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Rekindling Phlogiston: From Classroom Case Study to Interdisciplinary Relationships

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ABSTRACT. First, I show how to use the concept of phlogiston to teach oxidation and reduction reactions, based on the historical context of their discovery, while also teaching about the history and nature of science. Second, I discuss the project as an exemplar for integrating history, philosophy and sociology of science in teaching basic scientific concepts. Based on this successful classroom experience, I critique the application of common constructivist themes to teaching practice. Finally, this case shows, along with others, how the classroom is not merely a place for *applying* history, philosophy or sociology, but is also a site for *active research* in these areas. This potential is critical, I claim, for building a stable, permanent interdisciplinary relationships between these fields.

1. INTRODUCTION

Phlogiston, like the Philosopher's Stone of the alchemists or cold fusion in this century, is often relegated to the scrap heap of misleading, erroneous – and even embarassing – ideas in the history of science. Sir John Herschel was particularly virulent in his 1830 criticism (pp. 300–301):

> The phlogistic doctrine impeded the progress of science, as far as science of experiment can be impeded by a false theory, by perplexing its cultivators with the appearance of contradictions, . . . and by involving the subject in a mist of visionary and hypothetical causes in place of true and acting principles.

We report here, however, on a successful application of the concept of phlogiston in a contemporary classroom (§2). We found the concept effective for introducing students to the notions of metals and oxidation-reduction reactions, commonly considered difficult topics in chemistry to teach. In addition, phlogiston served as a vehicle for discussing the historical nature of science and philosophical questions about realism and reliability. This project may serve as a model for both teaching content and for integrating basic science, history, philosophy and sociology in a science classroom (§§3.1–3.4). The lesson may exemplify what can be achieved while teaching fundamental scientific concepts in a typical high school science course.[1]

This case was also the occasion for a participant-observer study of history, philosophy and sociology of science in the science classroom. The experience of this project, for example, offers a well-situated critique of constructivist models of learning (§3.5). In addition, our experience in the classroom highlighted significant areas for growth in current history, philosophy and sociology of science. Indeed, properly construed, the experience of this project demonstrates the extraordinary potential for professional historians, philosophers and sociologists of science to enrich their own research by collaborating with science teachers and students in the science classroom (§4).

1.1. *Phlogiston*

A fully developed notion of oxidation and reduction as we now view it did not emerge until after a model of the atom provided a framework to characterize reactions in terms of electron transfer. But reduction reactions were known to the first miners and metallurgists, who reduced ores to their corresponding metals. They sometimes considered the metallic property to be conferred by a substance from the fire – an association no doubt made reasonable by the resemblance of a shiny metal surface to the light of the fire. Oxidation reactions, too, were familiar, of course, to anyone who built a fire. By the early 18th century, these phenomena had become linked by the notion of a material principle of fire or inflammability: phlogiston. Using the concept of phlogiston, chemists explained why things could burn and why they would emit heat and light when they did. Wood, oils, alcohol, charcoal, metals, sulphur and phosphorus were rich in phlogiston. Combustion (of organic material) and calcination (of metals) – both oxidations in today's terms – each involved the release of phlogiston. Phlogiston thus powerfully unified the mineral kingdom with the plant and animal kingdoms, earlier considered wholly distinct. Chemists also related reduction to its reverse reaction, calcination: metals lost phlogiston in becoming an earthy material, the metal's 'calx'; ores or calxes gained phlogiston to yield metals. Phlogiston thereby also accounted for the unique properties of metals – their luster, malleability and ductility. The basic notion of phlogiston may be summarized in the more familiar form of equations:

calcination:				
metal	→	calx	+	light, heat
(compounded of		(for us – the		(released
calx + phlogiston		metal oxide)		phlogiston)
combustion:				
charcoal	→	earthy residue	+	light, heat
(rich in phlogiston)				
reduction:				
calx (or ore)	+	phlogiston	→	metal
(from charcoal)				

In today's terms, phlogistonists had identified something akin to chemical energy or reducing potential (Odling 1871).[2] That is, phlogistonists had identified the importance of energy relations in reactions and then described it in material terms.

Later in the century, chemists began to collect gases, or various 'airs', and to examine them as products of reactions. Without knowing about oxygen, they realized that burning was limited by the amount of air, and that burning 'fouled' the air for further burning – and for breathing, too. Drawing on the image of smoke leaving a burning substance into the air, many chemists extended the notion of phlogiston. During combustion, air could become 'phlogisticated', even saturated with phlogiston, and fail to support further burning. Likewise, 'dephlogisticated air' – oxygen, in today's terms – could support extended combustion. In the late 1700s Lavoisier, of course, identified oxygen as a distinct elemental gas, able to combine with other elements in solid compounds. Explanations using oxygen made consideration of phlogiston unnecessary in discussions about 'airs'. In conventional histories, Lavoisier's explanation for combustion – as a reaction with oxygen – conceptually eclipsed all explanations using phlogiston: metals were simple substances, not compounds with phlogiston; calxes were not simple, but compounds with oxygen (e.g., Conant 1957). Indeed, the concept languished in the following decades and since then, phlogiston has become notorious perhaps (as exemplified in Herschel's assessment above) as a substance that never was. Yet by today's reckoning, Lavoisier failed to explain adequately aspects of heat, light and combustibility. Indeed, late phlogistonists criticized these deficits in Lavoisier's scheme, while emphasizing the corresponding strengths in the initial concept of phlogiston (as above, not related to 'airs'). Thus, many could accept the discovery of oxygen, while still maintaining the original role for phlogiston – say, in explaining the heat and light of burning (Allchin 1992, 1994). Understanding this overlap allows one to approach phlogiston and its role in metals without addressing its separate (and less secure role) in pneumatic chemistry. Indeed, because phlogiston had been at the leading edge of efforts to understand combustion and related phenomena, apart from any concerns about gases, it seemed to us ideally suited – despite its sometimes maligned reputation – for exploring conceptions of oxidation and reduction on an introductory level. We 'rekindled' phlogiston for teaching chemistry.

1.2. *Teaching strategy*

This project began as an open-ended collaboration between a high school chemistry teacher and a historian-philosopher of science with a background in science teaching. Our aim was simply to find how we might benefit from drawing on a historical perspective in one case, while also being sensitive to philosophical and sociological factors of science. The final product was left undecided. At the outset, then, our own methodology was guided by a non-teleological and cooperative orientation familiar to many educational constructivists.

METALS	**calcination** (corrosion, rusting, tarnishing)	**reduction** ('reverse calcination')
ORGANICS (Carbon/Wood)	**combustion**	?
	I.	II.

Figure 1. Relationship of reduction, calcination, combustion and – as our students were able to tell us – photosynthesis (here a '?'). The Metals/Organics categories follow a more familiar distinction between Mineral and Plant & Animals Kingdoms. After first elucidating the relationships, we identified column I as 'oxidations' and column II as 'reductions'. Phlogiston is lost in the processes on the left, gained in processes on the right.

We chose metals as a topic because, educationally, it was a definite, though ill-defined problem: the unit was difficult to teach, both conceptually and motivationally, but was nonetheless preliminary to understanding the fundamental concepts of oxidation-reduction reactions. Historically, this would take us into the 18th-century concept of phlogiston, a topic central to research one of us was just then completing. Equally important, perhaps, the case posed an intriguing philosophical challenge about how we might cast a concept with such low historical esteem into a more positive role. This perhaps unlikely choice – reviving an entity now considered not to exist – ultimately proved valuable for teaching in each of these contexts.

Conceptually, our approach to the material was guided (we may say comfortably in retrospect) by the organization in Figure 1. That is, we wanted the students to address and find relationships among the following:

1. reduction of 'ores' (metal oxides, chlorides, etc.) to metals
2. oxidation of metals (calcination)
3. calcination and reduction coupled together
4. combustion.

This provided a fairly well bounded 'problem-space' that each class could explore in a context of inquiry. Students would easily be able to generate and draw on a set of observations largely available in the early and mid-18th century, when the concept of phlogiston flourished.

Pedagogically, then, our strategy was to situate the students as a group of investigators in a historically informed scenario (Johnson & Stewart 1991; see also §3.5.2 below). We guided each class contextually in finding their own way through the problems and their solutions, occasionally asking simple questions to help them see adjacent areas of the problem-space. The students conducted simple experiments and demonstrations, punctuated by sometimes quite extended discussions in which they collaborated to interpret their results and to map out successive phases of their inquiry. Each class was free to pursue its own path, and each eventually tackled the material in a different sequence (see §3.5.1). Our approach was thus fully constructivist, in the sense of working from the students' perspectives and the contigencies of their development (see also §3.5.3). Moreover, our strategy was 'socially constructive', in relying on interaction among individuals – that is, on criticism and cooperation, both in small groups and in each class as a whole (see also §3.5.3).

Sharing curriculum designed in a constructivist mode is challenging because applications are highly contextual and contingent on local features, such as teacher strengths, student abilities and class profiles, curricular setting, institutional resources, time, etc. We assume, however, that one profits from well articulated exemplars or paradigms (Kuhn 1962), and we describe the unit below as concretely ours. We also note specific elements that shaped our project and possible variations that we considered but did not pursue. We present the unit as a flexible and adaptable model.

