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Reworking Recipes and Experiments in the Classroom

Thijs Hagendijk, Peter Heering, Lawrence M. Principe, and Sven Dupré

Introduction

The reworking, reproduction, or re-enactment (RRR) of experiments has a long and rich tradition in the history of science. This methodology has revealed considerable information and insights for historians of science and technology that would otherwise have been unobtainable.[1] Historians of science and technology based in (history of) science and technology museums, use methods of reworking (including the 'restoration of behaviour') to access skills in the production and the use of instruments, tools and technological artefacts.[2] Experimental history of science, as it came to be known, has also been deployed in science education. An influential moment in this regard arrived in the 1990s when a reform of physics teacher training at the University of Oldenburg added a new laboratory course that used replicas of historical scientific instruments. This pedagogical innovation encouraged analogous work with carefully-reconstructed instruments to address historical questions by historians of science, such as Otto Sibum's work with Joule's paddle-wheel device.[3]

Today, historians of science, most prominently Peter Heering and Hasok Chang, continue to re-enact historical experiments as an important element in science education. While Heering has advocated the role of reworking for teaching students about the nature of science, Chang has emphasized the potential of 'complementary experiments' for recovering lost scientific knowledge and for instilling a sense of wonder in students that might attract them to science.[4] Science educators like Elizabeth Cavicchi use comparable approaches to help students develop a better understanding of science and its exploratory nature.[5] As we will briefly discuss below in this chapter, the latter aspect proves highly relevant from the perspective of science education, as recent education policies emphasize the development of concepts about science in addition to scientific content.

More generally, hands-on educational approaches have emerged within the arts and humanities. For example, at the beginning of the twenty-first century the Stanford Humanities Lab developed 'Artereality' as a new model for arts education within the academy. This new model helps shape the pedagogical environment and learning processes in ways that apply to reworking both historical experiments and recipes in the classroom: 'teamwork-based education as a complement to the traditional individualized studio; a scrutiny of process as an essential complement to product; the embrace of project-based and performance-based learning'.[6] Similarly, the use of a hands-on approach in science education, now widely applied at all levels from primary school to university, is based on similar insights about the benefits of learning by doing. However, an important distinction between such hands-on approaches and the use of RRR in the classroom is that the latter adds the historical dimension. The courses discussed in this chapter use historical experiments, recipes, and artefacts, and shows how instructors also benefit from elaborating historical questions in collaboration with students.

Throughout this chapter, we use different RRR-terms for two reasons. In the first place, different terms help us to subtly highlight different aspects of RRR-methodologies. For instance, reworking puts emphasis on the *doing* by endeavoring to access and understand the manual, sensual, and bodily skills of an experiment or process for historical purposes. Reproduction, on the other hand, draws attention to the final products and the means of their production, working to explain the underlying processes or reactions involved as well as the material circumstances that help shape these products. Likewise, reconstruction addresses the process of making a device according to source information; a replica is the outcome of this process. In the second place, RRR-terms are intended to point towards a richer historiographical tradition, and to underscore the crucial place of gaining specifically historical understanding through these practices.

While experimental history of science in its educational dimension has interdisciplinary potential, bridging (what C.P. Snow famously diagnosed as) the gap between the 'Two Cultures,' that is only one of its many benefits. We argue that the use of RRR methods in the classroom also creates fruitful ground for raising new and often unanticipated questions, in both the sciences and the humanities. We discuss here three cases of classroom RRR for contemporary education in science and the history of science and technology: a science teacher training program in Flensburg (Peter Heering), a liberal arts and science program in Utrecht (Thijs Hagendijk) and an interdisciplinary history of science and technology program at Johns Hopkins University in Baltimore (Lawrence Principe and Yulia Frumer). In Flensburg, the study of the nature of science and the reflection upon students' experimental practices are central aims of the science teacher training program. In the other programs as well, classroom RRR serve to teach the exploratory nature of science. As emphasized in the discussion of the courses in Utrecht and Johns Hopkins, they focus attention of students (who have lost the material literacy of previous generations) on materials and the sensory dimensions of experiments. Moreover, the interdisciplinary programs in Utrecht and Baltimore bring methods of the humanities to science students and scientific methods to humanities students through close engagement with material culture, historical texts, and their parallel investigation. Together, the three cases make an argument that the use of RRR methods in the classroom allows teachers to engage students, and to offer students the opportunity to participate in research, here specifically in the history of science.[7]

I. Science teacher training at the Europa-Universität Flensburg

Starting in the mid-1980s, the University of Oldenburg group led by Falk Rieß played a key role in the development of experimental history of science for educational purposes by implementing reconstructed historical experimental set-ups in a compulsory lab course for teacher students in their third or fourth year of study.[8] The experiments included several that used canonical instruments such as Coulomb's torsion balance and Ohm's balance, but also lesser-known devices such as a Gauss-Weber magnetometer and even a device historically rejected – Thomas Young's eriometer.[9] Besides this compulsory course, students had the option of writing a thesis on one experiment or instrument, and the thesis was also an option for students enrolled in a master's program in physics. As a result, a number of instruments were reconstructed and several experiments analyzed using the replication method.[10]

