transversal
International Journal for the Historiography of Science

Transversal: International Journal for the Historiography of Science 2018 (5): 34-48
ISSN 2526-2270
www.historiographyofscience.org
Belo Horizonte – MG / Brazil

IDTC Dossier
Methods and Cognitive Modelling in the History and Philosophy of Science–&–Education

Representing in the Student Laboratory

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Abstract:

In this essay, I will expand the philosophical discussion about the representational practice in science to examine its role in science education through four case studies. The cases are of what I call 'educational laboratory experiments' (ELEs), performative models used representationally by students to come to a better understanding of theoretical knowledge of a scientific discipline. The studies help to demonstrate some idiosyncratic features of representational practices in science education, most importantly a lack of novelty and discovery built into the ELEs as their methodology is solidified when it becomes a widely spread educational tool within a discipline. There is thus an irreducible role for the historical development of ELEs in understanding their representational nature and use. The important role of the historical development of ELEs leads to an interesting way that educators can use ELEs as a means of connecting students to important historical developments within their disciplines.

Keywords: Models; Representation; Educational laboratory experiments; Science education

Received: 25 January 2018. Reviewed 10 September 2018. Accepted: 27 September 2018.
DOI: http://dx.doi.org/10.24117/2526-2270.2018.i5.05

Introduction

As numerous investigations have revealed, the representational practices of science are numerous, wide-reaching, complex, and varied.[2] Some philosophical studies of this complex practice have been made by examining different sorts of representational vehicles, including models (Morgan and Morrison 1999; Knuuttila 2005, 2011; Bailer-Jones 2003; Mäki 2009;

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[2] For an overview of philosophical literature on scientific representation, see (Boesch 2015; Frigg and Nguyen 2016; Suárez 2015).

Weisberg 2007; Godfrey-Smith 2006) and diagrams (Woody 2004; Perini 2005a, 2005b; Sheredos et al. 2013), among others. Other philosophical studies have offered a general theory of the nature of representation in science – whether that theory be what Anjan Chakravartty (Chakravartty 2010) calls an informational account (Van Fraassen 1980; Giere 1988; French and Ladyman 1999; French 2003; Bueno and French 2011) or a functional account (Boesch 2017b; French 2003; Giere 2010; Hughes 1997; Suárez 2004; Van Fraassen 2008).

Most of the aforementioned studies of scientific representation and its vehicles have focused on the nature, use, and role of scientific representation and representational vehicles in the scientific research conducted by experts. While such studies are doubtlessly informative, they ignore an important part of the practice of science – namely, science education. Indeed, some views of the nature of skills within action theory lend hand to the idea that a study of educational contexts of skill transmittance will provide a useful window into expertise (Small 2014). Regardless of whether such a view of skills is correct, it is true that science education is an important part of scientific practice which influences and informs the work that scientists do for the remainder of their careers. It is of interest to spend some time exploring the representational practices found within science education.

In this essay, I will explore one form of representational activity conducted by students: what I shall call 'educational laboratory experiments' (ELEs). I begin by identifying and describing an ELE from each of four major scientific disciplines (biology, physics, chemistry, and economics). These case studies help to expand our understanding of representational practice in science by exploring a novel form of representational vehicles in a context which has not yet been thoroughly explored by philosophers-science education. After describing the cases and their historical development, I will show that ELEs have some unique representational features which do not hold of other forms of representational vehicles (e.g. models). Most important among these features is a lack of novelty and discovery built into the ELEs as their methodology is solidified when it becomes a widely spread educational tool within a discipline. There is thus an irreducible role for the historical development of ELEs in understanding their representational nature and use. The centrality of the historical development of ELEs provides an interesting way in which instructors can help students to connect to important historical developments within their disciplines.

Educational Laboratory Experiments

Representational vehicles are most commonly explored in the context of scientific research – i.e. in the use of representational vehicles by experts as applied to novel contexts with the ultimate aim of developing a new explanation, some new knowledge, to make a novel prediction, and so on. However, there are other areas of science in which representational vehicles are also used –policy-making, science communication, science funding, and so on. For example, Kevin Elliott and Daniel McKaughan (2014) have an interesting discussion of the nonepistemic aims of scientific representations as they are used in wetland-loss mitigation efforts. One area which has been underexplored (at least among philosophers of science) is the use of representational vehicles within science education (Stoeltzner 2012). There are two primary reasons why greater attention to the use of representations in science education would be of value in increasing our philosophical understanding of the nature and role of representation in science.

First, science education is the means by which scientific researchers became scientists in the first place. It, therefore, constitutes a significant part of how scientists experience and understand their practice. So, to understand how scientists are using representations in cutting-edge research (as well as for other purposes), it will be of use to consider how students of science are taught to represent. What are the elements of the representational vehicles they use? What skills are they being taught? While a study of representation in science education will not result in a *complete* understanding of representation in scientific research, it will still provide insights into some of the elements of the representational practice which informs scientific research.