2. THE CASE STUDY

We introduced the unit with a general overview of the cultural role and importance of metals (e.g., 'The Age of Metals: Can it Last?' from the public television series *Out of the Fiery Furnace*). We then allowed students to observe and record in lab the differences between metals and their 'ores' (or their oxides – their 'calxes' in 18th-century terminology). We also noted the centuries-old problem arising from the economic value of metals: how does one transform an ore into its corresponding metal? We primed the problem further by showing how a metal can apparently 'burn', producing once again its chalky calx (our surrogate ore). We used, first, steel wool, and then, for sheer effect, magnesium ribbon (spectacle may be included along with 'discrepant events' as powerful tools in building images from which to teach). These observations served as foundations for guiding subsequent work, organized around the questions: what is the nature of the difference between a metal and its 'ore', and how does one interpret the transformation from one to the other?

2.1. *Reduction*

One class was particularly intrigued by the smelting process. They started off by researching this for homework. Fortunately for them, we could direct them to a convenient chapter section in their text (!). One could well have used this opportunity, though we did not, to delve deeper into the history of metal technology – elaborating on discoveries in the Iron and Bronze Ages, their implications for civilization, etc. Once students had acquainted themselves with the critical role of 'coke' or charcoal, they were ready to reduce their own 'ores', using partially covered crucibles as mini-furnaces. We allowed different groups to use $CuCl_2$ and CuO, to provide some variation in trials – and to establish the benefit of sharing results.[3] Using their makeshift smelting apparatus, students successfully produced small granules of metal; in some cases, they found a thin, but unmistakably-colored lamina of copper on the outside of their crucible (from vapors which had rolled over the crucible lip and condensed, we concluded). They confirmed the presence of their products through observable traits and tests for conductivity which they had learned on the first day of the unit. The charcoal had been able to confer some metallic properties to the ores. In this laboratory exercise, then, they had established one piece of the puzzle, summmarized in their reaction equation:

$$\text{calx/`ore'} + \text{carbon} \rightarrow \text{A} = \text{metal} \qquad (1)$$

The remaining question was, of course: what was carbon's role? They would need to pursue other inquiries, especially about the burning of coal, before being able to answer this directly. In subsequent investigation, in fact, this class would also learn that they had inadvertently omitted a key product from their equation: where had the carbon gone, or was it part of the metal?

2.2. *Calcination and combustion*

The initial demonstration of 'burning' metals prompted other classes to focus first on the role of the heat of the fire. We provided samples of metal powder for them to roast or 'calcine' in simple crucible set-ups. Again, they noted the recognizable features of the metal calx change. In group discussion, we posed the question whether there was a basis for comparison: did the transformation between metals and their ore-like versions occur elsewhere? Their observations of different samples now provided clues and some cases were forthcoming; others we teased out by suggestion:

tarnishing – of brass candlesticks or doorknobs; of silver jewelry or cups, silverware or other cutlery

corrosion – of bronze statues or copper roofs and pipes – each signaled by distinctive color changes.

rusting – or iron nails or fenceposts, cast-iron frying pans, etc. – also marked by color change.

Our intent, clearly, was to link the science with more familiar phenomena and to use that familiarity as a channel for introducing their emerging theory into a vernacular or quotidian perspective. By comparing these cases with their own, students were able to notice that heat was not exclusively responsible, though it did seem to hasten the process. Most students seemed satisfied by this conclusion and we passed over the opportunity to construct a more carefully controlled experiment. In all cases, however, the metals were exposed to the air or rain or water.

When students reconsidered calcination as burning, they were able to draw on their prior knowledge about the combustion of wood or coal as possibly applicable to 'metal burning'. They speculated about the role of oxygen as a reactive agent or catalyst. Students were able collectively to design experiments to test their hypothesis: compare metals in pure oxygen test chambers with those in oxygen-deprived atmospheres. We recalled that during the early 18th century chemists had discovered different 'airs' and devised the equipment to collect and manipulate them. So we challenged our 20th-century student counterparts to create on their own any special lab materials: how did one obtain this sample of pure oxygen, for example? (How might a modern chemical supplier get it?) The students were forthcoming in suggesting that burning a candle in a closed system would create the requisite oxygen-free atmosphere. They were a bit more baffled about the oxygen, but some remembered a reaction they had done with red mercury powder in chemistry class some time earlier; others suggested gathering the 'air' from plants or seaweed. Again, we had the opportunity to pursue a tangent – here, into pneumatic chemistry – but we opted for a narrower focus and having recognized their conceptualization, we assured them that their tests would confirm their expectations. Another piece was thus added to the puzzle, summarized again in their equation:

$$\text{metal} + \text{oxygen}\ [+\,?] \rightarrow \text{calx/`ore'}\ [= \text{an oxide?}] \qquad (2)$$

This still left open the questions of the light, so dramatically exhibited by the magnesium fire, and of the heat known to accompany burning. Many were ready to speculate that something – akin to smoke, perhaps – was given off during the burning process. (Here, they re-expressed the naive chemical views documented in many cognitive studies – see e.g., Driver *et al.*, 1985 – and we did nothing immediately to suppress the misconception; pursuing a 'strong' constructivist mode, we trusted their own investigations and discussions as a route to a proper conception.) One may note, here, that a role for phlogiston was being established, even as they spoke about oxygen (further comments in §4.1).

2.3. *Coupled calcination and reduction*

Given these preliminaries (and in one case, even prior to completing them), we were ready to introduce formally the notion of phlogiston. We asked rhetorically whether it might not be possible to transfer the metallic qualities from one metal to another, producing a new metal from its ore without charcoal. We then proceeded with what was perhaps the theatrical highlight of the unit, a demonstration of the thermite reaction. In this reaction aluminum reduces iron ore to iron, while it is oxidized to aluminum oxide. The reaction produces spectacular fireworks and enough heat to melt the iron product – which dripped nicely, glowing orange, out of our flower-pot reaction vessel. (One may appreciate why we performed this demonstration on the school's baseball infield.) The demonstration was calculated to have an effect (see above) and the students were suitably impressed by the pyrotechnics, even given our hyperbolic predictions.

Students confirmed the cooled iron metal product by measuring conductivity (resistance). We then returned to the blackboard to summarize the reaction:

aluminum + iron 'ore' → iron + aluminum 'ore' + LIGHT, HEAT! (3)

Though the thermite reaction was not known to 18th-century chemists, we confidently interpreted the results in terms of phlogiston. We announced to the students that they had witnessed the transfer of an inflammable (and metal-conferring) substance, which we called 'phlogiston', from the aluminum to the iron ore, while some was lost, accounting for the light and heat. This, clearly, was what had allowed carbon to reduce their metal 'ores' earlier: carbon was a rich source of phlogiston (witness, for example, the combustibility of coal). Though many remained suspicious, the demonstration allowed the class to recognize and address the strong link between calcination (here, of the aluminum) and reduction (of the iron calx). A transfer of properties of some kind had occurred (and we reminded them of their speculations about things emitted during burning). We sent them home with the entry 'Of the PHLOGISTON' from the 1771–73 *Encyclopedia Brittanica*. The results of all the investigations were ready to be integrated.

2.4. *Combustion revisited and synthesis*

Through several days of following leads, students had accumulated a wealth of 'unfinished' information: about the roles of oxygen in calcination and of carbon in reduction (though this was cast in doubt by the thermite reaction), and about the release of heat and light. To facilitate the synthesis of information from the different contexts, we constructed the table in Figure 1. Once the elements of the table had been explored separately, the organization suggested some broader comparisons and posed several questions. We include some details of this discussion precisely because it illustrates how a teacher must be prepared to follow a multitude of possible paths (see 'Caveats' below). It can also help one unfamiliar with phlogiston to appreciate how to think like a phlogistic chemist.

(a) How did the thermite reaction involving aluminum metal (eq. 3) relate to their earlier reduction exercise involving organic carbon (eq. 1)? (How did top and bottom rows relate?) Can charcoal reduce ore precisely because it can combust – the phlogistic explanation? Does charcoal 'burn' at the same time it reduces metal ores?

(b) Metals become calxes (top row), but what does wood or coal become when it burns (bottom row)? As one student expressed it – catching us off-guard, but delighting us nonetheless: what is the 'calx of carbon'? Alternatively, substituting coal for aluminum in the thermite reaction (eq. 3): what is 'coal ore' as a product?[4]

(c) If oxygen is acquired during combustion and calcination (left column), is oxygen lost during reduction, as the reverse process (right column)?

(d) If light and/or heat are released in combustion/calcination, is heat or light therefore required for reduction (in addition to whatever carbon does)?

(e) If reduction and calcination are complementary processes, is there a process complemetary to combustion? That is, how would one characterize '*reverse combustion*' – the gaping hole, now a question mark, in the chart?

Each comparison provided an entry into bringing information together and for filling in the holes. Students 'discovered' from their own knowledge that coal ore was the more familiar carbon dioxide: a gas, not an earthy material. It must be formed in reducing metals (revealing an additional, missing product in eq. 1). They concluded that calxes must be metal oxides and that reduction must involve the loss of oxygen. Carbon can be a reducing agent partly because it accepts the oxygen. Oxygen is lost in the processes in the right column, but oxygen is gained in the processes on the left – hence the name 'oxidation': a new label that expresses how metallic and organic reactions are unified. Similarly, phlogiston – or some equivalent – must be lost on the left, yielding light and heat, and gained (or required) on the right. The reactions also seem to be coupled: every loss entails a gain somewhere else, and vice versa. But what was reverse combustion? They reconstructed the necessary equation:

$$? + \text{phlogiston (light)} \rightarrow \text{carbon fuel} + O_2 \tag{4}$$

and they did not disappoint us by identifying this as photosynthesis: familiar, but now with new meaning in the context of similar reactions with metals.

