Chapter 60
Science Education in the Historical Study of the Sciences

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60.1 The Historiography of Science Education

Historical scholarship since the 1930s has demonstrated that science education is not merely a minor subfield of historical investigation somewhat akin to institutional history, but is in fact central to understanding the contours of scientific practice, the formation of scientific personae, and ability of the scientific community to reproduce and survive. The historiography of science education to date has highlighted the ways in which educational settings sustain clusters of values, mental habits, and material practices that make possible the epistemological and social dimensions of science, including the transmission and popularization of scientific knowledge; the conduct of teaching and research; the training of recruits; and the public's views on science, including its social, political, cultural, and economic functions and the image of the natural world it conveys.

What occurs *inside* educational settings has much to do with what is *outside* them. The values, habits, and practices of scientific practitioners acquired in training are sometimes drawn from culture at large, as they are when craft or technical practices are adapted to the study of nature. Conversely, the values and habits cultivated in science instruction are part of the socialization of the pupil, and thus, science education participates in the construction of the individual, society, the state, and civil society. In addition, norms of social interaction in educational – and by extension, professional or workplace – settings have been shown to be as important as knowledge transmission in the course of training scientists or educating pupils at all levels of instruction. Crossings between "outside" and "inside" or between science and society provide a way to understand the mutual integration of science and culture, including national goals. Studies of science education have thus

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demonstrated that the vitality of the sciences and their practices has as much to do with their internal robustness as with their linkages to broader historical contexts, including daily life.

The history of science has reached a point where science pedagogy now has a secure place in understanding the nature of science. Simply put, science cannot exist without institutional and intellectual forms of disseminating knowledge and educating students and practitioners. Yet the historical study of science pedagogy transcends concerns for disciplinary reproduction in the sciences. The histories of science education are now many, and major review articles on the topic have become more common.[1] Historical approaches to the topic, however, are bifurcated into historians of science who view science pedagogy largely (but not entirely) as a problem in disciplinary creation and reproduction and historians of education who view science pedagogy and science popularization more broadly as a means of transferring value from institutional science to the public at large for the purpose of securing social stability, economic well-being, cultural hegemony, or political power (Rudolph 2008).[2] School science, popular science, university science, laboratory science, industrial science, and government science are some of the most salient sites of the many types of science pedagogy that not only sustain the scientific enterprise but also present the public with value-laden options of how to live their lives.[3]

While current scholarship takes into account the wide variety of institutional spaces in which the transmission of scientific know-how, intellectual and manual, occurs, much remains to be done. This essay treats scholarship by historians of science who have studied science education at either institutions of higher learning or sites of professional scientific activity (e.g., postdoctoral training). To a large degree, these studies have focused on the training of practitioners, but they have also considered the broader social, cultural, economic, and political functions of science education in producing secondary school teachers, administrative bureaucrats, and engineers or in realizing the ideological goals of dominant elites, such as the German notion of *Bildung* or the American Cold War ideal of a national security state. After a brief historiographical review, this essay examines four principal loci of historical investigation: scientific textbooks; science pedagogy, or how science is taught and learned; pedagogical practices in the generational reproduction of scientists; and finally the political, social, and economic dimensions of science education.

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[1] For overviews of the literature, see Macleod and Moseley (1978), McCulloch (1998), Mody and Kaiser (2007), Olesko (2006), Rudolph (2008), and Simon (2008).

[2] Concerning the transfer of values to the public, Rudolph (2008, p. 65) perceptively argues that the exchange goes both ways and that the boundary between scientific values and nonscientific ones is a zone of conflict worthy of historical investigation. Rudolph's review of the literature on science education and the lay public is exemplary (2008, pp. 69–75).

[3] For representative variety of settings, see Daum (2002), Dennis (1994), Geiger (1998), Holmes (1989), Kohlstedt (2010), Leslie (1993), Nyhart (2002), Olesko (1988), Olesko (1989), Pauly (1991), Rudolph (2002), and Schubring (1989). Studies of science instruction in primary education, secondary education, and the public sphere deserve their own dedicated historiographical reviews along the lines of Rudolph (2008).

It concludes by reflecting on how the emerging area of scholarship known as the history of the senses can be incorporated into the history of science education.[4]

60.1.1 The Early Twentieth Century

Before the 1930s dry-as-dust histories of educational institutions, dating from the late nineteenth to early twentieth centuries, had valorized the training of scientists in the industrialized world without casting a critical eye on the pedagogical process itself. With largely descriptive surveys underpinned by tables and statistics, these studies helped to create founder myths and institutional shrines within specific disciplines that subsequently proved difficult to displace in the historiography of the sciences. These myths helped to entrench a logical positivist historiography by viewing education through the lens of the progress of research. That approach faded in the 1930s when sociologists of knowledge, struck by the contrast between the liberal, rational conception of the individual promised by the Enlightenment and the conformities pressed upon the masses by totalitarian states, began to unpack the relationship between reason, behavior and social norms, and identity formation (Elias 1939; Fleck 1935; Schutz 1932).

Among this generation of sociologists of knowledge, Ludwik Fleck had particularly perspicacious insights into the nature of science learning in the context of what he called the "genesis and development of a scientific fact" – the general idea that facts are not discovered, but are rather made in a process that involved intellectual decisions, institutional practices, and social judgments that are all learned in training. Science education in his view created the mental and social frameworks necessary for the cohesiveness of a scientific community and for the creation and acceptance of new ideas. Education also established links to the past via the "syllabus of formal education" (Fleck 1979, p. 20). Fleck thus embedded the educational processes of socialization and training in broader contexts, claiming that "In science, just as in art and life only that which is true to culture is true to nature" (Fleck 1979, p. 35). Most relevant to this essay, Fleck believed that "initiation into science was based on special methods of teaching" (Fleck 1979, p. 112). But his views on science went largely unnoticed until the translation of his work into English in 1979. By then whatever he could have offered the historical analysis of science education was eclipsed by the popularity of Thomas S. Kuhn's *Structure of Scientific Revolutions* (1962) which, Kuhn later revealed, may in any event have had its origins in Fleck's work. Kuhn, however, quickly forgot he had read Fleck and could later only surmise his indebtedness to him (Kuhn 1979, pp. vii–ix).

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[4] I thank Michael Matthews, editor of this volume and of *Science & Education*, for permission to reproduce and paraphrase parts of Olesko (2006) in this essay.

60.1.2 The Later Twentieth Century

In the aftermath of the Third Reich and the ideological realignment of postwar educational systems into the Cold War intellectual factories for defense, studies of the social system of science fell into two distinct phases, both of which shaped perceptions of the historical significance of science education. The first, from the end of World War II to roughly the beginning of the tumultuous social and political movements of the 1960s, was marked by an ideological capitulation to a system that placed great faith in science and technology as guarantors of the strength of the nation state, whatever its political orientation. Science education became one means among many for bolstering national security and tipping the global balance of power, as had occurred in the United States, the Soviet Union, and Great Britain and other nations that became members of the nuclear club. It also became a sine qua non for developing states that aspired to become modern. Key concepts defining the social system of science originating in this period tended to follow politics and shielded science from a deeper examination of certain features of its internal operation, including the question of how science was learned in the first place. A prominent example is Polanyi's notion of "tacit knowledge" which rendered ineffable some of the techniques of science as well as the methods of how scientists were trained (Polanyi 1958).