Second, there is an additional point of connection between scientific research and science education. Textbooks and laboratory manuals are, on the whole, written by scientists with doctoral degrees, i.e. scientific researchers (or at least former researchers). Undergraduate courses and laboratories are, on the whole, taught by scientists with doctoral degrees (or those on their way to having doctoral degrees). Thus, in coming to understand science in the context of education, we can come to understand how scientists themselves conceive of their practice seen in the way they share and transmit that practice with others. Of course, there is the stereotype of the professor about whom students say that she or he 'is a brilliant scientist, but a horrible teacher'. We cannot, therefore, assume that each and every science classroom and laboratory will be useful as a means of gaining insights into how scientists conceive of their practice and communicate it successfully to their students. But nonetheless, generically speaking, we can approach the classroom and laboratory settings as contexts in which scientists are teaching students to do as they do and in which they are imparting the knowledge and skills that they themselves have come to develop. In short, scientific education is the context in which scientists initiate others into the broader scientific practice and help them to become scientists themselves.

There is also some evidence, coming from the philosophy of action, that science education is a meaningful means of coming to understand the sorts of skills found in a practice. Will Small (Small 2014) offers just such a view of the nature of skills which begins by focusing on a central idea which is "plain to us in ordinary life": (Small 2014, 88) that skills are transmitted through teaching and learning; that skill transmittance and acquisition (i.e., teaching and learning) are deeply tied to (and not separated from) a skill itself. Skills, on Small's Aristotelian account, are rational practical capacities which have a 'life cycle' of three stages: learning, practicing, and teaching (Small 2014, 102-5). The acquired skill is the same exact skill practiced by experts and transmitted to others. On Small's view, a complete understanding of the nature of skills will require that we pay attention not *only* to expert practice, but also to the ways in which skills are transmitted and acquired, since these are part of the 'life cycle' of a skill. Put more plainly: philosophers would do well, when aiming to understand a practice in science, to attend not only to the contexts of expertise, but also to the educational contexts in which skills are transmitted from experts to novices.

In this paper, I will explore the teaching and learning of some skills associated with the practice of scientific representation, as found in the undergraduate student laboratory. To do so, I will examine several case studies of the representational uses of laboratory experiments. The choice of an investigation of the laboratory is driven primarily by the fact that, for the most part and contrary to the typical undergraduate lecture hall or classroom where the educational aims are typically related to the direct transference of disciplinary knowledge, the undergraduate laboratory aims primarily at imparting *practical* knowledge: e.g. to learn the method of scientific inquiry, to develop particular disciplinary techniques (e.g. measurement, gas chromatography, etc.), and so on. To put it in a pithy slogan, we might say that, for the most part, while the science classroom aims at leading students to *think* as scientists think, the laboratory is aimed at guiding students to *do* as scientists do. If, as many have suggested, scientific representation is grounded in action (Boesch 2017b; Giere 2010; Hughes 1997; Suárez 2004; Van Fraassen 2008), then it will be of use to study the ways that students are practically taught to use representations, developing skills and expertise. Thus, the practical orientation of the student laboratory provides an important access point into the practice of representation within science. In particular, I will examine what I shall call "educational laboratory experiments" (ELEs, for short). ELEs are constructed and performed primarily for the sake of an increase in knowledge (both practical and theoretical). Though they involve many of the features typically found in experimentation –data collection, variable control and manipulation, hypothesis testing, statistical analysis, etc. – I shall argue that they also contain an important representational component.

Four Cases of ELEs

I will now turn to examine four examples of ELEs, each drawn from a different discipline. In each case, I will describe three parts of the ELE: the background, methodology, and evaluation. The background includes an overview of the theoretical knowledge which the ELE represents. The methodology describes the steps that students take when they perform an ELE. The evaluation describes the way in which instructors measure the success of the ELE in terms of learning outcomes in the students. Throughout each case, I will also aim to offer an overview of the historical development of the ELE, including an account of how its methodology became standardized over time.

Marbles and Genetic Drift (Biology)

Genetic drift is the change in the allelic frequencies of a population due to random effects. Since there is an important stochastic element to reproduction and survival, any given population is likely to differ, at least slightly, in allelic frequency from that of its parent generation. In some cases, these random changes can accumulate and permanently alter the allelic make-up of a population, sometimes leading to sufficient genetic and phenotypic differences so as to cause speciation, i.e. the development of a new species. Genetic drift is more likely to lead to such changes when the given population is small, since a small population increases the likelihood that random effects will accrue over time.