All the reasoning here was straightforward, but the students needed time to cross the observational ground several times and notice all the connections. Just as a teacher needs to operate with Max Delbruck's 'principle of limited sloppiness' earlier in the unit, allowing classes to pursue their own investigations somewhat haphazardly, so, too, does one need patience in allowing students to make the conceptual links and communicate them to their peers. But this, too, can be a lesson about how real research in science proceeds: as a balance between blind groping, reasoned guesses about where to go next, and empirical confirmations. We were satisfied that patience on our part was rewarded with the appreciation by students that they had largely reached their conclusions on their own.

Because our students had already learned atomic theory, they were well prepared to appreciate further lessons about what some perceived as the fuzzy concept of phlogiston (why wasn't it on the periodic table?!). Phlogiston, they could interpret in modern terms, was a form of energy that one might construe crudely as chemical bonds. But they also knew that light, produced by the release of phlogiston under one conceptual system, was to them associated with the release and capture of electrons (associated with spectra lines). They thus re-mapped what they learned about phlogiston to what they already knew about atoms. They could easily reinterpret oxidation (calcination and combustion) and reduction in terms of a more sophisticated or more deeply articulated notion of electron transfer. This reinterpretaion is significant, because it demonstrates that one need not follow a strict historical sequence across the curriculum. Historical episodes or vignettes can be used intermittently, even perhaps anachronistically, to great effect.

2.5. *Other opportunities*

The encounter with phlogiston opened several tangential excursions we wanted to pursue more fully, but could not due to our particular schedule. Each could extend the phlogiston/ox-redox unit and/or serve to segue to other units of study.

1. *Sulpheration.* – Despite the term 'oxidation', oxygen is not the only element capable of converting metals into earthy ores. The sulpheration of iron was known early in the 18th century, but did not become a major component in the debates over combustion and phlogiston. Some, however, used the phenomenon to argue that the oxygen theory of combustion was incomplete, and that it could not therfore fully replace the notion of phlogiston in burning, as many at the time contended (Allchin 1994). Some students in one class found that they could get a fine-grained metal to lose its metallic properties by heating it with sulfur powder.
2. *Acid-metal reactions, reduction by hydrogen.* – Some students, prompted by the similarity of calcination with corrosion, wondered if acid could calcine (corrode) a metal. By heating zinc with hydrochloric acid under the hood, they demonstrated that indeed they could. Had they been able to isolate the gas released (clearly evidenced by the fizzing bubbles), they might have been surprised that it was highly

flammable. In fact, hydrogen had been called 'inflammable air' when it was first isolated by phlogiston chemists – and it seemed to have taken phlogiston from the metal as it was calcined by the acid. With a bit of guesswork, they might have predicted that a phlogiston-rich gas such as this could reduce calxes – a speculation that could be confirmed by further testing.

3. *Electrochemistry.* – The thermite reaction offers a suggestive model for the reactions in a galvanic pile – and indeed, Humphrey Davy used a phlogiston-like concept to interpret some of his early work on electrolysis (Siegfried 1964). One can thus pose a challenge to students: given the concept of phlogiston, and the knowledge that some metals seem to be able to release it to others (as in the thermite reaction), can one generate or harness a flow of phlogiston? The reducing potential of different metals (at opposite poles in a battery) could well be interpreted as reflecting characteristic levels or amounts of phlogiston. Here, one would be building on work of many chemists in the 18th century who saw a connection between phlogiston and electricity. The light of electrical sparks, they speculated, was analogous to combustion and indicated the release of phlogiston. Indeed, some researchers successfully reduced metals with electricity – a prediction students might also make under appropriate circumstances (see Sudduth 1978; and Allchin 1992).
4. *Respiration.* – In a classroom prepared to make cross-disciplinary leaps, the discussions of phlogiston, carbon and photosynthesis could lead to a further pursuit of biological oxidations. Here, the burning of wood would be an explicit analog of the 'burning' of plant fuel by an animal.
5. *Mining and metallurgy.* – As noted above, the encounter with metals and ores provides someone with a Science-Technology-Society orientation to linger on the metal industry and the historical developments of the Bronze Age, Iron Age, etc. For example, how does one determine the purity of a metal extracted from its ore – especially of gold or silver, whose values are closely related to their purity?

2.6. *Evaluation*

This project was ripe for several alternative modes of assessment. For example, we asked the students to keep scientific notebooks/journals of their lab results and their thinking along the way. Initially, we planned to have each student summarize his or her observations and interpretations, along with the class's collective reasoning – all in the format of a modest scientific paper, as though they were reporting original research. By the end of this relatively complex project, however, this seemed somewhat daunting. We also passed up the opportunity for peer review – made even more promising by the possible exchange of papers between classes that had reached their own results in slightly different ways. Nor did we ask students to plan a research agenda or experiments that might investigate one of the 'Opportunities' above.

The solution for the teacher, in this case, was to have students write an essay on one of several topics. One option was to write a letter to a phlogistonist (Georg Stahl) and to explain, in terms he could understand, how we now interpret the four processes in Figure 1. A more straightforward version asked about the role of light and heat in the same set of reactions, comparing explanations using phlogiston and electrons. Another, more philosophical topic invited the students to comment on the claim that 'phlogiston is just as real as the electron'. The most challenging (and least selected) question asked students to consider the results of combining of carbon or silicon with (a) coal, (b) iron ore and (c) an acid. The intention, here, was that they might predict or articulate the properties of a 'semi-metal'.

3. COMMENTARY: HPSS IN THE CLASSROOM

What does one gain from rekindling phlogiston in the chemistry classroom? How might one generalize from this case to others? What lessons from this activity apply to science education more broadly?

3.1. *Science*

First, we found that by using the concept of phlogiston, students developed a concrete knowledge of oxidation and reduction that does not rely on atomic theory and its sometimes foreign abstractions. We felt confident that they could relate a broad spectrum of phenomena: they were able to view tarnishing or corrosion as analogous to an extremely slow form of burning (both as a loss of phlogiston); and they could connect (non-intuitively) photosynthesis and the production of metals from ores (both as a gain of phlogiston) – all without having to refer to electrons. By reifying chemical energy or reduction potential as phlogiston, they were prepared to see that oxidation and reduction reactions will always be coupled – where every transfer of phlogiston involves both donor and recipient (and some release of heat and/or light). While one might convey these concepts of oxidations and reductions in more conventional terms, phlogiston provides a comprehensive scheme for organizing the fundamentals before one understands the more detailed mechanism. Perhaps most importantly, on this more basic level, students can participate in framing their own knowledge; one can engage their interest more and give them a greater sense of authority over the concepts.

Even teachers who appreciate the value of history in science teaching may balk at or feel uncomfortable with teaching phlogiston, when one views the concept as not only outdated, but 'wrong'. We hope that our application highlights how the concept was once used historically, and how it effectively captures the basic relationships of oxidation and reduction reactions. That is, phlogiston is far more relevant conceptually than its sometimes undeserved reputation suggests, especially when one does not introduce concerns about gases or confuse them with energy relations. We found that our students were not misled into learning a 'false' concept. They transfered what they had learned to a framework involving electrons, while still appreciating the phlogistic explanations, as well (see below, §§3.2, 3.3).

As noted above, we allowed students to make errors early in the unit without correcting their misconceptions: about carbon possibly combining with ores to constitute metals, or about smoke indicating the release of something material from the fire. Withholding comments at such times was difficult, and required a fair amount of confidence that the students' ensuing research would isolate such errors and correct them. By the end of the unit, these assumptions had indeed resolved themselves into more developed understandings. The danger, of course, was that individuals might not recognize these connections or transformations. In many cases, therefore, we tried to re-introduce the early conceptions into their final discussions, so that they could couple them with their later knowledge and reinterpret them explicitly using their more sophisticated conceptual frameworks. Where possible, we directed questions specifically to the student who originally introduced the simpler notion. Here, we emphasized the revisions and the reasons for shifting explanations. These provided good occasions to acknowledge and celebrate the students' own discoveries and learning.

Experimentally, our lab experience was modest technically, but hopefully rich and challenging cognitively. For example, the question-oriented framework allowed us to ask students to design experiments. Students reasoned both from hypothesis or question to experiment and from experiments to new concepts. Our physical movement back and forth between the discussion area and lab benches, we hope, reinforced their appreciation of the close interactions between theory and observation, and between investigation and interpretation.

Authentic research involves uncertainty. Admittedly, the problem-space we selected was carefully bounded. But it was also shaped by historical awareness. Through historical precedent, we expected students to be able to make discoveries by exploring on their own without getting 'lost'. The students faced (for them) genuine unknowns. Sometimes, in fact, we found it necessary to adopt the role of fellow investigators and pose new questions (in context) to guide further research. Each class seemed to present its own limits or thresholds. We recognize the challenge in framing tasks that are both challenging and not fearfully overwhelming or frustrating (see also §3.5.3).