60.1.2.1 The 1960s and 1970s

The 1960s marked the beginning of the second phase when methodological changes in the history of science lifted the veil of secrecy that had hitherto concealed aspects of scientific work, revealing more clearly the interweaving of scientific and social practices. From historians as diverse as Michel Foucault (1966, 1975), Thomas Kuhn (1962) and Jerome Ravetz (1971) came a matrix of fruitful questions about the role of science education in the practical work of science as well as in discipline formation and maintenance.

By viewing scientific education as a process of near totalitarian indoctrination, Kuhn highlighted the powerful role of science pedagogy in transmitting paradigmatic problems, solutions, skills, and other guidelines for scientific practice. Practical activities, including instruction and knowledge production, were united in what Kuhn called normal science, his epithet for everyday scientific practices and beliefs. In his view the external world intervened in scientific practice only during periods of crisis that evolved into paradigm shifts when methods and skills metamorphosed in response to cognitive dissonance (Kuhn 1962).

More sensitive to the nuances of science pedagogy than Kuhn, Ravetz prioritized the social dimensions of instruction over intellectual ones. Training in how to make the kinds of sound judgments that avoided the pitfalls of scientific research (i.e., unsolvable problems and the dead ends of fruitless research trajectories) attracted his attention more than the content of knowledge or the means of its transmission.

Yet Ravetz was also deeply indebted to Polanyi and could not abandon the notion that skills were tacitly learned under the guidance of a master scientific instructor much in the same way that craftsmen learned trade skills. By definition skill learning could not be the object of historical investigation because it was ineffable. Ravetz viewed teaching as an intensely personal process, one so personal that were the precepts of scientific practice made explicit, learning the craft work of science would be irreparably damaged. Despite his insights, his impact on the historical study of science education has remained limited (Ravetz 1971).

Historians of science education may still genuflect to Kuhn, but it was Foucault who most invigorated theoretical discussions of history of science education. His intentionally ambiguous use of the word "discipline" – as conceptual organization but also corporeal training *and* character development – united the social, moral, and intellectual normalizing functions of education (Foucault 1975). Foucault was persistently critical of historians of science for their inability to grasp what was at stake in the construction of scientific regimes. For him the notion of "discipline" encompassed a plethora of minor procedures with major repercussions. Enforced by institutions of higher learning and the legal apparatus, disciplining *made* the modern individual and hence was constitutive of the formation of both modern society and the modern state. In three particular components of disciplining, Foucault discovered, too, the social processes at work in the pedagogic formation of modern scientific disciplines: hierarchical observation, normalizing judgment, and the examination or test (Foucault 1975). Although Foucault's views were not uniformly adopted, historians of science echoed his point of view in their study of systems of examination (Clark 2006, pp. 93–140; Macleod 1982) and in their affirmation of the centrality of teaching to launching and sustaining the disciplines (Pyenson 1978, p. 94). In other respects, however, the views of Kuhn and Foucault were often at odds with what more empirically based studies have demonstrated (Simon 2008, p. 105).

60.1.2.2 The 1980s and Beyond

A third conceptual phase, the focus of this essay, began in the last decades of the twentieth century. This phase was characterized by a deeper examination of the empirical record of science education in local, national, regional, and global contexts; a methodological pluralism that circumscribed the interpretive power of theoretical studies of science education (based nearly exclusively on Kuhn and Foucault) and expanded the role of historical contingencies in the shaping of science and its pedagogical practices; and a recognition that while science education was a subject in its own right, it was also an important site for understanding not only the larger structure and operation of the entire scientific enterprise but also more broadly in the construction of modernity. Consequently the historical study of science education became a window on the larger political, economic, and social environments of which science was a part. Due to the dominance of the military-industrial-university complex in the post-World War II period, the focus of historical studies of science education was largely, but not exclusively, upon the physical sciences.

Historiographical developments since the 1960s have refined the methodologies used to study the trio discipline, pedagogy, and practice. While not abandoning institutional contexts, new approaches have nonetheless gone beyond them. An important fruit of this effort has been the detailed historical examination of the training of neophyte scientific practitioners, which in turn has led to a recasting of how disciplinary history unfolds. Yet the historical significance of pedagogical experiences goes beyond the admittedly artificial confines of disciplinary history to include social, political, cultural, and economic history. These larger contexts have shown how widespread and necessary the framework of support and approbation was (and still is) for science education, dispelling the idea that science education is a self-driven enterprise.

60.2 Scientific Textbooks

The study of scientific textbooks was among the earliest genres in the history of science education. It still remains the most popular. Textbooks are enticing as historical objects of investigation because they present neatly packaged compilations and arrangements of scientific knowledge suited for instruction. They also confound historical investigation because they represent a selective history of their subjects. These contradictory traits led Kuhn (1962) to view them as little more than static moments or paradigms in the history of normal science and so as constraining in their effect upon students. Fleck (1935, 1979), however, created a dynamic conceptual framework that illuminated their role in discipline formation. He viewed textbooks as part of an intellectual continuum, occupying a position between journal and vademecum (handbook) science and popular science. As an intellectual hybrid, textbooks both initiated students to scientific ways of thinking and preserved some contact with ordinary knowledge.

Recent scholarship has cautioned against defining the textbook genre too narrowly, as an organized distillation of the results of research and in contradistinction to scientific popularization. The boundaries between different representations of knowledge now appear more fluid, and the distinction between genres less clear. At the most general level, textbooks are indispensable sources for capturing how thousands of students (and not merely future scientific practitioners) are exposed to science and what image of science they are likely to form. In the mid-1980s, sociologists of knowledge reinforced the association between textbooks and discipline formation by defining disciplines as “knowledge assembled to be taught” (Stichweh 1984, p. 7). Textbooks now are considered integral to understanding not only traditional topics of historical investigation, such as the development of ideas, epistemological choices and debates, the taxonomy of skill-based learning, and even the social dynamics of science such as priority disputes, but also the shifting relationship between science and society and the transnational nature of science (Simon 2011; Vicedo 2012, p. 83).

60.2.1 Textbooks and the History of the Disciplines

A defining feature of historical scholarship on scientific textbooks is its emphasis on discipline formation. Chemistry textbooks have attracted particularly sustained attention in this regard. Hannaway (1975) pioneered this branch of the historical study of science pedagogy in his study of Andreas Libavius's *Alchymia* of 1597. Regarded as the first chemistry textbook, *Alchymia* organized knowledge and united knowledge with practical skills; proffered plans for a "chemical house" or laboratory where hands-on learning would take place; and, in Hannaway's view, offered an alternative to the secretive nature of Paracelsus's alchemy by creating open chemical knowledge. By teasing out *Alchymia*'s long-standing usefulness and popularity across the century after its publication, Hannaway argued that *Alchymia* made vital contributions to intellectual dialogue on the nature of chemistry – quite the opposite of the deadening routine that Kuhn had identified with textbooks.