Genetic drift is better understood through a well-known analogy to random draw from a jar of marbles. Imagine that we have a jar full of ten red and ten blue marbles. If we select only eight of those marbles, there is a decent chance that the frequency of the colors in our sample will not match the frequency of the colors of the marbles in the original jar. If we change the distribution of marbles in the jar to match the frequency of colors in our sample and draw a second time, we might find that the sample, once again, fails to match the distribution of the jar. Depending on the color frequency of the sample, changing the jar's distribution of colors a second time might move the relative frequencies back towards an equal number or may enhance a shift towards a higher frequency of one color over the other. Over time, this may lead to a population which has only red or only blue marbles. The analogy to genetic drift is fairly clear: the different colors represent the different alleles of a population. Through random chance, one allele may be more highly represented in later generations. Over time, these changes can accumulate, leading to the fixation of whatever allele remains.

The original analogy between genetic drift and marble drawing goes back to Dubinin and Romaschoff (Dubinin and Romaschoff 1932), as described by Theodosius Dobzhansky in his *Genetics and the Origin of the Species* (Dobzhansky 1937, 142). A few decades after the introduction of the analogy, several authors described the value of using the analogy as a model in classroom lectures, either as a thought experiment or lecture demonstration (Bonnier 1947; House 1953; Johnson 1958; P. Moody 1952; P. A. Moody 1947). In 1971, Jamie Thomerson proposed that the analogy be turned into an experiment to be performed by students, rather than just an analogy or thought experiment present in the text or a demonstration conducted in front of students. In an acknowledgment, Thomerson says that he "first became aware of this kind of simulation experiment in a population-genetics course under E. Peter Volpe of Tulane University" (Thomerson 1971, 45). His acknowledgment suggests that the experiment was at least somewhat widespread by the 1960s, since Thomerson performed his graduate studies at Tulane University from 1961-1965 (Keevin, Nico, and Taphorn 2015, 1096–97). As an experiment to be performed by students, it quickly became widespread. Since the 1990s, it has been a relatively standard experiment within high school and undergraduate biological laboratories (McComas 1994; Froehlich and London 1996). Presently, it can be found easily online, oftentimes with an outline of instructions, guided questions, and suggestions for forms of evaluation on the part of instructors. While some of the details may change (for example, Nancy Staub (Staub 2002) suggests using chocolate candies instead of marbles or beads), the general methodology remains more-or-less the same.

The ELE, whether conducted with marbles or chocolate candies follows the conditions of the analogy I described above. The difference is that in this case, students are practically engaged in performing the actions described, rather than merely imagining them. That is to say that they actually engage in drawing marbles, measuring frequencies, recording changes, altering the distributions of the jar over time, performing statistical analyses, and so on. Typically, students are asked to perform the experiment multiple times, using variable starting frequencies among the colors of the marbles, quantity selected in each draw, total number of marbles, and total number of colors. Students are also asked to compare their results to others to help make salient that their results are stochastic. Oftentimes, the experiment is tied together with other similar experiments, like having different sized marbles and therefore a different variable selection rate which can be used to demonstrate the effects of natural selection.

Of course, students conducting this ELE are encouraged to draw conclusions not about marbles but about populations of species and the effect of genetic drift on variation within those populations. The methodology of the ELE, as described in standard laboratory manuals and guides, begins with an introduction of relevant evolutionary terms and concepts. McComas, for example, suggests that before performing the experiment "[t]he students should have had some introduction to population genetics concepts – perhaps a general treatment of the Hardy-Weinberg Law and some explanation of the concept of selection – before they attempt this exercise" (McComas 1994, 92). After collecting data and manipulating the systems, students are asked to respond to questions which encourage them to use their manipulation of the marble system as a means of understanding the effect of genetic drift. Froehlich and London (Froehlich and London 1996) ask students to analyze how the forces of evolution were demonstrated within the experiment. Staub (Staub 2002, 375) suggests that, in order to measure the successful outcome of the experiment, students should be asked to read Peter Buri's (Buri 1956) study of genetic drift in fruit flies, and should compare their results with Buri's. In this case, they are asked to apply their insights to a real-world case.

The conceptual preparation and assigned forms of evaluation suggest that the main purpose of this experiment has (unsurprisingly) nothing to do with investigating the actual system of marbles, but rather with investigating the nature of genetic drift. Students are led to begin considering concepts related to population genetics and genetic drift before performing an experiment on a system of non-living marbles. After performing their experiment, they are not asked to draw conclusions or statistical inferences which apply only to the system of marbles, but rather about the evolutionary mechanism of genetic drift, thinking of marble colors as allele-types, sampling as reproduction, changes in the color frequency of marbles as changes in allelic frequencies in a population, and so on. Students are asked to experiment on a system and use it as a vehicle for surrogate inferences about a different system (Suárez 2004). In short: students are representing genetic drift in this ELE.