3.2. *History*

We borrowed the concept of phlogiston from history, but ultimately our project was not completely faithful historically. First, the students had learned about combustion and the role of oxygen – and even about electrons – well before our unit on metals and phlogiston. This clearly contradicted the actual historical sequence. In addition, we used the thermite reaction anachronistically and interpreted it as though it had become known decades earlier, when phlogistonists would have used it to illustrate their doctrine. By contrast, we entirely omitted discussions about phlogiston and air, and metals and acids (see note 2 and §2.5, #2). In a sense, then, ours was not a very historical 'historical simulation'. But our aim was not to replicate or recapitulate history – a goal now questioned by many. Rather, we used history as a tool (Allchin 1993b). The history sensitized us to initial and simplified impressions about reduction and oxidation reactions. It also highlighted the relevant observations for developing the concepts fully. Our scenario was not so much historical as historically informed. More broadly, then, one need not strive to repeat history to find history enriching for teaching science.

In violating historical accuracy, however, we did not abandon the perhaps more important historical principle: respecting historical perspective. That is, we preserved the context in which talking about phlogiston did – and still does – make sense. Our application of phlogiston to the thermite reaction – anti-historical in one respect – was, in fact, governed by just this principle. Nor did we shoehorn phlogiston to fit into a modern concept (see Gould 1990, pp. 244–45, 266–77, on 'Walcott's shoehorn'). We did not treat it as a historical 'precursor' of electron theory, or as an elementary or primitive version of potential energy or reduction potential. Thematically, these links exist; historically, they do not. Throughout, we were sensitive to the historically contextual view – and its virtues and limitations both.

As a result, we think our students learned something about the history of ideas in science. Their final letters to Georg Stahl, in particular, demonstrated that they could see the same data in two ways. That is, when comparing interpretations using phlogiston and electrons, they were able to appreciate the historical change in concepts, along with the merit and context of the original interpretation. They thus understood that ideas can change: even an entry in an encyclopedia (our excerpt from *Encyclopedia Britannica*) can later be considered 'wrong'. Finally, they were able to realize that the development of knowledge is not the mere accumulation of facts. Sometimes there are dramatic reconceptualizations – exemplified in the long-term shift from phlogiston to electrons. By having used the concept of phlogiston themselves, however, they were less likely to see current ideas as self-evident, or to regard as ignorant or foolish those scientists of the past who advocated ideas we now regard as mistaken (see e.g., Gould 1977). Some students also clearly appreciated, by analogy, the tentative status of our current knowledge (about electrons, etc.). Working with the historical ideas, rather than merely learning about them through a presentation, may have been critical to appreciating their legitimacy and thus understanding the historical 'moral'.

Finally, our project also introduced the possibility of going beyond history, or of (re)constructing history only as it might have happened. That is, by pursuing the concept of phlogiston in the contexts under 'Other Opportunities' (§2.5), one could develop a possible post-Lavoisian history that preserved the concept of phlogiston. In a radically confident constructivist classroom, one might well rewrite history (see also §4.2). One can well imagine the lessons about historical contingency and theoretical pluralism involved in building or establishing empirically well-founded theories that might diverge from their historical counterparts.

3.3. *Philosophy*

Our consideration of phlogiston led students to philosophical questions of reliability and realism. If scientific theories can be limited, should we construe them realisitically or not? How would one prove what is real or not? Our success in provoking philosophical reflection may be indicated, perhaps, by the students who stayed after class to argue about whether the phlogiston concept is still relevant – and who also arrived at class the next day brimming with fresh thoughts. For many of our students, phlogiston was not 'real': it was not in their textbooks – and it did not appear on the periodic table(!). Once we had re-introduced the more familiar concept of electrons into the picture, they abandoned the 'old', outmoded concept. As an idea from history, it no longer had 'currency' and could thus be rejected as imaginary, not real. We emphasized the explanatory adequacy of the concept, how it could guide their own interactions with the materials, and asked how else they would judge the concept. Our strategy was to create a 'discrepant event' *in philosophy*. We turned their skepticism back on them: how would they know if electrons (their preferred explanation) were any more 'real' than phlogiston? Did phlogiston, like electrons, not explain things in a definable context? Did phlogiston not help describe and predict the reactions for them now just as effectively as it had for chemists in the 18th-century? They gradually recognized that phlogiston and electrons were both humanly developed, possibly limited concepts. Still, they were grounded empirically and extraordinarily powerful in interpreting the world around us. We could assess the reliability of the concepts without having to answer questions about their reality. The concept of phlogiston, they admitted, was certainly reliable and warranted within a prescribed domain of application – and had been accepted historically within this domain. It could be 'wrong' and 'right' at the same time, depending on context. Phlogiston was as 'real' for 18th-century chemists as electrons are for us now. This, we felt, was a profound philosophical (and historical) lesson about science – and one that could be learned from posing very simple problems.

In teaching, we often adopt elementary theories from history – even those we now construe as 'wrong' – as simple models. For example, textbooks frequently draw on the fluid model of electricity to explain current, resistance, capacitance, etc., especially in complex circuits, though we abandoned the notion of an electrical fluid in the mid-19th century. Likewise, the Bohr model of the atom is a standard part of teaching atomic theory and spectra lines, though by the next week we are often celebrating how it was replaced and shown to be 'wrong' by quantum theory. We use such models because they can help lead students from simple to more complex ideas, but we may need to dwell on their simple applications and contrast their adequacy in certain contexts with their inadequacy in others. These models are excellent opportunities for introducing students to the role of 'models' as conceptual maps, and the ways in which any model both simplifies and misleads (see also Wimsatt 1987a; Judson 1981, Chap. 5 on "Models"). We may need simply to reflect and comment on the virtues and qualifications of scientific models or theories as we teach them.

3.4. *Sociology*

On this occasion, we did not emphasize the social or cultural context of the research. But we did illustrate the social nature of research and the development of facts. Our classes were already accustomed to group work, but we could easily have used the various discussions and the process as a whole to highlight how criticism as well as the sharing of ideas was essential to the outcome. No one person had all the answers – and this method of exchange and critique allowed the group to synthesize their individual strengths. Science, students can learn through experience, is a social, interactive process.

3.5. *Caveats for constructivists: from theory to classroom practice*

The classroom experience in 'rekindling phlogiston' gave the author and a collaborating teacher a practical perspective on applying many popular ideas from constructivist theory. We designed our project keeping in mind various constructivist principles (as interpreted by different proponents) and we feel that the lessons were certainly enriched by applying them. Nevertheless, we encountered many practical difficulties – worth noting here for their deeper implications. The comments are largely cautionary. I hope to raise important questions and pose challenges for further constructivist thinking applied in a classroom context.

Constructivism is an extraordinarily slippery concept, both within educational circles and more broadly in science studies (e.g., Grandy 1995; Sismondo 1993). There is no commonly accepted model. Criticism of any particular model, therefore, would lack generalizability. Instead, the comments below focus on three selected themes common to many constructivist models (characterized more fully in each subsection below):

(1) developmental or stage approach;
(2) cognitive recapitulation; and
(3) student-based inquiry.

The critique, here, is based on detailed case study analysis. In addition, however, I have been mindful to connect my views with the larger debates in science studies. I trust that vivid personal experience, well characterized, can reveal critical aspects of the *practical* dimensions of teaching that is informed by constructivism in a way that many theoretical discussions or formal investigations cannot.

3.5.1. *Developmental or stage models*

Do students learn according to an ideal prescribed sequence of concepts and 'discrepant events'? An answer is fundamental to curriculum design. A cognitive developmental approach to constructivism emphasizes how students build new knowledge on prior conceptions, ideas or cognitive frameworks. Does this imply, however, as some assume, that the learning path follows (or should follow) a predictably unfolding sequence or proceeds through certain invariant stages?

Feminists, among others, have challenged these types of serial or stage models in fields other than science (e.g., Gilligan's, 1982, critique of Kohlberg's, 1981, framework for ethical development). Based on our experience we, too, are skeptical of assumptions about necessary order. Our four chemistry classes found four different ways through the problem space described above (§1.2). Each class pursued topics in its own distinctive order, but all eventually passed through every item on our original list of phenomena:

Class A* → 4 → 2 → 5 → 3 → 1
Class B → 2 → 1 → 3 → 4
Class C → 2 → 3 → 4 → 1
Class D → 1 → 3 → 2 → 4
(*One class also considered sulpheration and treatment of metals with acid, labeled #5: see §2.5, #1–2.)

Each class also raised and addressed its final questions (§2.4) in a different order. We obviously facilitated the ability of all classes to develop a common set of information by choosing a problem-space that was well cross-linked and by guiding students along the way. Yet given a rich collection of phenomena, there were many different ways to reason to a conclusion. We suggest that it may be important to select a field of observations that overdetermines the conclusions (see Wimsatt 1981) or that has multiple ways of reaching the same concept (consider Merton 1973a; for comparison, see Allchin 1993a).

3.5.2. *Constructivism and history: cognitive recapitulation?*

Does the individual student 'recapitulate' history in learning scientific concepts? One widespread theme of constructivism regards history as one – perhaps *the* – model for designing appropriate instructional sequences.

Proponents of this view draw on the biological notion that 'ontogeny recapitulates phylogeny' and postulate that individual conceptual development recapitulates, or parallels, history. While the notion is intuitively appealing, our experience demonstrates that history need not be the exclusive authority in specifying a conceptual sequence.