Historians have since qualified Hannaway's ambitious claims without dismantling its position as a turning point in the history of chemistry textbooks. *Alchymia* spread Paracelsian techniques by incorporating some of them into chemistry – thereby uniting the practical arts with science and academic forms of argument – and so to a limited degree became a textbook that was suited for both university instruction and the needs of the practical arts. According to Powers (2012), Herman Boerhaave (1668–1738) completed the transformation begun by Libavius. Boerhaave took a didactic form of chemistry based on some skills and operations, but lacking in concepts suited for examining the properties of chemical species, and combined it with elements of alchemy, chemically based medicine, and experimental natural philosophy – all of which he believed could fill in the conceptual gaps of a didactic chemistry. Furthermore, according to Powers, the instrumental practices of these latter three subjects (practices Libavius did not fully address) were crucial in shaping the practical side of chemical instruction. The result was Boerhaave's *Elementa Chemiae* which, in 40 editions between 1722 and 1791, set a pedagogical and research agenda for chemistry and defined chemistry as both an academic discipline and a practical art years before Antoine Lavoisier. Powers noted, however, that the assimilation of *techne* into teaching at the University of Leiden was not easily done, but once accomplished, chemical instruction assumed a dual nature as both theoretically and instrumentally based, with each side influencing the other. Thus, both Libavius and Boerhaave used science pedagogy as a platform for defining chemistry as a discipline.

Bensuade-Vincent in her review of textbooks from the chemical revolution (1990) argued that textbooks not only serve as snapshots of a discipline, but they are also essential for understanding the formation of schools, and so they function as tools of training, professionalization, and standardization (Bensuade-Vincent 1990). In this vein Hall (2005) has demonstrated that Lev Landau's and Evgenii Lifschitz's *Course of Theoretical Physics* played a decisive social role in the 1930s and later in shaping a Soviet research school in theoretical physics by framing problems and techniques for solving them that later carried over into research practice. In this way Soviet theoretical physicists could differentiate themselves from other schools, such as Arnold Sommerfeld's (whose German school was also created through a distinctive pedagogy and a defining textbook, *Atomic Structure and Spectral Lines,* which went through several editions during the crucial phase of quantum mechanics in the 1920s). Hence, although some textbooks defined transnational scientific communities, these Soviet and German cases indicate that the social and intellectual training of scientists could very well result in more localized sets of practices.[5]

In some quarters it has become commonplace to define and even to identify a discipline in terms of how it is taught or even represented in textbooks (Simon 2011). Certainly the creative role of textbooks in *helping* to create the disciplines cannot be denied. As textbooks are widely translated, reach transnational audiences, and become the foundation of national examinations in the sciences, the urge to associate them closely with discipline formation is compelling (Simon 2008, 2011). Especially when the creative processes at work in textbook construction, revision, and translation are considered, the ability of textbooks not only to *define* disciplines but also to *reshape* them is incontrovertible. Textbooks are remarkably fluid intellectual products (Bensuade-Vincent et al. 2003; García-Belmar et al. 2005).

Yet there are limitations to this perspective. Chief among is the danger of viewing the evolution of a textbook as teleological – as inevitably and directly reaching the terminus ad quem of a "discipline." That approach creates a deterministic pathway of analysis that could obscure the historical significance of a textbook that goes off the beaten path. Textbooks can be transnational, but they are also historically contingent in both creation and use. They can be universal, but they are also sites of conflict and competition. Arguments over which textbooks to use (or even to create) in science education are instances where there are competing views of reality, interpretation, and method coming to terms with one another. Such arguments could also be indicative of a struggle for scant resources (as when representatives of different approaches compete for the same clientele) or a struggle for prestige (as when scientists define their allegiances through the use of a particular textbook in teaching). These and other adaptations to or constraints of context limit the universal and transnational nature of textbooks. And context, in turn, modulates the degree to which a textbook does or does not contribute to discipline building.

The persistence of local scientific practices (especially industrial ones of relevance to the sciences, such as chemical technologies) that resist incorporation into textbooks, for instance, forestalls their broader recognition and acceptance and makes their adaptation elsewhere difficult if not impossible (Lundgren 2006). Other countertendencies to discipline building include the production of textbooks that challenge what later become dominant approaches (say alternatives to Newtonian physics in the eighteenth and early-nineteenth centuries, including Romantic nature philosophy) (Lind 1993, pp. 278–314). Examining only those textbooks which fed into the dominant tradition would be to represent falsely what historical reality was at the time. Most textbooks also fail to address some of the investigative techniques and skills of scientific practice which are incorporated, instead, into laboratory manuals (Olesko 2005). A textbook may be a partial map to a discipline, but it is not the discipline as a whole.

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[5] As also demonstrated by Kaiser (2005a), Olesko (1991), and Warwick (2003).

60.2.2 Textbooks and Their Historical Contexts

Textbooks can also be viewed as focal points for many of the historical contingencies that shape both scientific practice and the roles of science and the scientist in society and so carry historical significances that transcend that genre. Their physical dimensions, for instance, are not boundaries that mark the "inside" and "outside" of science but rather can be likened to porous filters that permit the intermixing of several different cultural elements and so have been studied as a part of culture writ large. Recent scholarship has exposed the connections between textbook culture and the constitution of the public sphere; teased out the relationship between textbook production and social structure; and, most importantly, provided strong evidence that the decisive century in textbook culture may not be the nineteenth, when textbook culture matured, but the eighteenth, when textbook culture was just beginning.

A particularly productive locus of scholarship on scientific textbooks has been the team of Bernadette Bensaude-Vincent, Antonio García-Belmar, and José Ramón Bertomeu-Sánchez.[6] Their collective results are the most comprehensive, thorough, and innovative studies to date of the textbook culture in any of the sciences. To their credit they have viewed textbooks as active agents of culture, but not necessarily as carriers or even creators of disciplinary knowledge as early works in the genre, such as Hannaway's (1975), argued. They view textbook writing as a negotiation between author, public, press, and state (García-Belmar and Bertomeu-Sánchez 2004). The richness of their collective findings is in large part of the result of their ability to assemble international teams of scholars whose combined linguistic abilities enable them to examine cultures less well known and to achieve results attainable only through careful comparative histories. Of special note is the team's decision to examine the scientific periphery, including such places as Portugal, Hungary, and the Greek-speaking areas of the Ottoman Empire. Just as earlier works on science pedagogy during the Cold War adapted to a culture of secrecy and national security, this team's work on textbooks shows the impact of ongoing European integration.

Although their collective approach is largely empirical, their findings nonetheless mesh with earlier theoretical writings on science pedagogy. Of relevance to their project is Fleck's depiction of the historical role of publishing in sustaining science pedagogy where published knowledge becomes a "part of the social forces which form concepts and create habits of thought" determining "what cannot be thought in any other way" (Fleck 1979, p. 37). His account of the viability of scientific knowledge necessitates a reading public that takes an active part in the public sphere where discussions concerning the relevance and interpretation of scientific knowledge occur. So when Antoine Lavoisier's chemistry entered Portugal by way of Vicente Coelho Seabra's *Elementos de Chimica* around 1790, the absence of a local chemical community and a weak public sphere, constrained by the inquisition

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[6] A partial list of their projects includes Bensuade-Vincent (2006), Bensuade-Vincent et al. (2002), Bensuade-Vincent et al. (2003), García-Belmar & Bertomeu-Sánchez (2004), García-Belmar et al. (2005), and Lundgren and Bensuade-Vincent (2000).

despite the expansion of print culture under Maria I (1777–1792), were reasons why Seabra's textbook was not adopted (Carniero et al. 2006).