Hooke's Law (Physics)

Hooke's law (*F=-kx*) describes the extension of a spring as being directly proportional to the force applied to the spring. So, any increase or decrease in the application of a force will result in a corresponding change in the extension or compression of the spring. The law was first described by Robert Hooke, who used an anagram ("*ceiiinosssttuv*") as a means of publishing the law. He unscrambled the anagram two years later as: "*ut tensio sic vis*" (translating roughly to: 'as the extension goes, so goes the force') (Rohland 2016). Given that the law was formulated in the middle to late 17th century, it is difficult to completely trace back the history of the use of experiments relating to Hooke's law in science education. One way that Hooke's law has long played a role in laboratories – in both student laboratories and in those of scientific experts – is through the use of spring balances, which measure mass proportionate to the extension of a spring as described by Hooke's law. Spring balances date back to the late part of the 17th century, with the work of Jacques Ozanam (Benton 1941, 66). In the late 1890s, LeRoy Colley's (Cooley 1897, 36) laboratory manual introduces the concept of Hooke's law in an introduction of the spring balance, though students are not asked to test the law in anything like an ELE. As a stand-alone experiment, we can trace the origins of the Hooke's law ELE at least as far back as the early 20th century. In 1911, C. L. Vestal described a tool which could be used in a classroom setting to demonstrate Hooke's law (Vestal 1911; Haupt 1929). Shortly thereafter, Gordon Fulcher (Fulcher 1915) included Hooke's law in his outline of a course on mechanics which offered an alternative to the standard "dogmatic, mathematical presentation of mechanics" (645) which included the calibration of spring balances as a way to study Hooke's law. The purported novelty of the practical orientation of his outline suggests that this may have been one of the first occasions when students were asked to test the law on their own, rather than as a demonstration to passively watch.

In the years that followed, an investigation of Hooke's law – whether through spring balances or through an alternative apparatus – became a standard experiment performed in physics laboratories (Turner 1944, 19-20; Tyler 1959, 18-19; Avery and Ingram 1961, 66-67; Harris 1972, 89-91; Wilson and Hernandez 2005, 179-88; Loyd 2013, 207-15). The methodology is fairly standard wherever it is presented. As a standalone experiment, students are typically given a spring from which they hang a series of masses, increasing in size. After the application of each mass, students are asked to measure the length of the extension of the spring. They then plot the change in extension as a function of the change in mass, which allows them to determine the slope of the line which is identical to the value of the constant *k* of that spring. Oftentimes, students are asked to perform the same process again for several springs, showing how *k* is a constant value unique to each spring. More recently, given the rise of distance education courses being taught online, some have created opportunities for virtual Hooke's law experiments. In one case, students are asked to interact with a virtual spring (Hatherly, Jordan, and Cayless 2009). In a different case, they remotely operate a real spring (Torre et al. 2011).

After the experiment students are often asked to answer questions about deviations between their measurement and calculation of *k* for a spring and the accepted or expected values of *k* for that spring. An important insight into the representational nature of the ELE arises from how it is that students handle these deviations. Indeed, most manuals ask students to explain their deviations, i.e. explain where they went wrong or what additional effects may have intervened and caused deviant results. Unexpected results are treated not as signs of novelty or of the need to rethink Hooke's law, but rather as evidence of a mistake in the experiment or the environment. Here we can see one of the features central to the representational use of ELEs, namely that deviations are not treated as evidence of something about the phenomenon, but rather as evidence of a mistake on the part of the student. More importantly, deviations from the expected values do not even prevent students from successful completion of the ELE, provided they are able to account for the deviations they observed. The fact that the aims of the activity can still be achieved even in the case of deviations highlights the representational nature of the ELE, since students can still come to understand Hooke's law even when an experiment goes awry, provided they can explain what went wrong. In short, students are representing the idealized theory of Hooke's Law, even though there are plenty of ways in which that law is not being perfectly instantiated or measured in their experiment.

Common Pool Resource Games (Economics)

Common pool resources (CPRs) are those resources which are not owned by any particular individual and are instead shared in common by a larger community. Problems arise with

CPRs when there is an economic gain for individuals who draw more heavily upon the resource, such that the CPR is unable to keep up with the heavy use, and so is depleted. In some cases, this can lead to a major loss in the resource, as was the case with the collapse of the Northern Atlantic population of cod in the 1990s, due to overfishing (Eisenkopf and Sulser 2013). To help students understand CPRs, the economic theory around them, and the way in which they can be depleted through seemingly innocuous actions on the part of individuals, some economics teachers have recently begun to employ a CPR experiment in their classrooms (Murphy and Cardenas 2004; Eisenkopf and Sulser 2013).