The Oldenburg model has been inspirational for the development of the science teacher training program at the Europa-Universität Flensburg. Here, physics teacher students begin with a module on the history of physics. This compulsory module consists of a seminar on the history of ideas (in which some instruments are demonstrated) and a lab course; the latter consists of five two-hour sessions. Prior to each session, students complete a reading assignment and afterwards write an essay reflecting upon their experiences. In the first session, making devices is the primary topic; each student makes a gnomon and uses it to determine solar noon in Flensburg (which poses an additional challenge considering usual autumn weather conditions). The second addresses Galileo's inclined plane experiment – the students are challenged to determine the movement of a ball rolling down an inclined plane. Here, the students are confronted with the twin challenges of analyzing movement without a proper stopwatch and of measuring length prior to the existence of the meter. The former in particular challenges the students, and in the end they are guided towards using rhythm to determine equal time intervals.[11] The third session deals with eighteenth-century electrical experiments. Here, the interplay between experimental procedures, social settings, and conceptual development are central. Both the lecturer and illustrations from eighteenth-century publications depicting the experimental settings guide the experiments. The fourth

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session deals with Ampère's work in electromagnetism[12] – experiments using coils, spirals, magnets, and batteries are used in order to understand the structure of electromagnetic interactions. In contrast to these experiments (which are *exploratory* in terms of Steinle's analysis), the students watch a video showing Ampère's current balance[13] in order to understand the difference between exploratory and theory-driven experimentation. This part of the course concludes with a visit to a modern lab where the students gain insights into current physics research.

A central aim of this course is to address issues related to the nature of science (NOS).[14] Science educators agree on certain objectives extracted from science standard documents including the following (to name but a few):

- Scientific knowledge relies heavily, but not entirely, on observation, experimental evidence, rational arguments, and scepticism;
- There is no one way to do science (therefore, there is no universal step-by-step scientific method);
- People from all cultures contribute to science;
- New knowledge must be reported clearly and openly;
- Observations are theory-laden;
- Scientific ideas are affected by their social and historical milieu.[15]

The experiments discussed here exemplify such aspects; students are expected to reflect on experimental standards as dependent upon time, place, and (scientific) communities. In so doing they develop the understanding that experiments may have various different purposes and that there is not a single scientific method (or even experimental method). At the same time, they come to understand that experimental evidence is crucial (but not unique) in producing scientific knowledge, that communication plays an important role, and that contributions to science come not only from scholars.

These aspects are relevant (and taken up again) in the course on the nature of science which students take in their fifth semester. This course is aimed at all science teacher students. From the discussions taking place among the students, it is striking that the physics students have a significantly more profound understanding of the relevant concepts. Developing a thorough understanding of the nature of science is fundamental to science education as advocated in the German educational system. Developing competency is a key aspect of education, and such competency is not limited to content: process-based competency is equally relevant. Future science teachers' understandings can be developed through the history of science, and in particular through the reconstruction of instruments and the re-enactment of selected experiments.

This laboratory course is not only about addressing NOS. Students are also confronted with unfamiliar experimental practices and standards, forcing them to think about their own practices and standards and to gain a fresh perception of experiments. The students have the opportunity to write a BA thesis (workload 300h) or MA thesis (workload 600h); one option for these theses is to carry out a study that applies the replication method. To do so, the students either build their own devices and carry out experiments, or use an already existing device and study its experimental practice in more depth. They do not aim to 'check' the initial experimental report. Instead, they try to develop an understanding of the experimental specifics, or try to characterize the device with which they are working by determining the relevance and effect of several parameters that affect the behavior of the device.

From an educational perspective, there are three relevant aspects to such work: First, the students are expected to carry out their research project in order to develop a hands-on understanding of research. This topic was already covered in seminars they took during

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previous semesters, however, it was then dealt with in a mainly theoretical manner. The thesis provides an opportunity to gain insights into inquiry-based learning.

Secondly, the students are enabled to gain insights about the interplay between experimenter, instrument(s), and conceptual understanding. To give but one example: One student concluded in her analysis of Benjamin Thompson, Count Rumford's experiments on radiant heat that 'Rumford's descriptions are formulated so illustratively and comprehensibly that initially I did not think the replication of his experiments would be problematic. A realization that I had to experience over and over again during my study is that becoming familiar experimentally with an apparatus can turn into a time-consuming process. I also initially underestimated the relevance of laboratory conditions'.[16] 'By using the replication method, I frequently had to put myself into a completely foreign way of thinking…'[17] Both aspects are typical for students working with such an approach. On the one hand, they begin to realize where problems can arise only when they are confronted with the task of reconstructing a set-up or of reworking an experiment. On the other hand, it is challenging for them to discuss apparently familiar phenomena in a conceptual manner that differs to their own. This quality is particularly valuable for future science teachers who are frequently in the role to talk to pupils who have different conceptions than the scientific ones; thus being able to argue within a different conceptual frame forms a substantial competence.