Likewise in Russia the cumulative effect of the Church's monopoly on printing was to stunt the growth of a healthy public sphere where the free exchange of information could take place, thereby also restricting the growth of scientific communities (Gouzevitch 2006). In the Greek-speaking regions of the Ottoman Empire along the western end of the Mediterranean, the dominating presence of merchant elites meant that practical knowledge, conversions (weights and measures, coinage, and the like), and navigational issues were more important than Isaac Newton's *Principia*, so the former dominated textbooks in the physical sciences (Petrou 2006; Patiniotis 2006). Yet in each of these cases, the limited audience reached by textbooks did not diminish their roles in creating conditions conducive to the future growth of the public sphere: to wit, they promoted the standardization of language, vocabulary, scientific idiom, and alphabet that would eventually promote a larger reading public and audience for the sciences.

Publication patterns in scientific textbooks thus help in understanding the social structure and technical and scientific interests of the region over which they are found. The strong elite merchant class in the Ottoman Empire accounts for Greek translations of textbooks on practical geometry, geography, and commerce (all were useful for trade) and the relative paucity of textbooks on physics and chemistry, which carried little of significance for merchants. Conversely, as Patiniotis (2006) has observed, the absence of social support can doom a branch of knowledge. Textbook distribution reflects the balance of power among elites, as it did in the Ottoman Empire where the laws of the marketplace were more important than the laws of nature.

Characterized by discipline building, university history, the reform and extension of the secondary school, and the professionalization of the career of the scientist, the nineteenth century is often considered the defining moment in the modern social and institutional forms of science education. Recent studies of scientific textbooks demonstrate, however, that the eighteenth century may actually have more to offer us in terms of *why* (rather than *how*) these changes took place. As Patiniotis (2006) has pointed out, the word *textbook* was coined in the eighteenth century. The protracted shift from Aristotelian scholarship to more recent knowledge, as took place in Portugal under the *estrangeirados* during a period of enlightened educational reform, suggests that the intellectual dynamics of textbook organization in the eighteenth century may have been more problematic and difficult than they were in the nineteenth. Likewise the rapid intellectual shift in those areas under Napoleonic rule, such as northern Italy in 1796–1797 where the new French chemistry was established by law under public educational reform acts (Seligardi 2006), calls to mind the popular and social support required to make the shift permanent.

60.3 Science Pedagogy

Yet textbooks have their shortcomings as historical sources: they cannot reveal what went on the classroom, and they provide little information on how students learned and what their experiences meant to them. Since the late twentieth century, historians of science have turned to other types of documents in an attempt to understand the behind-the-scenes activity of teaching and learning in the sciences. Lecture notes, problem sets, student notebooks, examinations, laboratory exercises, instructional instrumentation, and multiple varieties of unpublished, duplicated materials have become privileged ways of reconstructing what went on in the seminar, lecture hall, and practicum. When supplemented by complementary materials, some published and some not (such as personal correspondence; diaries; autobiographies; laboratory notebooks or simply notebooks; and published versions of lectures, often straight from raw notes), the resulting historical scholarship reached even beyond a deeper understanding of science instruction to reveal how dependent all aspects of science as a human activity were upon educational processes. From primary education to the professional level of postdoctoral fellowships, apprenticeships, and the acculturation of mature researchers to new institutional settings, pedagogy played a part.

To confine science education to the transmission of knowledge or to the internal practices of the scientific community, then, is to mischaracterize the historical roles of science pedagogy. Science education has played a role in forming value systems; the scientific self (mentally, bodily, behaviorally, sensory, affectively, emotionally); social norms, including where in the social hierarchy different kinds of sciences fell; gender relations, both in- and outside the sciences; the power relations that determined the relative position of science and scientists vis-à-vis the state, society, and the economy; the cultural function of the sciences; and, finally, the role and perception of rationality in modernity. Science pedagogy thus has become the fulcrum which rests some of the most important dimensions of modernity. With what regard science education was held and why, as well as how much support that it garnered from the state and society, have become key historical questions in the study of both local manifestations and larger systems of science instruction.[7]

60.3.1 The Pedagogical Dimensions of Science Instruction

An early focus in the study of science pedagogy was the introductory science course offered in colleges and universities. Although it goes without saying that introductory courses had to be carefully framed to both attract and retain recruits in the sciences, only slowly did historians realize that their constitution demanded historical explanation. Geison (1978), Holmes (1989), and Olesko (1991) in their studies of, respectively, the physiologist Michael Forster at Cambridge, the chemist Justus Liebig at Giessen, and the physicist Franz Neumann at Königsberg are three early examples of how student needs shaped the tenor and texture of introductory courses. The pedagogical strategies of these scientists were instrumental not only in

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[7] Major studies that contributed to the broader significance of science pedagogy include Clark (2006), Gooday (1990, 2005), Gusterson (2005), Hentschel (2002), Josefowicz (2005), Kaiser (2005a, b), Olesko (1991, 2005), Pyenson (1983), Rossiter (1982, 1995, 2012), Schubring (1989), Traweek (1988, 2005), and Warwick (2003).

accommodating their student clientele but also in preparing them for advanced exercises and eventually research.

The instructional successes in each of these cases were dependent upon intimate knowledge of their students' prior preparation, a judicious integration of the techniques of research into teaching, and a willingness to deploy pedagogical techniques that both worked and accommodated student needs. Effective teaching also depended upon coordinating the introductory science course with secondary school science instruction. Foster's evolutionary approach to biology and physiology challenged the former anatomical bias in English physiology; Neumann's instrumental use of mechanics brought astronomical techniques into the core of physics teaching; and Neumann's and Liebig's emphasis on instrumental and error analysis promoted more rigorous standards of precision in physical and chemical investigations (Geison 1978; Holmes 1989; Olesko 1991).

Using the introductory science course as representative of science teaching and learning, though, is a bit like claiming that a textbook represents what is taught and learned. In both cases access to what actually went on in the classroom is limited. The sources available to Olesko in her study of Neumann's seminar, though, overcame that limitation. With seminar reports, seminar exercises, correspondence, lecture notes, and student problem sets, she was able to render how both teaching and learning transpired in the seminar. The results were unexpected. Rather than inculcating only the mathematical techniques of theoretical physics, Neumann concentrated instead on teaching his students the methods of an exact experimental physics: to wit, the determination of both the constant and accidental (random) errors of an experiment, the latter by the method of least squares. Bessel's exemplary seconds-pendulum investigation, undertaken for the determination of an official unit of length in Prussia, served as a model for the precision-measuring exercises of the seminar (Olesko 1991) (Fig. 60.1).