The precise details of the experiment are variable, but the general methodology remains the same in either case. Students are told to imagine themselves to be in some particular setting in which they are drawing upon some common resource. One example had students drawing "fish" from a pond (Eisenkopf and Sulser 2013) and another had them "working" some number of months to collect firewood from a forest (Murphy and Cardenas 2002). Both experiments were based on the data and details collected from real studies that had been performed for people drawing on CPRs in those settings, i.e. a real fishery and a real forest. Students then proceed through several rounds in which they alter their load on the CPR, changing the number of fishes they draw or hours they work to collect firewood. To help students behave sincerely, students are offered a reward for whoever can gain the most resources (or income from the resources) – e.g. candy. Because of alterations in the scenario made according to the data collected in the real studies, the students' choices will affect the CPR – changing the amount of the resource remaining after each round and its value. After each change in the CPR, students will once again alter their load on the CPR. This cycle will occur through several iterations, perhaps ultimately resulting in the depletion of the resource.

Throughout the experiment, students are asked to consider the nature of CPRs and how our interactions with them can result in their depletion. Students are often asked, after the completion of the experiment, to apply contemporary economic theory to the scenario they experienced. This payoff of the CPR ELE is highlighted by the way in which economics instructors measured the success of the CPR experiment to show that they are a valuable addition to an economics course (Murphy and Cardenas 2004; Eisenkopf and Sulser 2013). In both cases, the instructors used CPR ELEs in their classrooms and measured the success of the experiments in terms of educational outcomes. In one of the studies, the success of the CPR experiment was defined in terms of the students' ability to calculate Nash equilibria under various conditions (Murphy and Cardenas 2004). The other study measured success in terms of the students' performance on a test of economic understanding (Eisenkopf and Sulser 2013).

Here, we can see that the measurable outcomes used by instructors who introduce the CPR ELE into the classroom laboratory reveal the true purpose of the ELE. Students are not merely altering some numbers and trying to win a piece of candy in a strange game. Instead, and unsurprisingly, students are performing these actions as a means of better understanding the contexts in which CPR problems can arise, and how economic theory can help to explain them. In short: students are *representing* CPR problems and the economic theory which explains them.

The Nature of Chirality (Chemistry)

Chemistry is an interesting and complex context in which we can examine the use of ELEs. The reason for the complexity is that the chemistry undergraduate laboratory is in most cases, first and foremost, technically-oriented. That is to say that students are primarily led to develop relevant techniques found in the discipline of chemistry. While a theoretical understanding of chemicals, compounds, and reactions are deeply implicated by the experiments, the primary aim of the laboratory is focused on teaching vital techniques in chemistry, things like titration, vacuum distillation, and the use of NMR, spectrometry, gas chromatography, etc. However, this is not the *only* aim of chemistry laboratory experiments. There is also, at least on some occasions, an important representational component of the experiment insofar as students perform an experiment not *only* to learn new techniques, but also to better understand some theoretical concept. Such is the case, I will argue, with an ELE in which students are asked to isolate Carvone.

Carvone is a common chemical found in both the oil of caraway seeds and the leaves of spearmint. Importantly, carvone exists as two enantiomers: (*R*)-(-)-Carvone and (*S*)-(+)-Carvone. The former enantiomer is present in high quantities in spearmint leaves and is responsible for the typical spearmint smell. The latter is present in high quantities in caraway seeds, and smells (unsurprisingly) like caraway – which, if you have never smelled it, is quite different from the smell of spearmint.[3] Enantiomers are forms of a chemical which have the same structure, but in a non-superimposable mirror-image fashion, like the non-superimposable mirror image relationship between the left and right hands. Measurable differences between these two enantiomers are fairly limited – they have the same boiling point, NMR spectrum, infrared spectrum, gas chromatography, and so on. There are only two differences which can be recorded: one is the difference in smell, and the other is the polarimetry of each enantiomer. One of them rotates light positively ((*S*)-(+)-Carvone) and the other rotates light negatively ((*R*)-(-)-Carvone).

It had long been suspected that there may be a sensory difference between different enantiomers, but this was not demonstrated by scientists until 1971 (Murov and Pickering 1973). At that time, two different pairs of scientists showed that there was a difference in the smells between the two enantiomers of carvone (Russell and Hills 1971; Friedman and Miller 1971). Shortly after the publication of their work, Steven Murov and Miles Pickering (Murov and Pickering 1973) suggested that experiments using carvone could be of value in education, specifically in organic chemistry laboratories. The experiment has since become widely used and frequently cited (Garin 1976; Davis et al. 2003; Kraft and Mannschreck 2010; O'Shea, Von Riesen, and Rossi 2012).