However, conceptual understanding and experimental practices are frequently not the only challenges. In addition, the completion of the instruments may cause substantial difficulties. In the case study on Rumford, a substantial challenge turned out to be the completion of a thermoscope. According to Rumford's specifications, the instrument consists of two blackened glass bulbs connected with a U-shaped capillary. A bubble of 'spirit of wine, tinged of a red colour' is to be inserted in the middle of the horizontal part of the capillary, before the capillary is sealed hermetically.[18] Even though the glass of the thermoscope already existed, there were a number of questions to be answered. How did eighteenth-century people tinge spirit of wine red? How does one insert the bubble into the capillary? How does one make sure it is in the middle when the air temperature in the two bulbs is equal? And, how does one seal the capillary hermetically? For questions such as these, the text does not provide answers. Further questions arose only during the practical work, and answers came only practically, some of which could not be adequately verbalized.

In this case study, the student aimed to develop an understanding of the historical practices through the analysis with the replication method. This is not necessarily the case in all studies; others relate more to physics in the modern sense. One thesis analyzed the electrical ignition of liquids, a popular electrical experiment of the mid-eighteenth century. The basis for this study were three letters by William Watson, published in 1746, describing his experiments in some detail. Watson reported that he ignited several substances: 'I have not only fired *Frobenius's* Phlogistion, rectified-spirit and common proof-spirit, but also Sal volatile Oleosum, Spirit of Lavender, dulcified Spirit of Nitre, Peony Water, *Daffy's* Elixir, *Helvetius's* Stiptic, […]'.[19] Watson used a poker connected to the conductor of the electrical generator to ignite the fluids that were held in a spoon, and identified several parameters that he considered crucial for success.

The student undertook a variety of experiments to identify parameters that may affect the outcome: The kind of liquid, its temperature, the amount to be ignited, the discharge voltage, the length of the spark gap, the air pressure and humidity, the form and material of the spoon, and the position of the poker with respect to the spoon. From his experimental analysis, the student identified several criteria that facilitate the ignition of the substance. He reflected upon his research process and wrote that 'all in all, the development of an experimental set-up that combines reliable measurements with reliable spark production turned out to be surprisingly difficult, as shown by the number of failed experimental setups'.[20] Yet, despite these failures, his summary of his work was positive and included

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reflections upon the research process: 'The experimental set-up initially produces unexpected data, yet these data can be explained using recent understandings of physics. In composing this study, it was not only the development of the set-up, but also the performance of the process that provided an idea of how much practical knowledge researchers such as Watson must have developed and which does not appear explicitly in their texts'.[21]

Reconstructing and working with historical instruments provides several learning opportunities. In reflecting their laboratory experiences with the historical set-up, students realize that experimentation is not done by blindly following a protocol but instead is to be understood as as a human activity localized in time and place. This understanding cannot be effectively communicated to students by means of lectures and seminars that address the topic predominantly cerebrally. Being confronted with unfamiliar experimental practices and standards helps students to reflect upon their own understanding and thus gain an awareness that may lead to a different perception of the role of experiments in science. In contrast to modern science experiments (which are not to be confused with teaching lab experiences), students can also reflect on different standards in the historical situation and what these standards mean for their practice – thus on a meta-level, they can reflect about experimentation.[22]

II. Exploring chemistry and art in the Liberal Arts and Science Program in Utrecht

Understanding the nature of experimentation and lab work is also one of the aims of the course *Chemistry and Art* which was offered for the first time in January 2017 at University College Utrecht, a Liberal Arts and Science Program within Utrecht University.[23] Students work with a selection of sixteenth-century recipes for artisanal materials and are asked to transcribe, rework and further investigate them in the laboratory.[24] Reworking early modern recipes not only fosters an interdisciplinary approach, it also turns out to be an excellent starting point for reflecting on the role of interpretation, failure, improvisation, and trial-and-error in laboratory work. After running a successful pilot, the decision was made to continue this course annually.

The course was initially designed as a practical module in which students develop basic laboratory skills, such as working safely, keeping a notebook, and mastering basic lab techniques. The contents came however from the history of art, science and technology, such that the course could be incorporated into an already existing Cultural Heritage Program offered by University College Utrecht. In principle, the course is open to students of all backgrounds, yet the vast majority of students have a background in the sciences, while occasionally an art history student enrolls as well. The course runs full-time for two weeks during which the students rework a selection of different recipes including iron-gall ink, a red brazilwood pigment, imitation pearls, and silver-plated copper. Students visit the Rijksmuseum Research Library in Amsterdam to inspect the early modern sources they work with, and receive lectures and demonstrations by historians, chemists and conservators, who teach them about the boundary between chemistry and art. In the end, students submit concise experimental reports on three different recipes and write an elaborate research report on a recipe of their own choice.