The cumulative effects of doing these exercises were transformative for students. Their investigations demonstrated how they acquired what Fleck called the professional habits needed to become a "trained person" (Fleck 1979, pp. 89–90). But something more happened. The emphasis on the precision and reliability of their data, the determination of constant and accidental errors, and the marginalization of techniques of approximation meant that there was an "epistemological and technical concern for certainty that at times bordered on obsession" (Olesko 1991, p. 17). That obsession, which Olesko called the "ethos of exactitude," failed to sensitize students to when the quest for epistemological certainty should end. The ethos became an ethic in the sense that it "guided professional actions and decisions by providing the ways and means of separating right from wrong, truth from error, and the even the called from the damned. It helped to define professional identities, structure investigative strategies, and identify significant problems" (Olesko 1991, p. 450). While this ethos thus played a determinative role in shaping the professional behavior of Königsberg seminar students, it also created psychological limitations that were often crippling: the quest for absolute precision was in the end an illusion, one that sometimes prevented them from seeing more pragmatic, and quicker, solutions to the problem at hand.

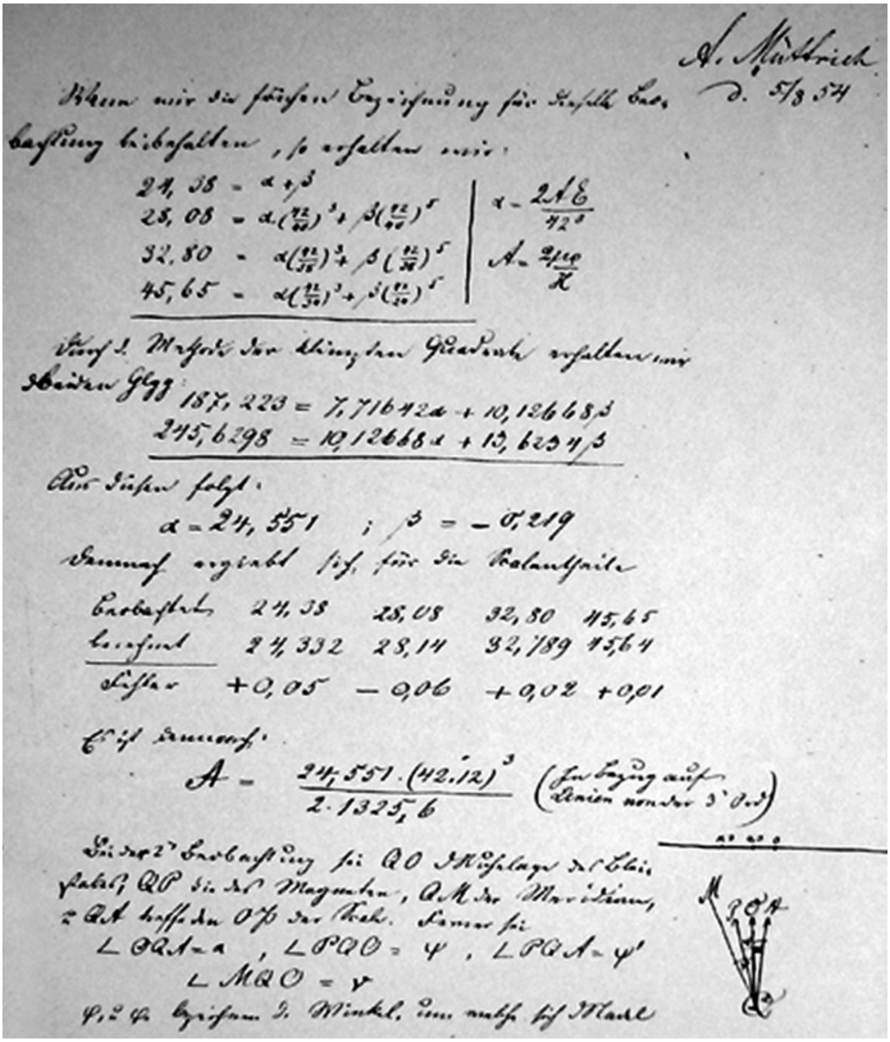
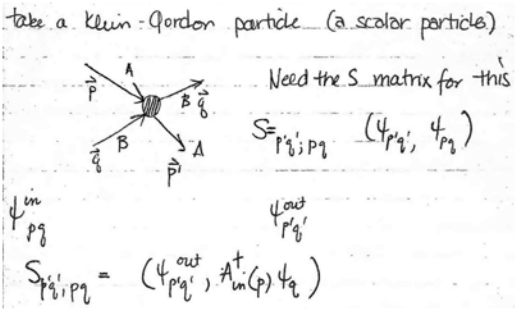


Fig. 60.1 Gottlieb Anton Müttrich (1833–1904), notebook from the physical division of Franz Neumann's seminar at the University of Königsberg, 1854. In his determination of the horizontal component of the earth's magnetism, Müttrich applies the method of least squares, a hallmark technique of the seminar (Source: Arbeiten der physik. Abteilung des mathem. Physikalischen Seminars der Königl. Universität in Königsberg 1854–55. Heft 1 [21945/55]. Abt. Va Rep. 11 Planck 1836/26. Max Planck Gesellschaft Archiv, Berlin)

Like the Königsberg case, other detailed studies of science pedagogy have demonstrated how intensely local some practices were. Warwick's history of the Cambridge Mathematical Tripos, an examination on analytical mathematical methods rooted in Newtonian mechanics, rested on actual tests (but not on the students' answers, which would have revealed how students performed) and other sources that illuminated the process of learning, including the notes of the coaches who offered preparatory training for the test. He concluded that coaches developed such distinctive solutions to problems that when they were applied outside of the Tripos setting, the Cambridge connection was immediately recognized. These techniques were designed to enable the virtuoso performance necessary for scoring high enough on the examination to attain the coveted rank of Wrangler. But at the same time, they restricted analytical solutions to closed algebraic expressions and eliminated infinite series or approximate solutions. The ability to engage in research was not the goal of instruction, yet the impact of these techniques upon practice in physics was profound and long lasting. Of note, James Clerk Maxwell's *Treatise on Electricity and Magnetism* (1873) was not a response to the British Association for the Advancement of Science's study of a suitable electrical metrology (as had so often been assumed), but rather an attempt to resolve pedagogical issues left unsettled when the Tripos incorporated electromagnetic theory in 1868 (Warwick 2003).

The maintenance of the Cambridge coaching system relied on forms of sociability that not only mitigated some of the intense pressures of the examination but that also guaranteed the type of intellectual self-identification associated with a scientific school: face-to-face interaction, bonding with the coach, and small-group learning. This sociability was certainly similar to that attained at Königsberg, but the results were different. Analytical virtuosity was the goal at Cambridge; in Königsberg, competency to pass the state examination for secondary school teachers. At Cambridge the Tripos was for undergraduates, was not in service of a profession, and was part of an intensely local culture. At Königsberg, by contrast, the state examination was for graduate students, was designed to certify the suitability of students who wished to teach mathematics or science in secondary schools, and was administered by academics for the entire state.