There are two primary methodologies for the experiment as it is performed today. One is to perform the experiment using vacuum distillation. The use of vacuum distillation requires that Carvone be separated from the other components present in the oil. There are two primary components in caraway seed and spearmint leaf oils: the respective enantiomer of carvone as well as limonene. The boiling point of limonene is significantly lower than that of carvone, and so can be boiled off.[4] The second methodology is to isolate carvone through the use of gas chromatography. Carvone and limonene have differentiated retention rates, and so gas chromatography can be effectively used to isolate both enantiomers of carvone. Whichever method is employed, students then perform various additional tests on their distillate or sample. Which tests are performed depends on the time allotted and instruments available, but typically include NMR and infrared spectrometry. These are often compared to the same tests performed for enantiomerically pure samples of (*R*)-(-)-Carvone and (*S*)-(+)-Carvone. Students are typically asked to notice, through comparison with a student who distilled the other enantiomer (or through comparison with their own results if they distilled both enantiomers), that there is no difference in mixed melting point, NMR, and infrared spectrometry for both of their distillates (barring the inevitable impurities which will typically remain) (Garin 1976). Thus, the standard presentation of the Carvone ELE includes a final step in which students measure the angle of rotation of polarized light through the use of a polarimeter. In so doing, students can recognize that (apart from the smell) the only analytical difference between the two forms of carvone is their chirality.

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[3] That is, unless you are among the approximately 10% of the population who are unable to distinguish between the two (Friedman and Miller 1971).

[4] The boiling point for each is fairly high – 177°C for limonene and 230 °C for carvone – so vacuum distillation is used to keep the temperatures more manageable, i.e. under 100°C (Murov and Pickering 1973, 74).

It is important to note that the bulk of the success of this experiment comes from the correct use of various tools, instruments, and methodologies. Thus, one of the primary aims of this experiment is purely technical in scope: teaching students to use various instruments and analyze their results. Such was the presumed primary purpose of the experiment as it was originally suggested by Murov and Pickering (1973), though they also note that the experiment is additionally useful insofar as it "familiarizes [the student] with the phenomena of optical isomerism in an unusual and dramatic way" (1973, 75). Such an aim is present, even if secondary, in most contemporary presentations of the experimental methodology. For example, David Garin says that "The fact that the enantiomers can be differentiated by odor heightens student interest in the topic" (Garin 1976, 105). The choice of carvone rather than some other essential oil is useful in that it provides the opportunity to think more carefully about the nature of chirality. In this case, the difference is particularly striking and salient – most of the measurements yield identical results for each enantiomer. The only difference is to be found in the polarimetry and in the corresponding scent. The interesting phenomenon and the design of the experiment are partially aimed at getting students to understand the nature of chirality, that though it may only be detectable by polarimetry, it can still have interesting macroscopic effects. In short: students are also representing the theory around chirality in the Carvone ELE.

Representing in the Student Laboratory

As I intonated at the end of each case study, there is an important representational component to each of the ELEs. The representational nature of the ELEs derives from the fact that they are being used for surrogate inferences (Suárez 2004) or, put otherwise, as a means to better understand some theoretical knowledge (Boesch 2017b). Since they meet the theoretical requirements of scientific representation that have been described by philosophers of science, there is good reason to include ELEs as representational vehicles – things used by scientists representationally. The representational role of the use of ELEs is most evident in the way that the ELEs are prefaced – m with references to the theoretical or empirical object being represented – and in the way in which students are asked questions and evaluated on their work in the ELE, as well as the way in which instructors measure the success of the use of an ELE in the classroom – both of which attend to the students' increased ability to demonstrate that they understand the theoretical or empirical phenomenon in question.

So, for example, preambles to the Genetic Drift ELE ensure that students are sufficiently familiar with population genetics and the concept of genetic drift. The questions they answer after the ELE ask them to demonstrate an understanding of the selective force of genetic drift and, in one case, to apply their results to a real-world study of fruit flies. These questions demonstrate that students are not *only* being taught to follow good experimental design and methodology (with good definition of the question, data collection and recording, and statistical analysis), but are also learning more about the theoretical concept of genetic drift and the way in which it functions as a mechanism for evolutionary change. Similarly, the Hooke's Law ELE asks students to account for any discrepancies between their measured values of *k* and the accepted value of *k* for the spring in question. Aside from growing in important experimental methodology and technical skills (measurement, recording of data, and management of significant digits), students are also coming to understand the generalizability of Hooke's law by seeing its predictive power in practice and demonstrating an increased ability to apply the law to various contexts. The CPR ELE was specifically evaluated by its designers in terms of the increased ability of students to understand important theoretical concepts related to the depletion of CPRs. Even when the development of technical and methodological skills is clearly at the forefront, there can still be a representational component to an experiment, as is displayed in the Chirality of Carvone ELE. In addition to learning how to perform vacuum distillation and use several instruments of measurement on their distillates, the choice of such a striking molecule along with the intentional design of the experimental methodology and student questions was clearly designed to help students come to a better understanding of the nature of chirality.