The recipes come from an English translation (1595) of Alessio Piemontese's *De' Secreti* (1555).[25] This book of secrets proved immensely popular in the sixteenth century and contains recipes ranging from alchemy and cooking through medicine to the decorative arts.[26] The book was chosen because it soundly illustrates the intimate connection between alchemy and the arts in the early modern period. It groups together alchemical, medicinal, metallurgical and artisanal recipes, which help students realize that the boundaries between these fields were, and in fact still are, very fluid.[27] This choice was further informed by the fact that the book went through multiple editions and translations, thus enabling students to

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compare recipes in different languages. Comparing translations was no mere luxury; it uncovered incongruities that significantly altered interpretations.

Interdisciplinary and boundary-crossing situations occur at several levels during the course. First, students are confronted with the fluid line between alchemy and the arts, for instance as demonstrated in a recipe for counterfeiting pearls. The recipe instructs the reader to take the shells of white mussels, grind them, and then heat them in a vessel covered with *lutum sapientiae*. The use of *lutum* and the practice of luting were rather common to alchemists. They covered their glassware with specific types of clay to prevent them from cracking when exposed to extreme heat. Students are shown that techniques like luting, but also ingredients such as vitriols or alum, commonly travelled between different workshops, and they are introduced to the idea that alchemy was not a 'dark and occult' occupation, but can also be understood as an archetypical material science.

Second, the luting technique immediately poses a new interdisciplinary problem for the students. Because it would be too dangerous to work with luted vials in an open fire, students are asked instead to carefully consider what happens during this procedure and to start working with the resulting compound. An understanding of modern-day chemistry becomes important. They learn that shells are composed almost entirely of $CaCO_3$. The question remains whether the heat would merely burn off organic contaminations, or whether it would lead to thermal decomposition of the $CaCO_3$ into CaO. It is left to the students to make a chemically-informed decision.

Third, after the students have decided how to substitute their processed shells, they combine the powder with egg yolk to shape the paste into pearls, as instructed by the recipe. To this date however, every attempt to create the much-desired pearls has failed. Disappointed by the results, the students are encouraged to take another look at the recipe and to compare different translations. Doing so, they learn that the English translation 'yelks of egges' is diametrically opposed to an earlier French edition of Piemontese's *Secrets* that prescribes egg white, or la *glaire d'oeuf* instead of yolk.[28] Eventually, most attempts with egg white fail too, but by then, students have already critically compared editions and traced the genealogy of recipes to decide on an interpretation. The ambiguity of recipes or mistranslations thus serves as an invitation to deploy humanistic methods in the laboratory.

The richness of an application of humanistic methods in the laboratory is even more evident when students transcribe their recipes prior to reworking them. To understand and rework a material procedure, they first need to work through typographical peculiarities such as the 'long S', deal with early modern orthography, and learn how to use lexica to understand terms like 'ciche pease' (chick pea). They discover how volumes and weights were measured before the metric system, and how recipes give indications like 'the bignes of a Walnutte'. Finally, they learn how materials were named before the era of IUPAC nomenclature, with examples as 'unsleaked lime' and 'roche alome'.[29] In short, a recipe does not provide clear-cut instructions but requires interpretation. Meanwhile, students learn that familiar and apparent unequivocal chemical concepts and nomenclature are relative and can be historicized.

Transcribing, interpreting, and reworking sixteenth-century recipes thus requires a combination of historical, linguistic, and chemical approaches. After the students have worked with each recipe, they are asked to pick one recipe on which to perform further research. Performing further research on a recipe can be understood as what Hasok Chang has described as 'extension'. He argues that once a historical experiment or procedure has been performed, it is 'difficult to resist the natural curiosity'.[30] In other words: historical recipes not only evoke historical questions, but can also trigger scientific interest and chemical wonder even today. Students are encouraged to use state-of-the-art equipment to find answers to their problems.[31] Sometimes problems lie in observed discrepancies between historical procedures and modern chemical intuition.[32] For example, a recipe to silver-plate copper employing

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common salt, wine lees, alum, water and silver.[33] When the recipe was tried for the first time, it was expected to fail. To silver-plate copper, a redox-reaction has to occur in which the silver must be dissolved first, which is unlikely to happen given the other ingredients. When after a few attempts the copper started to look like silver nonetheless, the question remained how this sixteenth-century recipe was able to get silver in a dissolved state, counterintuitively to modern chemical theory. Several possible explanations can be tested by the students. For example, the mechanism might rely on a natural tarnishing process in which silver reacts with sulphides from the air, prior to the reaction prescribed in the recipe. More than once, the unmistakable smell of rotten eggs was noted, indicating that sulphides were actively involved in the process. Another possibility is that common salt is more corrosive to silver than initially assumed. To date, the definitive mechanism has not been found, but the recipe's ability to puzzle the minds of both chemistry students and experienced chemists alike is fascinating. It demonstrates that it pays to keep an open mind, even when modern chemistry curbs expectations.