Similar to the nineteenth-century examples of Cambridge and Königsberg was the twentieth-century implementation of the newly created Feynman diagrams as a quick way to train physicists, the largest group in the postwar glut of science students. Feynman diagrams were in this sense created to accommodate a particular student clientele. This example demonstrates how a technique that began as a *pedagogical* device ended up as a *standard* tool for solving particular kinds of problems in quantum electrodynamics. In other words, a pedagogical device became a practice not only in the field for which it was created but also in nuclear physics, particle physics, and various forms of experimental physics. Moreover, this new calculational and visual tool "transform[ed] the way physicists saw the world" and eased the conceptual difficulties in teaching quantum electrodynamics (Kaiser 2005c, p. 4). Although the population that used Feynman diagrams was composed mostly of graduate students, the physicists who found them useful constituted a community that recognized the diagram's ability to solve certain problems quickly. Feynman diagrams are thus an example of a pedagogical innovation that was created to accommodate a large student clientele but also became a means to ease the computational tasks in a growing field of science (Kaiser 2005a; Kaiser 2005c) (Fig. 60.2).



take a Klein-Gordon particle (a scalar particle)

Need the S matrix for this

$S_{p'q';pq} \quad (\psi_{p'q'}, \psi_{pq})$

ψ^{in}_{pq} $\psi^{out}_{p'q'}$

$S_{p'q',pq} = (\psi^{out}_{p'q'}, A^{\dagger}_{in}(p)\psi_q)$

Fig. 60.2 Feynman diagram (Source: Kathryn M. Olesko, Notes for PHYS 490: Quantum Electrodynamics, Cornell University, Spring Semester 1973.Taught by Howard Tarko. Author's personal possession)

60.3.2 Science Pedagogy as Learning by Doing

While much of the historical literature on science pedagogy has focused on how science is *taught,* a small but growing body of scholarship has examined how science is *learned.* The methodological challenges of studying the latter are considerable, for the historian must find sources – notebooks, correspondence, and the like – that reveal the experiences, values, and attitudes of students as they make the transition from neophyte to practitioner. How brightly historians have been able to shed light on what transpired in exercises has depended upon available sources, not only written records of laboratory exercises but also instruments used for them. Success has been mixed, and much has to be inferred. Holmes' (1989) study of the relationship between teaching and research in Justus Liebig's Giessen chemistry laboratory relied on traces of laboratory teaching in either Liebig's publications or those of his students, and hence, his findings were necessarily incomplete. Liebig's concerted efforts to transform chemistry instruction through the introduction of the components of research procedures as smaller manageable exercises can only be inferred indirectly.

To varying degrees historians have been able to ascertain the exact exercises assigned to students and to assess their ability to complete them, but largely only for the case of physics. In the United States, Great Britain, and Germany, laboratory instruction began between the 1860s and 1880s, although, in Germany, smaller private instrument collections enabled hands-on learning decades earlier. But here too the results are skewed toward what documentary evidence is available. What is known about British laboratory practices also comes from comments in scientific publications. Far better reconstructed from printed sources are the reasons why such instruction succeeded in the first place and how that instruction was sustained. In Britain the factors contributing to the introduction of precise measuring methods into teaching laboratories between 1865 and 1885 were the development of precise measuring methods in the committees of the British Association for the Advancement of Science (e.g., for electrical standards), the inauguration of a student laboratory at Glasgow by William Thomson in 1855, and the example of professional physicists using precise measurements. Precision in measurement as a part of instruction was legitimated by the presence of a type of liberal education that emphasized rational and accurate reasoning, especially for future teachers; by the need to demarcate scientific methods from craft-based procedures; and by the association of precision measurement with economic production, especially in the telegraphic industry (Gooday 1990).

Industrial connections and lofty ideological goals were less in evidence in the United States when student laboratory instruction started after 1850. Here findings have relied on manuscript sources, laboratory manuals, and the printed record. Laboratory exercises became especially popular after the publication of Edward C. Pickering's *Elements of Physical Manipulation* (1873–1876), a manual adopted by most universities and colleges having the necessary space and instruments for such instruction (Kremer 2011). Laboratory instruction and instrument production were robust and flexible enough in America to accommodate student exercises in the new field of spectroscopy, which relied on precision gratings of sufficient resolution to give sufficiently differentiated visual results for instructional purposes and to do so at affordable cost (Hentschel 2002).

The development of laboratory instruction and the construction of university laboratories in Germany arose in response to student needs around 1870, although private collections afforded the opportunity to offer exercises earlier in the century, especially in Germany's numerous science seminars (Cahan 1985; Olesko 1991; Schubring 1989). For the German case, the archival record is rich and rewarding. Not only do historians have access to student notebooks, student exercises, lecture notes, and annual reports on teaching; they also have, in some cases, notebooks depicting the genesis of laboratory exercises. Such is the case for the most well-known and popular of laboratory manuals in physics, Friedrich Kohlrausch's *Leitfaden der praktischen Physik* (1870), which by 1996 went through 24 editions. Kohlrausch, who became an assistant to the physicist Wilhelm Weber at the University of Göttingen in 1866, worked for 4 years exploring which physical exercises worked best especially for beginning students. He left behind meticulous records of his experiences with exercises, as well as of student responses to them. Historical documents of this type, while rare, provide unsurpassed insight into how hands-on learning took shape, as well as student reactions to it (Olesko 2005) (Fig. 60.3).

60.4 Generational Reproduction

Generational reproduction is a complex issue in science pedagogy because it straddles traditional and nontraditional pedagogical settings. The reproduction of scientists is in one sense the direct result of the efficacy of science pedagogy. Yet that reproduction is also dependent upon robust pedagogical practices at the postgraduate institutions. At the simplest level, handbooks – compilations, distillations, and novel organization presentations of "what everyone knows" – are examples of higher-level pedagogies that sustain scientific practice in professional settings (Gordin 2005). At the next level, bureaucracies like standards institutions have to develop and deploy pedagogy simply to accomplish their mission. For instance, at Germany's Imperial

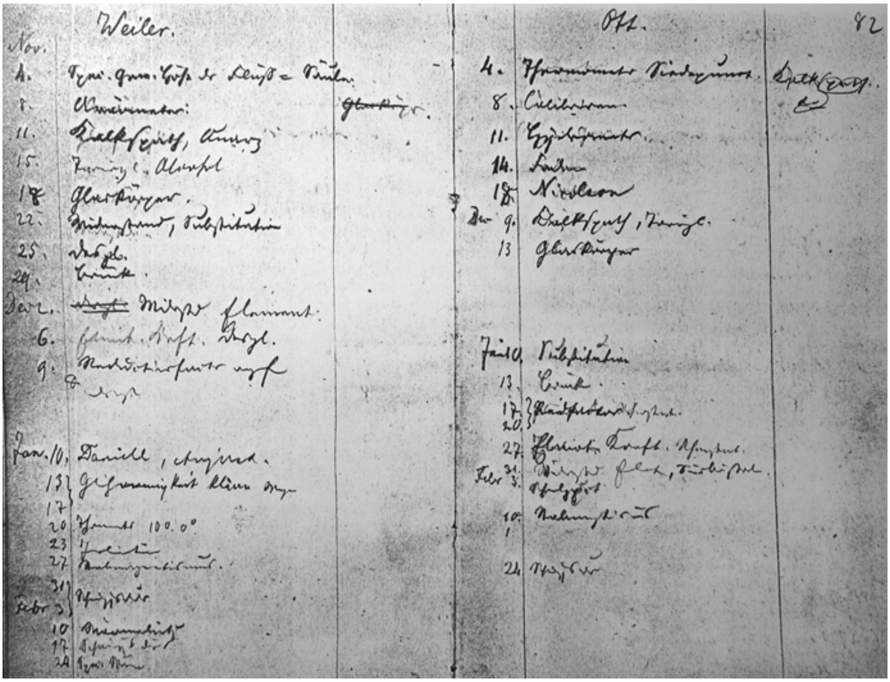


Fig. 60.3 Friedrich Kohlrausch's journal of laboratory exercises assigned to two students, November 1871–February 1872 (Source: Friedrich Kohlrausch Nachlass, Tagebuch Nr. 2504, Deutsches Museum Archiv, München)

Institute of Physics and Technology (established 1887), young physicists fresh from their doctorate had to acculturate themselves by learning the institutional norms of a bureaucracy whose purpose was both fundamental (as in standards determination) and novel (as in measuring black body radiation) (Cahan 1989). Indeed standards institutions around the world rely on higher forms of pedagogy not only for their own practitioners at home but also in order to normalize metrologies across the globe.