We taught oxidation-reduction in an historical context, yet students had already learned certain relevant concepts developed only later in history. We introduced the 18th-century concept of phlogiston *after* the students had learned about oxygen and Lavoisier's system of the elements, *after* they had learned the role of oxygen in combustion – even *after* they had learned about electrons, atomic models and the electron's role in light and spectra lines. We allowed students to 'construct' their notions on concepts that, historically, were not available at the time of their historical counterparts. Our chronological juggling, nonetheless, yielded a penetrating interpretation that reconciled phlogiston and oxygen. Indeed, the students' interpretations paralleled many late phlogistonists (Allchin 1992). As a result, our classes encountered no 'Chemical Revolution' (see also §4.1).

Using the cognitive recapitulation model, a teacher may use history too literally. At the same time, we suggest, a teacher can use history too liberally. One might easily want to borrow freely from history, removing a concept, such as phlogiston, from its original context. We were careful to preserve the historical *perspective* and how it could inform our teaching. We reordered history only to enlighten our subject – the science and the nature of history both (see Kragh 1992). We used the thermite reaction anachronistically, for example, yet we interpreted it appropriately (we felt) in a phlogistic context. That is, we regarded it as a phlogistonist would have, had it been discovered earlier. Indeed, our reconstruction gave the idea of phlogiston more support than traditional historical accounts present. We could convey to students the notion that oxidation and reduction reactions (releasing and gaining phlogiston, respectively) would always be coupled – a view never explicitly articulated by phlogistonists. Because we did not present the material in any strict historical format, though, we avoided generating any historical misperceptions (§3.2). We did not violate the historical *perspective* or oversimplify the process of science in adapting the history. More generally, we would stress the difference between: (1) trying to replicate history and (2) using an understanding of historical context in adapting the history creatively (see also Allchin 1995).

3.5.3. *Student-based inquiry: theory and practice*

Who decides curricular content, the student or the teacher? If students, is it the individual or the group as a whole? Does the teacher follow a pre-planned lesson or pursue opportunities as they arise? One strand of constructivism emphasizes the "construction" of knowledge by each individual, based on his or her cognitive orientation and resources. However, another strand highlights the "social construction" of facts by a community. The first implies (at an extreme) a framework of independent, individualized study (allowing each student to proceed in his or her own way). The other stresses group consensus and skills in collaboration and criticism. Our classroom experience illustrates how one might balance or reconcile these two diverging perspectives (see Rowell 1993, p. 122).

On this occasion we highlighted the social, or collective, nature of scientific research. In our classes (as in scientific communities[5]), individuals interpreted experimental findings in different ways and proposed different explanations for the same events. We guided them in resolving those differences, following the spirit of Richard Levins' (1965) wry comment that 'truth is the intersection of independent lies'. Our students thus demonstrated that they could benefit from social interaction in several ways:

(a) by sharing findings from similar, though not identical investigations;
(b) by comparing different interpretations of the same findings; and
(c) by critiquing each other's ideas.

Our students "constructed" knowledge "socially", yet did not become mired in the dire metaphysics of relativism considered inevitable by some commentators (e.g., Slezak 1994). We suggest that while the term 'social constructivism' has generated much controversy, it may be appropriate to describe the experience of our students, in the limited sense of interactive or collective learning.

While our students worked socially, or collectively, we also held each individual accountable for his or her own learning. Each student kept a journal. Many homework assignments were based on individual reflection. The final assessment was also individual, based on each student's ability to use their recorded data, to recapitulate the reasoning of the group, and to interpret the group's conclusions in their own way. In this way, we also preserved a notion of learning as an individual task and responsibility (see BSCS 1996).

A further problem within student-based inquiry is the degree to which a teacher allows each student or each class to guide the pathway of its own learning. In our case, we tried to follow our imagined ideal that students should take responsiblity for their own learning wherever possible. There was, understandably, a deep tension with the teacher's responsibility – and desire – to convey certain fundamental principles. The *teacher* clearly selected the content for this unit. *We* posed the initial problems for the students to consider, though we drew on history to frame a context that could help motivate the students' inquiry. The students obliged us by discovering on their own many of the connections we hoped they would find. But on other occasions, the students felt stumped and frustrated. We had to step in to suggest clues – trying to frame our contributions as fellow investigators, using only the knowledge at hand. In every class, we intervened to introduce the thermite reaction. This was a key element in being able to understand the close relationship between oxidation and reduction reactions. Many students felt that we wanted them to "discover" something and some were anxious, even impatient to do so. Their anxiety may have reflected the fundamental tension between trying to encourage students to "discover" something specific and allowing them to explore on their own.

We were concerned not only that students learn the content, but also that they have a rewarding experience in scientific investigation. That is, we were sensitive to the *affective* dimension of science and wanted to ensure *closure* and *success* in problem-solving in an educational setting. We thus departed from the ideal of student-based inquiry by carefully selecting a problem-space that was relatively simple to explore. We are well aware, for example, that students can learn from lab "failures". At the same time, students are often enormously discouraged by such "failures". We thus invested considerable time in preparing the unit by trying several investigations and materials that the students might likely have selected on their own. We used that knowledge to shape and limit the students' "construction" process, establishing boundaries that would allow the students to explore the phenomena "successfully" without getting lost in the complexity of the real world. Again, the effective teaching scenario was, in some ways, student-based in appearance only (see also Nott & Smith 1995, on 'rigging' and 'conjuring').

As noted, our ideal was student-based inquiry. And, indeed, our students became generally more enthusiastic and more engaged in their own learning. At the same time – paradoxically perhaps – the teacher's workload increased dramatically. We found that to be able to pursue contingencies as they arise, one must be ready to accommodate them. In principle, this is simple. In the classroom, it is not. In planning the unit, we felt the need (confirmed in retrospect) to scout the territory ourselves and be prepared for the many possible contingencies. Many prospective experiments were not fruitful. We were surprised, for example, that using the apparatus commensurate with our students' level of expertise, many metals did not oxidize or reduce as neatly or fully as the simple chemical equations suggest. We also abandoned intentions to replicate Lavoisier's measuring of the weight in calcining metals after finding how difficult it was experimentally to get a complete reaction. History was poor guide, here – and Cohen (1993, person. common.) has underscored how many classical historical experiments, so simple conceptually, are devastatingly difficult in practice (see also Heering 1992a). Planning our phlogiston unit (which covered 7–8 class days) involved six 1–1½-hour sessions. Preparing for contingency, we found, is extraordinarily time-consuming.

Moreover, managing the classes as they followed their divergent trajectories required extra time. To document the variation in discussion from one class to another, for example, one of us took notes (as participant-observer) while the other led discussion. We then needed time to assess the shifting horizon of *each* class and consider where *each* might lead, and how one might respond to *each* contingency. In a few cases, we found ourselves improvising in the midst of class – but not to great effect. Constructivist theory perhaps considers only one class trajectory. But practically, we were teaching four classes. Often, the teacher needed to prep the lab for multiple (different) set-ups on the same day. A further adminstrative concern was to keep classes on somewhat parallel schedules, so that the classes would conclude the unit as an ensemble. Teachers are already challenged by the differences among their classes, but the constructivist aim of capitalizing on contingency accentuates and deepens these problems. The effect was visible in subsequent years. Without an auditor in the room to rely on, the teacher used a more directed version of the unit, where all classes followed a common path and schedule. Given institutional constraints, this teacher clearly found the theoretical ideal of non-teleological curriculum ill-suited to practice. We feel that there is a significant gap between educational theory and practice, which educational theorists need to address.

Based on our experience, several challenges face models of student-based inquiry or learning:

- How does a practicing teacher reconcile student-based learning with aims to convey basic concepts or principles? Pragmatically, does the teacher reserve constructivist strategies only for some occasions, while using more traditional lecture or presentational techniques at other times?
- How does the teacher motivate all students in a classroom simultaneously towards the same end?
- How does the teacher help resolve debate "constructivistically" (without exerting the authority of prior knowledge) where students cannot agree but acknowledge that there should be only one solution?
- How does the teacher ensure that an inquiry will lead to a cognitively productive and affectively rewarding learning experience?

We suggest that these questions are not peripheral to educational theory, but are critical for transforming constructivist concepts into classroom practice.

3.5.4. *Summary on constructivism*

The challenges I cite are as much practical as theoretical. But this makes the problems no less real. Constructivist methods, we found most notably, demand the most precious and limited of a teacher's resources: time. I contend that teachers need adequate professional time to teach in a constructivist style – and suggest that they will (and perhaps already do) abandon the ideal when the time is not available.

I do not wish our concerns to discount the value of constructivism. But I hope attention to the practical context may help redefine the nature of the challenges. Constructivist models are ideal for one teacher with one student with unlimited resources and time. They are far more problematic for a single teacher managing multiple groups of multiple individuals. Researchers need to supplement the conceptual foundations of constructivism with strategies for realizing them in a real setting.

3.6. *Summary*

The 18th-century concept of phlogiston provides an effective structure for understanding the basic relationships of oxidation and reduction reactions, including production of metals from ores, combustion, calcination, corrosion, and photosynthesis. The concept is simple enough to allow students to rediscover it by exploring phenomena easily produced with simple equipment and supplies. Teaching phlogiston illustrates how one may adapt history productively without sacrificing the principle of respecting historical context. The context of phlogiston as a simple model also helps convey philosophically the role of models or theories in science.