Another advantage of this course's RRR-approach is that students learn to work with raw materials and simultaneously learn to rely on their senses for reworking the recipes. They become familiar with historical laboratory practices and modes of chemical experimentation, often characterized by a high degree of sensual experience and practical knowledge.[34] Recent scholarship has for instance emphasized the historically important role that the senses played in the classification and recognition of chemical substances.[35] However, such practical and sensually-rich modes of investigation are no longer obvious for students of chemistry today.[36] In practical training, the importance of the senses is significantly downplayed and substituted by a wide range of analytical equipment. Moreover, materials in the laboratory are often no more than a series of greyish bottles containing extremely purified white powders, and working from predetermined protocol is the rule rather than exception. Indeed, each time students enroll this course, they exhibit an overreliance on text and theory, are easily daunted by failure and have to be pushed to observe more closely what happens to their materials.

An illustrative example of overthinking and overreliance on theory and texts is the following. When the students start working on the recipe for iron-gall ink, they are first asked to transcribe the recipe, do some research, and write a chemical translation that can be taken into the laboratory. All this happens in the lecture room. They receive about two hours for this task, which they spend frantically writing and looking up information on the internet. They usually gather more than enough information to start their practical work. The students are taken to the laboratory, asked to suit up accordingly and start their experiments. What usually happens instead is that they look around for the nearest table, sit down and continue their theoretical discussion, oftentimes not even deigning to look at the raw materials prescribed by their recipes. A major aim during this course is therefore to try to make students stop thinking *about* materials and instead think *with* the materials by engaging with them.[37] The outcome of this approach is illustrated in the following example. Once, after about thirty minutes and two failed attempts at reproducing the pearls from the pearl recipe, one group simply gave up, stating that their protocol obviously did not work. After they were encouraged to forget the protocol for a while and to just continue experimenting, they had fun for another two hours and came up with something that, much to their own surprise, started to look like a pearl. This shows the importance of a creative and improvisational attitude. The students learned that there is no harm in forgetting the protocol for a while, and that much can be learned by simply following the materials. The final results from past courses demonstrate that students start to use their senses in a way they had not been doing before. Their reports contained sentences like this one, which concerns iron-gall ink: 'As a result, a viscous, sticky dark green mixture was created, that smelled like a mixture of vinegar and apple cider'.[38]

The *Chemistry and Art* course illustrates that reworking historical recipes is a valuable tool that help students develop a set of epistemic attitudes that complement the skills taught in

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traditional lab courses. The ambiguity of early modern recipes means that there is no obvious best practice or correct way to solve the puzzle. The course trains students to deal with failure, use trial-and-error, and teaches them to trust not only in theories, but also in materials and their own senses. Moreover, these centuries-old recipes quite naturally invoke interdisciplinary approaches. Working these recipes successfully encourages students to integrate scientific reasoning with humanistic methods, and to bridge the 'Two Cultures' as defined by C.P. Snow.[39]

III. Thinking through things for historians of science at Johns Hopkins University

Similar to the *Chemistry and Art* course at Utrecht University College, exposing students to the sensory experiences of materials is one of the central aims of courses taught at Johns Hopkins University. However, these courses further demonstrate the utility of reworking experiments for students in the humanities as well as for those in the sciences. The reproduction of experiments and the engagement with material objects has been used, for example, to supplement the traditionally lecture-based history of science surveys for undergraduates. In addition, two recent upper-level courses – *Thinking Through Things and Thinking Things Through* (designed and taught by Professor Yulia Frumer) and *Practical History of Science* (Professor Lawrence Principe) – involved a wide range of practical engagement with objects, historical artifacts, and experimental reproductions. The subject areas of these interactions ranged from physics and astronomy to chemistry and technology, and in time period from Late Antiquity to the twentieth century.

Some exercises were intended simply to expose students to the sensual experience of materials and objects. Today's students increasingly lack the direct experiences that were normal and expected for students of previous generations. The current world of the computer and the recent, and ill-advised, substitution of 'virtual' simulations for traditional laboratory, anatomy, and other training experiences, has led to this state of affairs. The unfortunate result is that today's students are increasingly separated from meaningful direct contact with real material world, do not develop adequate manual skills (except perhaps for pressing buttons on a portable device), and are thus disabled from coming to understand the observations and thoughts of those authors and workers who *did* engage directly with materials on a daily basis.