Such strategic interventions of science pedagogy have become apparent especially in instances of scientific disputes over the interpretation of data or when analytical representations fail to mesh. As Gooday has shown, pursuing solutions in the manner of the Mathematical Tripos could persist years after taking the examination, resulting in conflict with other professional norms. That's what happened to John Hopkinson who, in posing a solution to a particular electromagnetic problem using Cambridge techniques, clashed with a well-entrenched engineering graphical tradition. In the end Hopkinson accommodated the analytical and practical-graphical traditions, but his story is one that underscores the persistence of science pedagogy in making sense of the world (Gooday 2005, p. 142).

A special case of the strategic role of science pedagogy is found in the realm of nuclear weapons scientists. From 1945 to 1963 when the Limited Test Ban Treaty was approved and nuclear bomb testing went underground, nuclear weapons scientists enjoyed what Gusterson has called the “charismatic” era characterized by high levels of innovation and guidance from physicists whose experience with testing was indispensable for training new recruits in the ways and means of above-ground testing. In the 1970s and 1980s, however, routinization set in, with the result that innovation slowed, bureaucratic hardening occurred, and individual contributions to the effort were small. By the 1993 ban on all testing, experienced nuclear scientists retired; a new generation of scientists came on board to maintain devices they could not test in reality, and virtual computerized testing replaced real-life experiences with the bomb. Less and less knowledge and know-how about nuclear bombs were passed down generation to generation, resulting in an “involuted pedagogy of diminishing returns” (Gusterson 2005). In other words, the absence of real-life exercises (in bomb testing) means that the teachers (older nuclear scientists) could not train students (newer nuclear scientists) in how to use a test as a feedback mechanism to improve a nuclear weapon. In this case, generational reproduction did not so much as fail as wither away.

Yet perhaps there is no more important issue in the realm of generation reproduction than why women are so poorly represented among the practitioners of certain sciences, especially the so-called “hard” sciences. The gender implications and consequences of science pedagogy are critical problems of its history that beg for deeper analysis. As Rossiter (1982, 1995, 2012) has argued for the American case, women’s gains in the scientific professions after initial marginalization and continued second-class status after World War II were ones that took place in the safe haven of women’s colleges, through activism and organization, by piggybacking on the women’s movement, and eventually favorable federal legislation. At the same time, however, educational benefits like the G.I. Bill of 1944 (and later amendments), the National Defense Education Act of 1958, the National Defense Student Loan program, and other Cold War measures to improve American standing in the sciences resulted in the further masculinization of science education at coed institutions.

In both science education and professional settings where postdoctoral training and professional grooming took place, institutionalized science pedagogy did more injustice than good for women scientists through its perpetuation and legitimation of sexism and other discriminatory practices. In addition systems of scientific training produced a gendered hierarchy of fields where the most impervious to allowing women entry were the hard core sciences. Traweek (1988) has demonstrated how training in high-energy particle physics promulgated gendered norms that worked against the incorporation of women. Over the long term, then, science pedagogy replicated the classical gender hierarchy of modernity.

60.5 The Historical Contexts of Science Education

As a disciplinary practice that often finds itself nestled closely to other branches of science and technology studies, the history of science often neglects, ironically, larger historical contexts as a venue for understanding the past. The result for the history of science education is a tendency to view key elements as static categories: discipline, pedagogy, practice, persona, textbook, and other units of analysis tend to acquire universal dimensions faster than they are understood as categories shaped by historical contingencies that change them over time. As a category of *historical* analysis, science pedagogy thus must be viewed from frameworks larger than either disciplinary or institutional history. The problem is to determine how large that framework should be and what factors are important within it.

For instance, the long-term transition from Aristotelianism to natural philosophy can only be understood by looking at what transpired in educational institutions, but to fully understand that transition, other factors such as the intellectual predilections and activities of religious orders have to be taken into account. Key agents in bringing about that transition were the Jesuits who, through teaching and textbook writing, were instrumental in institutionalizing newer frameworks for learning such as Cartesianism, Newtonianism, and, by the eighteenth century, hands-on learning (Brockliss 2006; Feingold 2003). At a later time, Boerhaave's *Elementa Chemiae* took shape within and absorbed the values of the local context of Leiden's religious, medical, and commercial cultures (Powers 2012). Great Britain's social transformation in the wake of industrialization played directly into Forster's innovations, which were implemented when Cambridge education became accessible to a broader socioeconomic clientele (Geison 1978).

In nineteenth-century Germany where mathematics had political value before it had economic currency, intimate forms of seminar instruction instilled in secondary school science teachers a belief in the powerful role of pure mathematics in interpreting physical reality, a perspective their students carried with them to the university (Pyenson 1977, 1979, 1983). Liebig and Neumann trained students for whom state qualifying examinations for secondary school teaching offered the possibility of upward social mobility and greater economic security (Holmes 1989; Olesko 1991).

Foucault thought that the problem of determining the relations of physics "with the political and economic structure of society" was to pose "an excessively complicated question" (Rabinow 1984, p. 51). Studies of physics pedagogy have nonetheless demonstrated a tightly woven connection between abstract knowledge and social norms and values. Warwick turned his study of the Cambridge Mathematical Tripos into a revealing window on Victorian culture by demonstrating how both mind and body were implicated in scientific and mathematical training. Coaching for the Tripos built character and cultivated the values of the Victorian gentleman. Public events surrounding the Tripos were filled with stress and sweat, ritual, and, for the highest-scoring Wranglers, an earned social status associated with merit (Warwick 2003).

Finally, a historically contextualized view of study of science pedagogy offers an unparalleled opportunity to examine the political dimensions, broadly conceived, of science education. Foucault is widely cited for his advocacy of viewing education as a political process: teachers, who controlled classroom disorder and reported on individual performance, were a strategic professional group whose members were the architects of power relations that both defined and disciplined the individual (Foucault 1975). But this focus on disciplining the subject has tended to ignore the degree to which individual agency was circumscribed by the systems and arrangements that make successful science education possible. Consider the nuclear scientists studied by Gusterson (1996). They learned while working in a nuclear weapons laboratory to create divided selves: a self that during the day created and maintained weapons of mass destruction and a self that on evenings and weekends cordoned off the workaday world in secrecy and silence. The history of science pedagogy is thus not only about understanding the transmission of knowledge and generational reproduction: it is more importantly about pedagogy as a moral and political practice where the examination of textbooks, pedagogical techniques, and institutions is part of understanding the structure of power (Giroux 2011), gender relations (Traweek 1988), civil society (Nyhart 2002), and other dimensions of extra-scientific contexts.