Insights about the Representational Practices of Science

I began this paper by suggesting that science education provides an interesting context in which to explore scientific practice. This holds true of the form of representational practice that I have described in this paper, ELEs. My primary task so far in this paper has been to describe a context of representation which has, so far, not been thoroughly explored: representation in educational contexts. In so doing, my goal was to increase our philosophical understanding of the nature of representational practice in science by drawing our attention to a form of representational vehicle (ELEs) which is distinct from other sorts of representational vehicles. It will be of use now to pause to consider explicitly what it is about ELEs that makes them distinct from other forms of representation in science.

The primary point of distinction between the representational use of ELEs and that of models in scientific research is the lack of novelty found in ELEs. Students use ELEs without any expectation of some novel explanation or knowledge, discovery, new predictions, and so on. This lack of novelty is a contrast to the use of, for example, models which are "supposed to produce other, preferably unexpected, results apart from the expected behavior" (Knuuttila 2011, 268). ELEs are useful precisely when they produce the *expected* results, the ones which could have been entirely predicted by theory beforehand. Indeed, ELEs are carefully constructed for the sake of these expected results, so that students will be in a position to draw the relevant theoretical insights about whatever topic is at hand. So, for example, the marble-drawing ELE is defined by a methodology which is constructed with constraints (number of marbles, colors, size of draw, relative frequencies of colors, etc.) which are designed to help students arrive at the expected results. These same results could be understood using mathematical equations of population genetics, but the use of the marble-drawing ELE helps to make the theoretical insights tangible and present (they are re-presented) to the students.

Better understanding the representational nature of ELEs can be of great use in better understanding other forms of scientific representational vehicles which lack novelty – e.g., representational vehicles found in journal articles, grant applications, and so on are similar to ELEs insofar as they are successful precisely when they make certain theoretical points clearer. Another reason it is important to attend to representational vehicles which lack an element of novelty, apart from the aim of better understanding representational practice in all its forms, is that measures of normative evaluation for these representational vehicles are distinct from those which do include a role for novel predictions or explanation (e.g. models). ELEs and the representations found in journal articles are measured by whether the user of the representation (the student or the scientist reading the journal article) can better understand whatever knowledge, theory, explanation, or understanding is being conveyed. The role of representations in these cases is more communicative rather than explorative. As they constitute a significant part of representational practice in science, it is worth understanding how these aims are achieved and how they function as part of the epistemic toolbox of science.

A second major payoff from an understanding of the representational practice associated with ELEs is that it helps to demonstrate the integral role in the representational relationship for 'licensing' (Boesch 2017a). I include a wide range of scientific activities in representational licensing, including "the context in which [a representational vehicle] was created, the application of theoretical and empirical constraints, the awareness of and management of idealizations, and the history of its reception and use" (Boesch 2017a, 979). We can see many of these elements on display in the use of ELEs. Among the important features are the historical elements – the way in which the ELE developed over time and became a solidified element of science education in that discipline. As we saw, for example, with the Genetic Drift ELE, there are plenty of variations about the precise details of how the ELE is conducted. However, the central features of the ELE have been standardized over time, tracing back to important work of population geneticists. Similar remarks hold true for other ELEs, including the Chirality of Carvone ELE, which traces back to important work from scientists on the link between chirality and sensation.

According to my concept of representational licensing, we cannot fully explain the way in which any vehicle (including an ELE) is representational without attending to these features of licensing, including its historical elements. The broader upshot for those interested in scientific representation is that greater attention should be played to the full temporal extension of representational vehicles. If we wish to understand how and why they represent, we must pay attention (in part) to these features of representational licensing which extend back to its very construction and introduction to a discipline. The examples given of ELEs in this paper help to demonstrate why this is important and the way that attending to the historical elements of representational licensing can yield insights into the representational nature of the vehicle.

Payoffs for History in Science Education

Aside from revealing insights which enhance a philosophical understanding of the nature and role of representation within science, the study of ELEs I have offered here provides a meaningful pedagogical payoff as well. If we generalize over the examples that I described above, the methodology for most of the ELEs contains three primary pieces: the background, the methodology, and the evaluation. Recognizing the general features of each of these elements is useful to the development of additional ELEs down the road. It importantly also demonstrates several ways in which instructors can help to connect their students to the historical elements of scientific knowledge, helping them to trace out the development of the ELE over time.