One of the professors (Principe) found that even advanced chemistry students had no concept or experience of the natural origins of metals, salts, and other chemical substances. Students were initially befuddled, for example, as to why early workers would have thought to put one stone rather than another into a fire (thus discovering how to extract metals). But after having actually handled chunks of metallic ores, they understood sensually, based on the striking colour, density, gleam, and other features of these minerals, why attention was fixed on these stones rather than on other, less unusual ones. In another exercise, students were given an array of different salts – all of them white, crystalline substances and thus indistinguishable by sight alone – and asked to identify them using the type of fire tests (i.e. throwing them on burning coals) described by the ninth-century Persian author al-Rāzī and other medieval authors. This experiment underscored the difficulties and ambiguities that premodern workers faced in classifying and identifying individual chemical substances (before the time reliable materials arrived in neatly-labelled bottles) and taught them the properties of several of these substances. Such work drove home the crucial role of the senses in scientific endeavors, and the value for historians in re-accessing some portion of that sensual experience in order better to understand the historical actors and their thinking.

Other exercises dealt with the role of instruments and the engagement with technological materials. Students explored, for example, the inherent difficulties of visual perception and discovery by using inexpensive telescopes of approximately the quality and magnification of Galileo's first instruments, and this hands-on experience occurred alongside their more traditional reading of Galileo's 1610 *Sidereus nuncius* that announced and described his telescopic discoveries.[40] They were thus able to read Galileo's descriptions (which of course embody his interpretations) in parallel with seeing for themselves approximately what he and his contemporaneous readers saw. Weather and celestial positions permitting, students were able to watch the nightly movements of Jupiter's moons (the Galilean satellites), see the phases of Venus, and observe the surface of the moon at different phases, and compare their own observations with the way Galileo described his. One aspect that students found particularly instructive was their encounter with the same sort of unexpected difficulties faced by early observers, such as how to find objects in the telescope, where exactly to position one's eye for observations, how to keep the instrument steady and focused long enough to make reliable observations, and most of all, how to interpret what they were seeing. Whereas modern accounts of telescopic observations elide the initial difficulty of using the instrument, through this exercise students came to understand some of the difficulties and uncertainties encountered by early observers at the start of the seventeenth century when faced with using this new instrument of vision. Some students noted how, when looking at a distant street light through a telescope with poor optics, a series of smaller, weaker spots of light sometimes appeared on both sides of the light, initially similar in appearance to the moons seen around Jupiter. With this observation, they were better able to understand the claims by some of Galileo's critics that the tiny 'stars' he saw around Jupiter, and which he interpreted as orbiting satellites, were actually optical artifacts of the instrument. This realization in turn explained why Galileo spent so much of the *Sidereus nuncius* (seemingly *too much* from a modern perspective) displaying the regular and changing movements of those 'stars' from night to night.

Both graduate and undergraduate students also worked with astrolabes (in simple cardboard format), using them as observing devices for surveying, astronomical measurements, and time-reckoning as well as calculating devices for predicting the rising and setting times of the Sun and stars. Some students in the *Thinking Through Things* course engaged in the process of 'making' by building their own scientific instruments using contemporaneous descriptions and depictions, such as the single bead-lens microscope devised by Antoni van Leeuwenhoek in the 1670s. This endeavor required them to deal not only with constructing a technological device from written descriptions, but also in acquiring, shaping, and engaging with the necessary materials, in this case, brass, steel, and glass.

The *making* of objects and materials was also inverted in order to study *already-made* technological artifacts. The goal was to tease out the manufacturing or technological know-how embodied in them, as well as to consider their original use and impact on users. Thus, students in the *Thinking Through Things* course had the opportunity to study and inspect an original and functioning 1918 Model T Ford touring car. They identified physical traces of its method of production, after having read about Ford's moving assembly line.[41] They were asked to put themselves in the position of the original owners and operators, to think about using the automobile and consider what drivers and passengers had to know, do, and encounter in order to operate and maintain it. The presence of the physical object itself inspired many questions that would never have been thought of otherwise. Without gauges how did drivers know how much gasoline was left? How many gas stations were there in 1918 and how could you be sure of finding one? Why is there no door for the driver's seat? After actually feeling the physical strength and technique required to pull the crank in order to start the engine, students wondered what less robust people could do if they wanted to drive. One student observed that several normal tasks (like raising and lowering the top, or starting the car when cold) generally required two people working together, and therefore cooperation between driver and passenger must have been essential at times. In this way, they explored questions of how human beings use, interact with, are changed by, and come to accommodate a complex, life-changing, and originally revolutionary technology.

