to perform a historical experiment. This understanding relates to scientific and practical components of experimenting, and to historical context. By combining these areas through explicit reflections on their research, students develop understanding in the nature of science.

Graduate student Ruben Holländer carried out a thesis research project on the ignition of liquids through an electrical spark from an 18th century electrostatic generator (Holländer 2017). Typically, the spark from a generator would ignite a liquid such as alcohol kept in a nearby spoon that was electrically grounded. Numerous accounts, including several images, depict this late 1740s experiment. On looking closer at these accounts, it becomes evident that several historical actors encountered difficulties when carrying out this experiment (cf. Heering 2014). These historical difficulties, combined with Holländer’s preliminary experiments in which the liquid did not ignite, made it evident that he needed to investigate this situation systematically. Amongst the challenges he encountered in developing an understanding of the experimental procedures was the elaboration of the exact conditions: Which are the materials, particularly the liquids? Substances such as “Frobenius’s Phlogiston … Peony-water, Daffy’s Elixir, Helvetius’s Stiptic …” (Watson 1746, 489f.) are no longer commonly known. Which conditions are relevant, and how can they be controlled? What about the humidity of the air, the temperature of the liquid, the geometry of the experiment, the amount of electrical charge etc.?

In experimenting on these issues and returning to written sources, Holländer finally gained a coherent understanding of the requirements in order to perform the experiment. Concurrently, he developed an understanding of the interplay between observation, empirical evidence, and rational arguments as well as scepticism. Scepticism became evident, as there were seemingly rules he developed during his study; later, he needed to question and in the end revise, some of these initial rules.

Student Sonja Woltzen analysed Jean Paul Marat’s optical experiments from the early 1780s. Later renowned in the French revolution, Marat was a natural philosopher who tried to modify Newton’s theory of optical dispersion. Since Marat’s experiments were rejected by the Paris Academy Royale des Sciences, historians assumed they were erroneous, Woltzen tried to reproduce the effects Marat described, and eventually succeeded. She was able to interpret the effects in terms of modern optics. Her self-reflections elucidate the relation between theory and experiment:

> “... it is clarified through Marat‘s optical researches that the interpretation of certain observations can be based on various theories and that from isolated experiments the universal validity of a theory cannot be concluded.” (Woltzen 2000, p.157, author’s translation, see Heering 2004).

This reflection demonstrates that Woltzen not only engaged with a historical experiment; her engagement resulted in the formulation of key NOS aspects. Through her study, she explicitly stated that science requires evidence, yet, at the same time, that scientific knowledge is tentative. Her historical analysis on the conflict between Marat and the Paris Academy reflects on social influences that characterize controversy about scientific experiments.

Concluding remarks

We provide examples that demonstrate how the practice of redoing historical experiments in the classroom can involve learners of all ages in coming to grips with the nature of science. Learners' own experiences support them in making such realizations that scientific experimentation is a cultural activity dependent on time and place and shaped by social, philosophical and political factors. Through contextualizing historical experiments, by having students contrast how similar experiments were done in different historical periods, learners come into contact with social and cultural influences on science, and observe how subjectivity functions in the conduct of science. While experiments that originate in history can be demonstrated in decontextualized instructional formats, doing so deprives the experiments of much of their meaning and power to connect with students – particularly with respect to the nature of science.

The activity of experimenting with phenomena, materials, instruments, and cultural perspectives originating in history accommodates diverse and provocative openings to student curiosity and involvement. From these openings, students initiate and create together personal and collective experiences, such as how a class investigation of the size of a face, as viewed in a mirror at any distance, originated in Lucienne's incredulity about Roman mirror artisans' work. Being instigated by students themselves, their experiments pertain to their own questions, assumptions, confusions, and context. Students' experiments produce findings, evidence and outcomes that challenge, surprise and impact their understanding of the science and history that they set out to investigate, and of the nature of learning and science. Having experienced for themselves the tentative, yet durable and self-correcting character of scientific knowledge, the necessity of evidence, and the creativity of scientists (McComas 2016, 1998), students come to value the nature of science. Being empowered to experimental and reflective practice in their classroom and everyday life, students are prepared to extend the footsteps of past experimenters into the unknowns of their future.

Several studies involving historical experiments show their potential in science education explicitly, or suggest historical experiments as an opening for teaching NOS. Chang (2011) is certainly one of the most relevant ones; he considers applying his case studies in electrochemistry and thermodynamics to teaching the nature of science. Eggen and colleagues describe the potential of experimenting with a Voltaic battery (Eggen et al. 2012). While describing many historical optics experiments, Kipnis (1993) did not elaborate on the nature of science; his materials could be adapted in this respect. Höttecke (2000) provides an excellent case study on very early electric motors that can be used in addressing mutual relations among science, and technology and engineering. Höttecke and colleagues (2012) provide substantial proposals on implementing historical experiments in education, particularly addressing nature of science. Teichmann (1999) discusses reconstructing some Galileo experiments in the classroom.

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