60.6 On the Horizon: The History of the Senses

Intellectual flexibility is a prime desideratum for the future of studies of science education: first, in order to make connections to new areas in historical scholarship and, second, in order to begin to analyze what is emerging as the next phase of science education in the early twenty-first century. Two developments – one historiographical and three contextual – loom large as challenges in writing the history of science pedagogy: the history of the senses, the emergence of massive open online courses (MOOCs), the corporatization of the university, and the growing number of technical professionals who bypass formal modes of science instruction en route to positions in the information technology and other economic sectors relying on scientific and technical knowledge. The controversies erupting over the latter three issues are fascinating (especially in the policy realm) and certainly worthy of study; but it is still too early to discern how they fit overall in the history of science education.

Nevertheless, these changes in the form and manner of science education at the beginning of the twenty-first century are designed to assist students where they need help most: in the mastery of foundational concepts. Scientists and policy makers argue that in the "learning science revolutions," training the eye is essential: "Visual representations are crucial to conceptualizing and communicating science, but students often have difficulty interpreting the models, simulations and graphs that are key to attaining a true understanding of science domains (Singer and Bonvillian 2013, p. 1359)." It seems appropriate then to conclude this essay with an examination of how the history of the senses can be incorporated into the history of science education as a tool of analysis as science instruction takes its next turn.

60.6.1 Integrating the History of the Senses

To a degree historians of science have taken the senses, especially vision, into account in their examination of science education. Most of these studies have focused on instruction in the life sciences, but the recognition that new printing techniques in the nineteenth century transformed textbooks has renewed the interest of historians of science in the role of vision more broadly in science instruction.[8] In addition to vision, hearing and touch are central to science learning, yet these have scarcely been studied and perhaps with good cause. Ideological frameworks, for one, make it difficult to isolate the historical roles of the senses. Karl Marx, among others, held that because the senses were alienated from the individual under capitalism, their history was impossible to write. Practical concerns too have impeded an examination of the senses in history. General historians have acknowledged over and over again the difficulties in writing the history of the senses even as they have maintained that cultural conditioning, which varies over time and across space, determines how individuals and groups deploy their senses (Jay 2011).

Science education is not only one of the strongest contributors to that cultural conditioning: science also cannot exist without sensory training, which in turn is a foundation for scientific judgment. Sharpening the senses to the point of achieving a disciplined focus (of several types) is a process that takes place both in science education and the practice of science. How science instruction enabled students to achieve focus is only beginning to be understood. Boerhaave, for instance, considered it essential to train students in the management of sensory data and for that purpose drew upon more general medieval pedagogical methods that fostered concentrated logical thinking. The new public course on instruments that he introduced in 1718 deliberately linked empirical information (the student's sensory perceptions) to chemical theory, trained students to interpret phenomena according to the instruments that measured their qualities (as in using Fahrenheit's thermometer to measure warmth), and educated the senses by disciplining them. His course on instruments thus complemented his course on chemical theory where the objective was to train reasoning processes (Powers 2012). Yet even as science education transformed the senses, the senses have a history of their own outside scientific contexts.

A transition from aural culture to an ocular one occurred in the passage from the eighteenth to the nineteenth centuries, opening the way for what both contemporaries and historians have called *Anschauungsunterricht* – a type of instruction that enables students both to visualize things and to interpret visual images. This passage entailed the cultivation of more impersonal forms of perception when abstract forms of representation replaced mimetic ones as the "culture of the diagram" replaced copying nature (Bender and Marrinan 2010). Moreover, visual learning expanded in the nineteenth century with the introduction of photographs, charts, spectroscopy, graphs, and X-rays. These instrument-mediated images revealed patterns, as in spectroscopy, that were typical of some aspect of nature (the wavelength patterns of elements) but also mysterious as to what they signified beyond a characteristic pattern. Spectral patterns were difficult to interpret, and so the student's perceptual apparatus had to be formally trained (Hentschel 2002, pp. 368–385). In the twentieth century, image-based science exploded to include electron microscopy, moving

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[8] See Anderson and Dietrich (2012), Bucchi (1998), Dolan (1998), Hentschel (2002), and Lawrence (1993).

images, and digital imagery. Concomitantly, images transformed textbooks to the point where "visual literacy" became essential both for science learning and as preparation for scientific research (Anderson and Dietrich 2012, p. 2).

60.6.2 Fleck and the Senses in Science Education

How might historians of science education take into account the history of the senses? Fleck's work (1979) could with profit be used here. By isolating three elements of learning that reshape (and so educate) the prospective knower – experience, cognition, and sensation – Fleck offers a way to view science pedagogy as a process that transforms science students into something they are not. The first, experience, concerns the formation of scientific behaviors like the acquisition of skills through observation and experiment and the ability to think scientifically, both of which Fleck claims "cannot be regulated by formal logic" (Fleck 1979, p. 10). What is seen in the form of "words and ideas," he warns, is merely the "phonetic and mental equivalents of the experience coinciding with them." They are merely symbols (p. 27).

Fleck challenges us to view the past of science education differently by replacing our rapt concern for the transmission of knowledge with a fresh look at the behavioral and psychological transformations of the science learner. Experience, sensation, and cognition are all socialized by training, a process he describes as a transformation of the senses: the "slow and laborious revelation and awareness of what 'one actually sees' or *the gaining of experience*" (Fleck 1979, p. 89). Experience thus reshapes not only our minds but also our bodies. Sharpened vision – the ability to identify phenomena, for instance – is indicative of a state of "readiness for directed perception" (p. 92). In a similar fashion, he interprets cognition as a social activity ("the most socially conditioned activity of man"), making knowledge "the paramount social creation" (p. 42). Cognition can, in fact, only be understood according to Fleck as a deeply historical and contextual process that renders the mind nearly one with the beliefs of others around it. So associations between knowledge and value (say when sickness is linked to sin) can only be explained through the lens of cultural history.

Taken together, experience, sensation, and cognition form the core of the professional habits that a scientist exercises day in and day out. They are the foundation of a "collective psychology" (p. 89) transmitted through education which keeps a scientist within the cognitive framework of his or her community. The main characteristic of a thought style is that through it a trained scientist progresses nearly automatically from a vague perception to a stylized and visual one "with corresponding mental and objective assimilation of what has been so perceived" (p. 95).

What makes Fleck's analysis of scientific training useful for the historical study of science pedagogy is its ability to account not only for *learning* science but also for *becoming* a scientist, a process that entails both mental and sensory transformations. Although the strength of a thought collective depends on the existence of active science pedagogies that can carry the thought style from one generation to the next (Fleck 1979, p. 39), Fleck believed that education, although a constraint that both compelled the learner to see only in a certain way, was also pliable enough to allow for the recognition of experiences that resisted their automatic inclusion in a community thought collective. In this way the learner could also become the creative scientist. Indeed he argued that the inability to recognize resistances was the mark of the "inexperienced individual" who "merely learns but does not discern" (p. 95).

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