4. HISTORIANS, PHILOSOPHERS AND SOCIOLOGISTS IN THE CLASSROOM

The case of rekindling phlogiston is valuable for offering a specific way to teach oxidation-reduction and nature of science, and for exemplifying, more generally, particular aspects of effectively integrating history, philosophy and sociology into science teaching. Yet the case is also significant on an even deeper level. In concert with other cases, it exemplifies how to conceive a more productive relationship between science educators and historians, philosophers and sociologists of science. The spectrum of contributions *from* history, philosophy and sociology of science *to* science education has been extensively documented (providing something of a manifesto for this journal – e.g., Matthews 1992). Yet the many potential contributions *from* science education *to* history of science, philosophy of science and sociology of science – based on the reciprocal relationship – have yet to be fully appreciated.

At first glance, it may seem that teachers can only "apply" the work of historians, philosophers or sociologists: what could a science classroom, where students merely learn about science, possibly offer to someone investigating genuine scientific research? In the face of such skepticism, the most powerful argument must be a robust set of concrete examples demonstrating the purported value – collected and presented below (§§4.1–4.4). Based on these examples, though, I suggest underlying reasons why such cases might have proven fruitful – offering possible clues for identifying other such cases. In addition, I suggest (though more tentatively) more fundamental reasons for conceiving the science classroom as a site for studying real science, not merely science education. My primary aim, however, is to *demonstrate* a hitherto underappreciated value and thereby (hopefully) stimulate further work and provoke further exploration and discussion of these fundamental questions.

Further, I claim that understanding these examples is critical for educators interested in bringing history, philosophy and sociology of science into the science classroom. The interdisciplinary relationship is *social* or *institutional*, as much as it is also based on content or curriculum. To build a productive relationship, educators must consider the motivations that make fruitful collaboration and exchange between individuals in different disciplines possible. In particular, they must recognize and support the contexts that appeal to or draw on the *professional* interests and *research* goals of historians, philosophers and sociologists (§4.5). The examples below show how historians, philosophers and sociologists have a potential stake in the arena of science education, thereby suggesting a strategy for educators in building a more stable and permanent relationship among the fields and enhancing the roles of history, philosophy and sociology of science in science education.

4.1. *New historical horizons*

First, science teaching can inspire fuller, richer history. The case of teaching phlogiston began with a simple historical question, but ultimately led to reinterpreting the Chemical Revolution. Originally, we turned to history for guidance. The teacher wanted to introduce oxidation and reduction, strongly emphasizing the metal/non-metal distinction, and we asked simply: when was this first known? How? Of course, chemists recognized the phenomenon of 'oxidation' before the discovery of oxygen and understood its relationship to reduction well before the discovery of electrons. Phlogiston was our guide. Due to our central aim, though, we were now well situated to appreciate certain elements of the debates late in the 18th century between phlogistonists and 'anti-phlogistonists'. Our preliminary work, and further work by the students, demonstrated that the notions of oxygen and phlogiston (in its early conception) could be used simultaneously. Indeed, the students came to appreciate that both concepts are essential if one is to understand both the material and energetic aspects of combustion, calcination, etc. The two concepts were not mutually exclusive, as is traditionally portrayed. *The classroom experience thereby offered an occasion for reassessing conventional historical accounts.*

In traditional interpretations, the discovery of oxygen and its role in combustion eclipsed explanations using phlogiston – a view widely conveyed with such terms as 'supplanting', 'substitution', 'supersession' and 'overthrow' (e.g., Conant 1957, pp. 65–115; Cohen 1985, p. 201; Holmes 1989, pp. 108, 110, 111). Phlogiston became useless and even 'false' after oxygen (e.g., Herschel's comment, §1). Indeed, many chemists of the period explicitly renounced one doctrine for the other. Because we focused on oxidation and reduction, however, rather than chemical nomenclature or gases, we could perceive phlogiston differently. As it turned out, our perceptions resonated with many late phlogistonists (Allchin 1992, 1994): our interpretations were not wholly anachronistic or Whiggish. *Had I not* *already been pursuing historical research on this topic for other reasons, I would have been prompted to do so by the classroom encounter.* When one examines the historical record more closely, in fact, one finds many late phlogistonists who accepted the discovery of oxygen and argued the points familiar to the students in the case study. One is thus led to an exciting new problem in interpreting the Chemical Revolution: the dramatic shift in lines of research was not necessitated by one approach conceptually replacing the other. The lesson is significant historically. But there is a further, perhaps deeper lesson. While a high school classroom can be guided by history, it can, in its own turn, guide a historian towards important new research.

The phlogiston case would not be quite so notable were it an isolated case. But it is not an exception. A similar pattern occurred when another teacher expressed interest in using history to teach Avogadro's number (Johnson 1992). Avogadro's number, of course, is fundamental in any introductory chemistry class. Yet its history is not readily available. It is not in Partington (1961); it is not in Ihde (1984); it is not in Brock (1994). Accounts of Avogadro's hypothesis abound, but no mention of the number or the corresponding problem of molecular size. (How could historians have passed over something so basic?)[6] The historical question is signficant. But, again, I want to underscore the source of the question. It was generated from a context of teaching science.

An even more significant case involves a group of physics teachers whose experimental work in the classroom has had substantial implications for historians. As part of their instructional program, a group at the Carl von Ossietzky University in Oldenburg, Germany, has constructed replicas of instruments used by Faraday, Joule, Volta, Ampere, Ohm, Coulomb, etc., to make their renowned discoveries. They use the equipment to teach physics to undergraduates in laboratories. Their work in trying to reproduce the original studies has highlighted the craft skills and techniques essential to many of these discoveries. It has also brought to light new historical facts. For example, when the teacher-researchers had problems with Joule's apparatus for studying the mechanical equivalent of heat, they returned to Joule's notebooks and even to the original device on exhibit at the British Museum. Eventually they found that Joule had produced a second rotating paddle that did not correspond to the published design, but that matched some drawings in his notes. It was only this design, the Oldenburg group found, that worked: Joule's published account was misleading, but it had gone unnoticed without the classroom replication (Heering 1992a; and personal communication). More recently, the group has encountered difficulties replicating Coulomb's experiment measuring the inverse square law of electrical charge. Their results have cast doubt on the integrity of Coulomb's published findings (Heering 1992b). Once again, significant *historical* research has emerged from an *educational* setting.

Together, these examples – of phlogiston, Avogadro's number, of Joule's equipment design and technique, and Coulomb's experiment – along with others[7], demonstrate quite vividly the potential contributions to history from the context of science teaching.

4.2. *An experimental history of science*

The work by the physics group at Oldenburg demonstrates how laboratory simulations can have a significant role in historical research, supplementing and extending the more traditional historiographic methods of interviews and examination of original documents. Indeed, many historians have drawn on their previous experience as scientists or on laboratory investigations to help them interpret history (Brush 1992; also Settle 1961, 1983; Stuewer 1970; MacLachlan 1973, 1976; Franklin 1981; Jed Buchwald, person. commun.). The phlogiston case futher illustrates how work of this nature might continue and be significantly expanded in science classrooms.

The students in the case study admirably demonstrated their ability to work productively in a historical context. They became well versed enough in phlogistic concepts to pose questions that an actual phlogistonist in the 18th century might have asked in the same circumstance. For example, students surprised us by pursuing the analogy between carbon and metals, based on both having phlogiston. 'What is the "calx of carbon"?', one student asked. In a different class, another student wanted to know about 'coal ore'. They might well have asked other questions, as well: why is carbon not shiny, malleable and conductive, if it does indeed have phlogiston and phlogiston is responsible for metallic properties? The students were historically naive. They were not biased by already knowing the "right" answers. Their insightful questions, therefore, showed how creative they could be in a historical scenario. They were particularly well situated to do genuine historical reconstructions, not merely simulations.

The students' performance, then, suggests a possible vehicle for asking serious historical questions: through open-ended reconstructions – that is, historical experiments. As noted, the four classes in this case did not pursue possible investigations into sulpheration, acid-metal reactions, reduction by hydrogen, electrochemistry or respiration (§2.5). Each phenomenon, however, was interpreted by some phlogistonists. Historically, for example, in the 1790s James Hutton stressed the role of sulphur as an alternative to oxygen in combustion, an observation that others did not seem to continue to address or pursue investigatively (Allchin 1994). William Withering framed several experiments in the 1780s based on the notion that electricity carried phlogiston (Sudduth 1978), but there is no record that anyone actually conducted them. Even Humphrey Davy speculated as late as 1812 that 'a phlogistic-like theory might be maintained' (Siegfried 1964). Further work by the students here could have illuminated how one might have developed the concept of phlogiston in these contexts in a way that was consistent with conceiving oxygen as an element. How might a phlogistonist have interpreted the galvanic pile, for example? How might one have responded to Davy when he hypothesized hydrogen 'as the principle which gives inflammability, and as the cause of metallization' (Siegfried 1964)? The responses to such questions by naive students in a science class would give concrete substance to possible alternative paths in history. And they would support historians' claims about the role of contingency in history.

Open-ended historical reconstruction will certainly not document history as it actually happened. Rather, it is an occasion for investigating counterfactuals. Historians draw implicitly on counterfactuals each time they suggest a factor of historical influence or importance. But counterfactuals, like all historical influences, are notoriously difficult to prove. As historians of science especially should know, such claims need to be supported by controlled observation or investigation. The constructivist classroom offers a site for such 'experimental history'. Historical reconstruction exercises can never replace the careful archival work which lies at the heart of all good historical research. But it can offer an additional context for evaluating many historical claims. Indeed, it may offer a new standard by which broad claims of historical causation can be measured. The unexpected performance of the students as neo-phlogistonists suggests a possible vehicle for addressing such questions seriously in the science classroom.