The first piece is a background, which typically contains relevant theoretical background details and helps to set the context. The background plays an important role in helping students attend to the representational context in which the ELE will be functioning. So, for example, the background of the Genetic Drift ELE was a theory about the selective mechanism of genetic drift. Similarly, the background of the Hooke's Law ELE is a discussion of the mathematical equation which describes the Law. Though I did not find any examples of a historical exposition of the relevant background theory of any of the ELEs I described in this paper, this is one of the ways in which instructors might demonstrate the historicity of scientific knowledge. At this stage of the ELE, a background could include not only the contextual theory which is at stake in the ELE, but also information about how that background theory developed – e.g., by discussing Dobzhansky's important (Dobzhansky 1937) book and his citation of the work of Dubinin and Romaschoff (Dubinin and Romaschoff 1932) for the Genetic Drift ELE. Similarly, the story of Hooke's discovery of his law would make for an excellent part of the background context for the Hooke's Law ELE, connecting students to the discovery of the law while also helping to set up the theoretical background knowledge.

The second generalized part of an ELE is the methodology. The methodology is the set of instructions given to students by which they conduct the experiment. So, for the Genetic Drift ELE, it is the instructions about how to set the original 'population' of marbles in the jar, and how to proceed through multiple 'generations' as they draw marbles out of the jars and change the population ratios of the marbles in the jars over time. Similarly, for the Hooke's Law ELE, the methodology describes to students how they should use different masses on springs and use a resulting measure of their extension to plot a trendline between extension and mass (as a measure of force). As I described above, there are oftentimes differences in the precise details of the methodology, but the broader, more general features of the ELE are fairly standardized. There are fewer opportunities for instructors to invite students to reflect upon the historical nature of scientific knowledge with regard to the methodology in particular, though the historical elements play an important role in the representational uses of ELEs, as I have described. All the same, instructors could ask students to compare their methodology with one taken from the past and use the alternative instructions as a way to alter the ELE slightly as they proceed.

The final typical part of an ELE, and the one in which there is the greatest opportunity for instructors to invite students to think about the historical nature of scientific knowledge is the evaluation. In the evaluation, students are required to produce some measurable outcome which is used by instructors to evaluate the students' work and assign grades. Oftentimes, this will be a lab report of some sort, a short descriptive essay, or a response to a set of questions. At this stage of the ELE, students are induced to make the clear connection between the theoretical ideas being represented, if they have not already made them. When analyzing the data of the marble-drawing in the Genetic Drift ELE, students are explicitly asked to explain how the data reveals the selective effects of genetic drift. The same is true for other ELEs, where students are asked to compare their data with the expected results (in light of the theory at hand) or to explain its relationship to the theoretical knowledge explained in the background.

Some of the ELEs already use this stage as an opportunity to connect more deeply to the historical roots of the ideas at play. For example, one presentation of the Genetic Drift ELE had its students compare their data to important work performed by Peter Buri on fruit flies (Buri 1956). Similarly, the CPR ELE relied upon data collected from actual examples of CPRs. A comparison to or reliance upon historical data is just one way to bring in a historical mindset to the evaluation phase of an ELE. It is easy to imagine (if the information is not provided in the background) assigning students to give a brief report on the source of the theoretical knowledge at hand – e.g., in the Hooke's Law ELE, tracing back the story of Hooke's Law to Hooke's work or briefly describing the development and use of spring balances. Similarly, in the Chirality of Carvone ELE, students could be asked to read the original papers describing the difference of smell associated with the enantiomers of Carvone (Russell and Hills 1971; Friedman and Miller 1971).

The historical nature of scientific knowledge is often ignored in science education or otherwise relegated to a brief introduction or a few dates offered in the lecture hall. But, as I have shown here, this need not be the case. Apart from providing philosophers with an interesting case of representational practice which helps to better understand how representation works in science, ELEs can be a useful means of bringing history into science education. Most importantly, it is interesting to note the way in which ELEs help bring historical insights into the laboratory, rather than just into the lecture hall. History becomes a part of the activities of students – a part of what they do – rather than something they just hear. Rather than being thought of as a mere precursor, students are invited to see the active role that the historical generation of scientific knowledge plays in the scientific activities they conduct week-to-week.

Conclusion

In this essay, I have identified a new context for the philosophical study of scientific representation: the representational use of ELEs in science education. The value of these studies extends beyond a philosophical analysis of scientific representation and extends also to offer a point of insight on pedagogy. In both cases, the insights are linked to the historical nature of ELEs. The historical nature of ELEs helps to demonstrate the nature and role of representational licensing in the use of a representational vehicle in science. It is the same historical nature which provides an interesting insight into science education pedagogy since instructors can use the historical connections to help bring historical insights into the student laboratory.

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