Some revealing results for both students and professor came from the reproduction of Robert Boyle's famous 1661 experiment on the 'reintegration' of saltpeter (potassium nitrate).[42] This process was performed as a demonstration before the *Practical History of Science* seminar, after the students had read and discussed Boyle's essay. Because Boyle's main purpose in writing his *Essay on Salt-Petre* was to call attention to the variety and changes of observable qualities in chemical processes (thus undermining the Aristotelian concept of substantial form), this experiment was especially valuable as a reconstruction since it exposed students directly to those observables. In the experiment, small pieces of ignited charcoal are dropped sequentially into a crucible of molten potassium nitrate. The mixture deflagrates violently with each addition until all the potassium nitrate has reacted, leaving behind a residue of 'fixed niter' (potassium carbonate). The slow, dropwise addition of spirit of niter (nitric acid) to this residue produces vigorous effervescence and mild heat – which can be heard and felt – at the end of which time 'regenerated' nitre crystallizes out of solution. In this case, the professor had not himself done this experiment nor practiced it prior to doing it with the seminar students, which led to a learning experience for all involved. In particular, the professor (who had assigned Boyle's essay to classes for many years) had long puzzled over Boyle's claim that the 'fix'd Niter' left in the crucible 'was of a deep colour betwixt blew and green' since the product to be expected from modern chemical knowledge, potassium carbonate, should be white.[43] Nevertheless, he was very surprised to find that Boyle's experiment, conducted as described, did in fact yield a deep turquoise-coloured product. (He was inspired thereafter to conduct further experiments that identified the source of this colour as trace amounts of iron present naturally the wood from which the charcoal had been made.) One student who was not experienced in chemical operations reflected that he was surprised, confused, and slightly frustrated by the implicit choices the professor made spontaneously during the demonstration – how much heat to apply to melt the niter, what size pieces of charcoal to add, when to conclude that the experiment was finished, how quickly to add the spirit of niter, as well as how exactly to manipulate the tongs, crucible, burner, and other tools necessary for the operation. His observations revealed more vividly (even to the professor) the depth and variety of unarticulated experiential knowledge an experimenter brings implicitly and unconsciously to any experiment, and also the various forms that such knowledge takes.

These courses at Johns Hopkins make a special point of bringing together both textual sources and experimental reconstruction or the direct engagement with objects. The purpose here is to ensure that the exposure to the sensual experiences is clearly directed towards gaining a deeper understanding of historical texts, in short, to set up a dialogue between text and object or experience.[44] The greatest benefit of reworking experiments for students of history accrues when historical questions spur the engagement with materials, processes, and objects and when such engagement answers historical questions and proposes new questions for consideration.

Conclusion

Why is it important to bring RRR approaches to the classroom? The cases discussed above show that engaging with historical instruments, materials and recipes allows teachers and students to address interdisciplinary questions and to activate different epistemic attitudes in the classroom. Still, bridging the gap between the 'Two Cultures' and the creation of an interdisciplinary learning environment in which science students are exposed to humanities questions, and vice-versa, while a valuable side-product, is only one of the goals. Why then should science students be introduced to the vivid sensual experiences of past materials, instruments and experiments? What is the added value of exposing students to the reworking of historical experiments and recipes? In this chapter we have argued that the pedagogical benefits of the use of RRR methods in the classroom are twofold.

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First of all, reworking experiments in the classroom is a powerful methodological tool to make science students reflect on the connection between the past and the present and to gain insights in their own laboratory work. One of the most important aims of courses in both Flensburg and Utrecht is to teach science students about the nature of experimental science. Explicit reflection on the experiences and the difficulties encountered in reworking a historical experiment on the basis of a text, such as a recipe from the past or historical experimental account, confronts science students with the intricacies of interpretation typical of approaches in the humanities, allowing them to question the protocol-like nature of experimental science as it is now often taught.

Yet a further innovative power of RRR approaches in the classroom is to create collaborative learning environments in which teachers learn together and alongside their students. In such a setting, teaching is not only research-driven, as one would expect in a university classroom, but research in the history of science and technology is also nurtured by teaching. Teachers learn about past historical practices of science from the inquiries of their students as students learn from their teachers. The use of RRR in the classroom is not unique in this regard, but the reworking of historical experiments and recipes creates a classroom setting which seems particularly apt in this regard. We have seen examples in which students reworking historical recipes are confronted with questions in science which for their teachers are also new and often unanticipated. Curiosity can be tremendously contagious if teachers are as interested in – or surprised by – the outcomes of an experiment as students. These reworkings of experiments and recipes are instantiations of the ‘extensions’ and ‘complementary experiments’, of which (as we have discussed in the introduction) Hasok Chang has argued for the usefulness to science students. However, as especially the pedagogical experience at Johns Hopkins University shows, this is equally true for students in humanities classes. Students’ inquisitive questioning of the teachers’ experimental skill and knowledge can help to make them articulate and address the historical questions which for the historians of science and technology teaching the class were the point of departure for reproducing the experiment. Thus, reworking experiments and recipes in the classroom allows teachers to engage students in their research, and to offer students the opportunity to participate in research in the history of science. Students and teachers become co-producers of knowledge, especially regarding the historical practices of science.

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Endnotes

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[1] See Fors et al., ‘From the Library to the Laboratory’ and the introduction to this volume.

[2] Boone et al., ‘Histories of Use and Tacit Skills’.

[3] Sibum, ‘Mechanical Value of Heat’.

[4] Heering,’Historical Approaches’; Chang, ‘Historical Experiments’.

[5] Cavicchi, ‘Historical Experiments’; Cavicchi, ‘Learning Science as Explorers’.

[6] Schnapp and Shanks, ‘Artereality’, p. 143.