The conceptual foundation for the role of historical reconstruction in the field of history is based on the very same claim that makes history relevant to learning science. Similarities between individual learning and history ('cognitive recapitulation') are frequently used to justify, by analogy, using historical cases as models for classroom learning, either explicitly or implicitly. Like any analogy, of course, this analogy can be reversed. The reverse analogy is based on the same similarities and has the same potential to prove fruitful. The science classroom can thus become a model for understanding the historical community (within the acknowledged limits of the analogy). In the case of the students who learned phlogiston, the prospective history still needs to play itself out. We need to return to the classroom and watch the outcome: will they revise and expand their concept of phlogiston, or abandon it as chemists in the late 18th century did? This is an excellent opportunity for a constructivist classroom. Historians may well consider the potential of what could very well be a rich and productive relationship with science classes as a research site for investigating alternative possible histories.

Ideally, the aims of science education can be combined with nothing less than a thoroughgoing *experimental history of science*. This is not a 'history of experimental science', nor a history of science enhanced by experimental investigations (exemplified by the historians discussed in first paragraph of this section). Rather, it is a history of science that relies on testing historical claims through experimental reconstruction. Historians will be able to *test* historical variables and investigate their claims about the effect of particular historical causes by trying to repeat the relevant aspects of history in controlled experiments of model scientists (science students). Again, this is no substitute for careful archival work. But the notion of a *test* should only be able to enhance a claim about historical causation.

4.3. *Problems for philosophers*

A third potential contribution of science education is in introducing new philosophical problems or framing existing problems in new ways. One promising avenue is to explore how science is adapted, often simplified, in educational contexts. What is the implicit philosophy of 'school science' and how (and why) might it differ from traditional philosophy of science? Below, I draw on student perceptions about the history of phlogiston and show how it offers a new perspective for thinking about the traditional problem of theory reduction. Second, classrooms can be relevant for assessing philosophical claims themselves. For instance, the students' use of phlogiston poses some interesting problems for Hacking's (1983) popular argument about realism. Finally, general educational theory about the development of knowledge in individuals poses some questions about how temporal ordering may affect the structure of knowledge. In the case study, students learned phlogiston after learning about oxygen and electrons. Though they ultimately covered the same content as their historical counterparts, did they learn the same thing? The comparison invites deeper consideration of theory structure. Together, these three concrete examples may reflect on the broader potential benefit for philosophers by affiliating with science educators.

First, one may consider how students responded to the problem of conceptual change posed by the phlogiston example. Having first learned the concept, then modifying it in light of their knowledge of electrons (§2.4), the students had a deep personal appreciation of the changing commitments to a theory. Some students were disturbed by the implications about the possible fallibility of current knowledge. They wanted to assert that electrons were real, while phlogiston was not. But they had worked with the phlogiston concept in a context in which it, too, once seemed "right". Nor, by analogy, could they rule out the possibility that the concept of the election might someday be revised. It was not that phlogiston was "wrong", one student argued (eager to distance himself from what he saw as an outdated concept), but that it was limited. For him and for others, the concept of the electron was far more powerful. Here, they were developing on their own a primitive notion of theory reduction commensurate with their level of cognitive development. Still, many admitted further, phlogiston was "real" in a specified context – in this case, functioning across a broad range of oxidation and reduction phenomena. If one did not go outside these boundaries, then they were content to regard phlogiston as real (see also Kuhn 1962, pp. 99–100).

The philosophical problems posed by phlogiston are not uncommon in school science. Teachers frequently draw on simple models – functional at one level, yet deemed "wrong" and misleading at another. These include: the fluid model of electrical circuits, the Bohr model of the atom, basic Mendelian inheritance, and all idealized models such as the gas laws, frictionless movement, and Hardy-Weinberg equilibrium of population genetics[8]. What is the status of these models? In all these cases, the theories or models do not neatly reduce to another on a deeper level. There are often inconsistencies (and sometimes, as in the phlogiston case, ontological differences) between the two explanations. Yet this does not necessarily vitiate the warrant for these models. As the students in the phlogiston case noted, one can explain many phenomena with phlogiston – and it appears "real" – in a certain context. The problem emerges only when one wants to link that knowledge with other knowledge – say, about spectra lines. One then needs an atomic model that includes electrons. The classroom case suggests that many problems about theory reduction or 'levels' of explanation may be profitably conceived instead as problems about the relation between local and more global explanations. Similar in spirit to recent semantic interpretations of reduction, this approach would stress the role of domains or scope of explanation (Shapere 1984). For example, why is specifying domain critical? Unlike semantic conceptions, however, the local/global problem-frame would focus more on the role of interfield theories (Darden & Maull 1977; Wimsatt 1976). For example, how does one characterize the relationship between the domain of phlogiston and the domain of atomic theory? How are the two theories linked, though incompatible? A philosophy of 'school science', then, far from being an analysis of elementary knowledge or diluted versions of more sophisticated theories, poses some fundamental questions about realism and reconciling alternative accounts of nature.

A second contribution to philosophy of science was exemplified by the phlogiston case. Hacking (1983) has argued that what makes entities 'real' – what warrants trust in their existence – is our ability to use them to interact with nature: to intervene. For example, because scientists can investigate hypotheses about fractional charge by spraying a niobium sphere with electrons, then electrons are real. For Hacking, 'if you can spray them then they are real' (pp. 22–23). Hacking has characterized phlogiston, by contrast, as the quintessential non-existent natural kind – something that is not real (pp. 86–87). Yet according to Hacking's own criterion, phlogiston must be real, because students in the case study could 'spray' phlogiston. That is, they successfully manipulated it in the lab. They released it from metals. They transferred it from charcoal to metal oxides. The teacher transferred it from one metal to another in the thermite reaction. Indeed, these *interventions* were not that different from those of the 18th-century chemists, who also construed phlogiston realistically. In addition, they reduced metals with the phlogiston in electricity. They proposed using the phlogiston in electricity in other ways consistent with their conceptual model: to burn diamonds, to blacken concentrated vitriolic acid, to effect changes on lime water, perfectly caustic alkali and acid of phosphorous (Sudduth 1978). How does Hacking's argument fare in this case? The answer, here, is not nearly as important as the source of the question: the science classroom. Science teaching can provide a context relevant to central philosophical discussions.

A third set of philosophical concerns arise from the broader process of learning itself. Educators have devoted considerable energy to understanding how knowledge develops based on earlier knowledge. In developing 'constructivism', they address themes not embodied by those in philosophy of science who use the same term. Philosophers have certainly considered questions of conceptual change on a historical time scale (Fleck, Kuhn, Hull, etc.) as well as on the level of individual scientists (Tweney, Nersessian, Giere, etc.). Yet philosophers of science have yet to consider fully how variation in sequence of learning may affect the structure of the resultant knowledge. The same set of concepts, addressed in two different orders, may lead to two different final conceptual structures. That is, the specific sequence in which concepts are adopted, not merely their content, may be relevant epistemically.

Students in the phlogiston case study demonstrated the potential implications. They approached the concept of phlogiston having already learned about oxygen and its role in combustion. They were thus positioned to appreciate certain 'novelties' captured in the phlogiston concept without trying to apply it further to interpret changes in the air (as was done historically). They thus did not find explanations using oxygen and phlogiston to be incommensurable, as portrayed by Kuhn (1962, pp. 56, 118; see also Conant 1957; Siegfried 1989; Margolis 1992). Their new observations did not violate any paradigm-induced expectations. There was no proliferation of versions of phlogistic theory, which Kuhn interpreted as indicating a 'crisis' in the historical episode (pp. 70–72). Students did not need to 'save' their theory by restricting the range of phenomena (Kuhn, p. 100) because the range of phenomena was already restricted. By approaching the Chemical Revolution from an historically reversed direction, these students encountered no revolution at all. Their example strongly implies that had oxygen been discovered earlier, or before Stahl had introduced the notion of phlogiston, a Chemical Revolution in a Kuhnian sense might never have occurred. Order of concepts or observations thus seems to be significant.

The students in this case also learned about electrons prior to learning about oxidation-reduction reactions. Did this affect how students assessed electrons and phlogiston as alternative explanations? What factors influenced either their readiness or reluctance to abandon phlogiston and to follow another interpretive framework? Similarly, the four classes in the case study followed different paths of discovery (§3.5). Guided by us, they seemed to arrive at the same ideas. Did they, in fact, learn the same thing? Is the internal structure of their knowledge comparable? Will they continue to build on this knowledge in the same way, localize new anomalies in the same way, identify significant new problems in the same way? The classroom case invites the question: does the *order* in which one acquires concepts affect *what* one knows?

Wimsatt (1987b) has addressed the notion that once ideas are adopted they form a basis for organizing knowledge "downstream". Concepts adopted early, he claims, become central to the matrix of subsequent ideas. To the extent that later ideas build on and thereby rely on pre-existing ones, the earlier ideas become developmentally or 'generatively entrenched' and thus resistant to change. For Wimsatt, historical or developmental order of concepts significantly affects later episodes of conceptual change. Given the classroom experience, Wimsatt's model offers a promising framework for addressing philosophical questions regarding the role of sequence in the emergence, modification and occasional abandonment of knowledge in science. The developmental model of theories is ripe for work, and certainly the most fruitful way to proceed is to open a dialogue with educators.