[7] This is, of course, not unique to history of science; compare Ingold, ‘The 4A’s’.

[8] See Heering, ‘Approaches’; Rieß, ‘Short History’. Other approaches include: Devons and Hartmann, ‘History-of-Physics Laboratory’; Hartmann Hoddeson, ‘Pilot experience’; Kipnis, ‘Rediscovering Optics’; Chang, ‘How Historical Experiments’; Chang, ‘What History Tells Us’.

[9] For a discussion of the instruments and experiments used, see Rieß, ‘Teaching Science’; Heering, ‘Role of Experiments’. The magnetometer allows the determination of the Earth’s magnetic field in absolute measures, the eriometer measures the diameter of a sample of small objects through analyzing the produced diffraction patterns.

[10] For the results of some case studies, see e.g. Beneken, ‘Robison’; Frercks, ‘Fizeau’; Lühr, ‘Ampere’; Nawrath, ‘Newton’, or Voskuhl, ‘Herschel’. In the evolvement of the program, the methodological approach developed further and at the same time theoretically reflected. Relevant publications in the latter respect are Heering ‘Grundgesetz’, Sichau ‘Replikationsmethode’, and Frercks ‘Forschungspraxis’ who developed a somewhat different notion that is not the basis of this discussion. The most recent approach in this respect was carried out in collaboration with colleagues from Jena, see Breidbach et al. ‘Experimentelle Wissenschaftsgeschichte’.

[11] This approach is a modification of the interpretation provided by Drake, ‘Renaissance Music’.

[12] This session is structured according to Steinle’s analysis of Ampère’s experiments, see Steinle, ‘Exploratory Experiments’.

[13] This video can be found at https://youtu.be/_qw5FHjmZY8. Checked on November 12th, 2018.

[14] NOS is a construct that has become relevant in science education for the last three decades, see Allchin, ‘Teaching’; Lederman, ‘Nature of Science’, and McComas, ‘Nature of Science’.

[15] These objectives are part of a list published by McComas, Clough and Almazroa, see McComas, ‘Nature of Science’, p. 6f. See also Lederman et al., ‘Views’.

[16] Mercier, ‘Rumford’, p. 89.

[17] Mercier, ‘Rumford’, p. 90.

[18] Rumford, ‘Enquiry’, p. 101.

[19] Watson, ‘Experiments’, p. 19f. Watson stressed that the spark ignitess the vapours of the liquids, not the liquids themselves. One challenge in the case study lay in identifying these [which? Does not follow logically from the first sentence of the note] (now unusual) names.

[20] Holländer, ‘Entzündung’, p. 41.

[21] Holländer, ‘Entzündung’, p. 41. Holländer uses the term ‘ Handlungswissen’, which I translate as practical knowledge – it is not clear from the context which epistemological concept he is addressing in this comment.

[22] Just to clarify: This is a discussion of a program for teacher students, not within a history, philosophy, or sociology program.

[23] Developed in collaboration with Gert Jan Vroege (Utrecht University) and Dominique Thies-Weesie (Utrecht University).

[24] Comparable courses (but with a different student audience drawn primarily from graduate studies in the humanities) are offered by the Making and Knowing Project at Columbia University, New York. See: Bilak, ‘The Making and Knowing Project’.

[25] Piemontese, *The Secrets*.

[26] Eamon, *Science and the Secrets of Nature*.

[27] Dupré, *Laboratories of Art.*

[28] Piemontese, *Les Secrets*, pp. 817-818; Piemontese, *The Secrets*, p. 252.

[29] Piemontese, *The Secrets*, pp. 58-59.

[30] Chang, ‘Historical Experiments’, p. 320.

[31] E.g. (electron) microscopy, UV-vis spectroscopy, pH-instruments, rheometers.

[32] Principe, ‘Chemical Translation’.

[33] Piemontese, *The Secrets*, p. 246.

[34] Principe, *Secrets of Alchemy*, p. 208.

[35] Ragland, ‘Chymistry and Taste’; Tillman Taape, ‘Distilling Reliable Remedies’.

[36] Chang, ‘What History Tells Us’.

[37] Ingold, ‘Materials against Materiality’; ‘The Textility of Making’.

[38] Patricia Jäger and Sebastiaan Berschoor Plug, ‘Recreation of an Ink Recipe by Alexis of Piemont’. Report written for *Chemistry and Art*, University College Utrecht, Summer 2016-2017.

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[39] Snow, *Two Cultures*.
[40] Galileo Galilei, *Sidereus Nuncius*, trans. by Albert van Helden (Chicago: University of Chicago Press, 2016).
[41] Mahoney, ‘Reading a Machine’. The course title is a tribute to the late Prof. Mahoney, who taught a graduate seminar by this title at Princeton.
[42] Boyle, ‘A Physico-chymical Essay’.
[43] Boyle, ‘A Physico-chymical Essay’, p. 96.
[44] See Fors et al., ‘From the Library to the Laboratory’.