4.4. *Opportunites for sociologists*

The science classroom is, of course, a rich society. When members of the class interact in constructing knowledge, they can thus model the dynamics of a scientific community (Finkel 1992). Sociologists of science familiar with Pickering's account of *Constructing Quarks* (1985) may well appreciate how this situation offers 'opportunities' for research.

The phlogiston project was not designed to focus on social factors in education or science. Still, some informal observations can suggest the potential of science classes as objects of study for sociologists of science. First, the reward and motivational structure in this class differed from contemporary science (or science in the West since the Scientific Revolution). For example, no credit was given for individual contributions beyond personal satisfaction and the pleasure of performing well among peers. Though the teacher organized groups for lab work, he did not adopt a framework of competing teams. Indeed, the teacher encouraged cooperation and opened ways for all students to participate. Is this system more productive than a competitive one (as suggested by Johnson et al. 1984)? If so, how might a motivational or reward structure for real scientific activity be structured to achieve this? One can see the potentially far-reaching implications for science policy. Social studies of the science classroom, however, may well offer the initial model on which new policy is developed.

Second, classroom dynamics in the classes investigating phlogiston were visibly affected by personality and by the relationships that the students established outside the classroom. Ideas advanced by "popular" students and those presented confidently tended to receive a more favorable hearing by classmates, at least initially. Though sociologists have examined the role of credibility and rhetoric in publication and acceptance of ideas, the classroom elements may be important variations yet to be elucidated in the professional community. For example, what is the role in science of professional friendships – of acquaintances from graduate school, of social gatherings at conferences, etc.? In addition, because the teacher promoted a cooperative environment, he elicited contributions from individuals that were otherwise silent or less outspoken. Some of the ideas introduced in this way were significant for certain classes. Again, is there an important corresponding role for this type of activity in the professional community – say, through review articles or conference sessions? Science classes offer a starting place for thinking about these ideas.

Sociologists may recognize the unique opportunities offered by small communities under relatively regulated conditions. The classroom can provide similar cases where certain variables can be studied in detail. Multiple classes within the same institution and with the same teacher provide an exceptional occasion for observing social variation against a relatively stable cultural and institutional background. Most importantly, perhaps, one can conduct research with modest investments of time and resources.

4.5. *Science teacher as collaborator, science classroom as research site for historians, philosophers and sociologists of science*

The examples in the preceding sections are more than mere curiosities. As exemplars, they are important tools for educators in encouraging or developing involvement by historians, philosophers and sociologists of science in education, thereby ensuring the quality of addressing the nature of science in the science classroom.

Educators should be concerned about the involvement of these professionals for several reasons. First, the history, philosophy or sociology that teachers incorporate or adapt into their educational lessons should be accurate and reflect expert opinion – best expressed by the professionals in their respective fields. For example, short biographical sketches of scientists or brief historical vignettes already pepper science textbooks, indicating at least one widespread use of history in science teaching. But these brief sections often follow Whiggish or "Great Man" views of history, now in widespread disrepute among professional historians of science. Professional review of the portrayal of the history and nature of science in the curriculum is needed.

Second, knowledge in each of these fields changes. Approaches to science teaching should reflect these intellectual developments. For example, at one level, philosophy has had an enormous influence on science education. The "scientific method" so firmly entrenched in textbooks and science curricula embodies much of the hypothetico-deductive model of science and was derived directly from positivist notions of philosophy popular in the 1950s and early 60s. Yet the consensus view among philosophers changed dramatically in the 1960s. While "the" scientific method is now frequently criticized even among educators as being too simplistic, philosophers were not a part of the educational community and did not effect a change there as it occurred in their own community. The links between those who study history, philosophy and sociology of science and those who teach science need to be sustained more permanently.

Third, there has been considerable discussion recently about what or "whose" nature of science is incorporated into science teaching (e.g., Harding 1991). There is substantial controversy, for example, between current sociological and philosophical interpretations. Which view of science should guide science education? The problem is compounded by the fact that not even professional philosophers in the same community agree about the nature of science (Alters 1995). The corresponding strategy among educators must be to bring those active debates into the science classroom – to promote discussion about the nature of science, rather than to teach any one particular version of it. This requires a close and on-going relationship between the fields.

Finally, and perhaps most important, one might see the challenge of integrating history, philosophy and sociology of science into science teaching as a joint endeavor, best achieved through synergistic effort. In this view, science educators must develop a close working relationship with historians, philosophers and sociologists that goes beyond simply reading their literature. For these many reasons, science educators may well view incorporating history, philosophy and sociology into science teaching not so much as simply applying knowledge as linking the professional communities.

But is involvement by historians, philosophers or sociologists a problem? Consider: from the perspective of a professional historian, philosopher or sociologist doing research, why is contributing to science education important? Personal interest or commitment, or a sense of service or "charity", perhaps? Educators would do well to recognize that historians or philosophers who contribute to science education receive no professional credit from their peers for their contributions. Even worse, such involvement "outside" the field is often viewed askance by colleagues as peripheral and not worthy of "true" professionals. While a handful of historians and philosophers (and an even smaller handful of sociologists) do now contribute to the science education literature (see, e.g., Finley *et al.* 1995), it is a decided minority. Moreover, patterns of institutional rewards discourage involvement. Those that are already involved face an uphill battle trying to encourage their colleagues to participate. While no educator would want to dismiss existing contributions based on personal commitment or a sense of service, these motivations are no basis for building a long-lasting or stable relationship between the disciplines.

One source for the unstable social structure, I claim, is the image that educators merely *apply* the research of historians, philosophers and sociologists. As a result the relationship between them is conceived asymmetrically: educators need the historians, philosophers and sociologists, but historians, philosophers and sociologists do not need educators. I hope my examples above show quite the opposite: that there are good reasons for them to take an active interest in what goes on in science education. Science educators will benefit from supporting or nurturing a more symmetrical relationship where benefits flow in both directions and the interests in exchange are mutual.

Many educators have turned to history, philosophy and sociology of science to enrich science teaching. Yet they may profit from recognizing that they also come to these fields with resources of their own to offer. Educators aware of such resources will be better positioned to stimulate and strenghten the interest of researchers from history, philosophy and sociology of science in the problems of science teaching. The educational community, in turn, will be further enriched by researchers who come to the classroom with a focused interest.

In the final sections of this paper, I hope to have highlighted the ways in which the relationship between the fields of science education and history, philosophy and sociology of science can be one of mutual benefit and exchange. In the prospective portrait I am painting here, science teachers and historians, philosophers and sociologists of science are collaborators, both in education *and* in studies of science. With a strong working relationship in place, science teachers will be better able to draw on the expertise of historians, philosophers and sociologists of science, who will be more sensitized to how their findings become useful in another context. Teachers will contribute, as well, from their own area of expertise. Historians will benefit from working with teachers on historical reconstructions as historical experiments, philosophers from working with teachers on the concrete problems of how scientific knowledge is generated among naive individuals, and sociologists from working with teachers on the social dynamics of model scientific communities. The science classroom is not just a point of application for studies about science. It is also a source of engaging questions and a site for active research in history, philosophy and sociology of science.

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NOTES

1. This paper expands on a briefer report published elsewhere (Swanson and Allchin, forthcoming).
2. Omitted in this brief account is the phlogistonists' approach to acids (e.g., sulfur as a compound of acid and phlogiston).
3. In our own tests before the unit began, tin, zinc and magnesium compounds did not prove as reliable in yielding identifiable products; lead, though potentially effective, was ruled out for safety reasons. By eliminating possible sources of experimental 'noise' – that is, by ensuring interpretable findings of some sort – we definitely made the task artificially simple. What we lost in 'authentic' constructivist methods, we gained in time and coherence of an already complex conceptual trajectory.
4. Here, students had fully adopted the historical perspective, enough to construct original questions within it. So far as we know, no one articulated the notion of carbon dioxide, then known as 'fixed air', as comparable to a calx of carbon. But the suggestion poses interesting historical questions: did anyone explicitly state the connection in this way? If not, why not? (see §4.1).
5. The view that all students are equivalent and that each will reach the same conclusions given the same data parallels Merton's (1973b) norm of 'universalism' – which casts individual observers as equivalent. Recent studies show, however, that real scientific communities do not match this ideal (e.g., Rudwick 1985; Hull 1988; Glen 1994). Indeed, both sociologists and hardcore experimentalists have found that resolving these differences in interpretation is central to scientific conclusions (e.g., Latour & Woolgar 1979; Franklin 1986).
6. Experiments to determine Avogadro's number did not occur until early this century (published by Languimir in 1913). In this case, the teacher found a brief treatment of the core problem of molecular size buried in a book on membranes and Benjamin Franklin's studies on the damping of waves with oil (Tanford 1989).
7. Another striking example of incomplete history is Kettlewell's now classic experiments on the evolution of peppered moths. The case is presented or referenced in virtually every introductory biology text as evidence for evolution by natural selection. Yet historian/biology professor Joel Hagen found no substantive historical accounts and available information grossly inadequate. By consulting the original papers, Hagen found, for instance, that the controls on the study were rather weak, and that the results were not immediately embraced by the scientific community (Hagen 1993; Hagen, Allchin & Singer 1996).
8. For a recent and thorough criticism of the fluid model of electric current in science education, see Stocklmayer and Treagust (1994). This critique may typify the current debate in that it highlights but does not address or resolve the fundamental philosophical status of simple but 'false' models (see also Wimsatt 1987a).

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