The Interaction between facts, ideas, and language in Lavoisier's chemistry practice: the case of the study of the composition of air

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Abstract: According to Lavoisier the physical sciences embody three important ingredients; facts, ideas, and language. Ideas had to be consistent with the facts generated from experiment and observation and language needed to be precise and reflect the known chemistry of substances. Lavoisier had no time for what he termed theoretical speculation about the fundamental nature of matter and avoided the use of the atomic hypothesis or Aristotle's elements in his *Elements of Chemistry*. In the preface to this famous work he claims he has good educational reasons for this position. This paper examines the extent to which Lavoisier kept to this agenda in his famous experiment on the composition of air and the implications of this for chemistry education are considered.

Introduction

In the 1930's the then professor of chemistry at the University of London, F.G. Donnan, proposed that, while the first great synthesis of *physical principles* occurred toward the end of the 17th century and culminated in Newton's famous *Principia Mathematica,* the first great synthesis of *chemical principles* occurred toward the end of the 18th century and culminated in Lavoisier's great *Traite Elementaire de Chimie* (McKie 1935, p.7). In the preface to this famous work Lavoisier sets forth his commitment to facts as determined from experiment and observation as follows: "We must trust to nothing but facts: these are presented to us by nature and cannot deceive. We ought, in every instance, to submit our reasoning to the test of experiment and never to search for truth but by the natural road of experiment and observation" (Lavoisier 1789, p.2). However, in categorizing his chemistry as a branch of physical science Lavoisier understood his chemistry to involve not only the facts of experiment which he sees as the objects of science but also the ideas which represent the facts and the language by which the ideas are expressed. It is in this context that Lavoisier gives no consideration to the constituent and elementary parts of matter as detailed in Greek philosophy such as in Aristotle's four elements of earth, air, fire, and water or indeed the atomic hypothesis of Democritus. He classifies a discussion of such as of a metaphysical nature, grounded in a philosophical tradition, and without any experimental justification.

In contrast Lavoisier relies on a practical definition of element or principle of a body using the

> idea of the last point which analysis is capable of reaching. (Thus) we must admit, as elements, all the substances into which we are capable, by any means, to reduce bodies by decomposition. Not that we are entitled to affirm that these substances we consider as simple may not be compounded of two, or even of a greater number of principles; but since these principles cannot be separated, or rather since we have not hitherto discovered the means of separating them, they act with regard to us as simple substances, and we ought never to suppose them compounded until experiment and observation has proved them to be so (Lavoisier 1789, pp.3-4).

Lavoisier did not deny the existence of atoms as the ultimate constituents of substances but did not have at his disposal any experimental test for their existence. Bensaude-Vincent and Simon note that, "Lavoisier's famous definition (of element) cited above, while it puts into

play what might be termed a positivist scepticism concerning the accessibility of the ultimate components of the material world, is not necessarily anti-realist……..Ultimate constituents of substances are not real just because they are not yet known" (Bensaude-Vincent & Simon 2008, pp.180-181).

Lavoisier's chemistry program involved determining the constituent principles of bodies, in terms of his practical definition of elements or principles, through the processes of analysis and synthesis. In the famous composition of air experiment Lavoisier believed that his heated mercury was able to divide air into two components, one that supported combustion and one that did not support combustion. How did one know that these components resided in the original air sample and were not the product of mercury or glass changing air into a different element or combination of elements? One way of checking this possibility was to combine the two separated components and check if the product of the combination had the same properties as the original air. However, it bears remembering that these procedures of analysis and synthesis did not originate with Lavoisier. Bensaude-Vincent and Simon indicate that alchemists "had long practiced the complementary processes of destruction and reconstitution as a way to counter accusations of trickery" (Bensaude-Vincent & Simon 2008, p.86). Moran links Lavoisier's so-called modern chemistry with alchemy by suggesting that, "Separating the supposed rational purity of chemistry from the alleged logical impurities of alchemy as a way to establish the compelling features of a new chemical discipline is also misdirected because chemistry itself did not so much replace alchemy as subsume it" (Moran 2005, p.184).

There is no doubt that when Lavoisier devised, conducted, and subsequently interpreted his composition of air experiment he depended upon ideas which were not just speculative but had some justification in experiment and observation. For example, he considered all substances to consist of a BASE component surrounded by heat matter which he called CALORIC. In the transition from solid to liquid to gas more caloric was added to the base and this idea was consistent with the experimental fact that one needed to heat a solid to convert it to a liquid and further heat was required to convert the liquid to a gas. One could say Lavoisier depended on the caloric theory in his investigations but the idea was consistent with practical circumstances. If Lavoisier was to comment on the nature and constitution of caloric he would have regarded himself as entering the field of speculation, an area he attempted to eschew at all costs. Bensaude-Vincent and Simon (2008, p.87) maintain that just because an idea might be classified as theoretical doesn't mean it is necessarily speculative. Such theories can have profound practical applications. For example, in the composition of air experiment, if one regards the red solid left in the flask as resulting from the combination of mercury and a component of air, one would expect heat to be liberated in the reaction since there has been a conversion from gas to solid leading to a release of caloric. The following details of the composition of air experiment are worth noting.

The Composition of Air Experiment

The apparatus used by Lavoisier is shown in Figure 1. Four ounces of pure mercury were heated over the furnace for a period of 12 days. The volume of air in contact with the mercury decreased from 50 cubic inches to about 42 cubic inches over this time and 45 grains of red solid had formed on top of the mercury. The 42 cubic inches of air remaining in the system extinguished a glowing taper. When the 45 grains of red solid were heated in a retort over a furnace 41.5 grains of running mercury were collected and 8 cubic inches of elastic fluid with properties similar to that reported by Joseph Priestley were formed. That is, this elastic fluid supported respiration and combustion better than common air. All volumes were

recorded at the same temperature and pressure (10^0 and 28 inches of mercury), all units referring to 18^{th} century French units.

It is surprising that Lavoisier didn't rely on experimental technique to ensure constancy of temperature and pressure given his emphasis on experiment and observation in chemical techniques. Instead he relied on a mathematical calculation based on Mariotte's

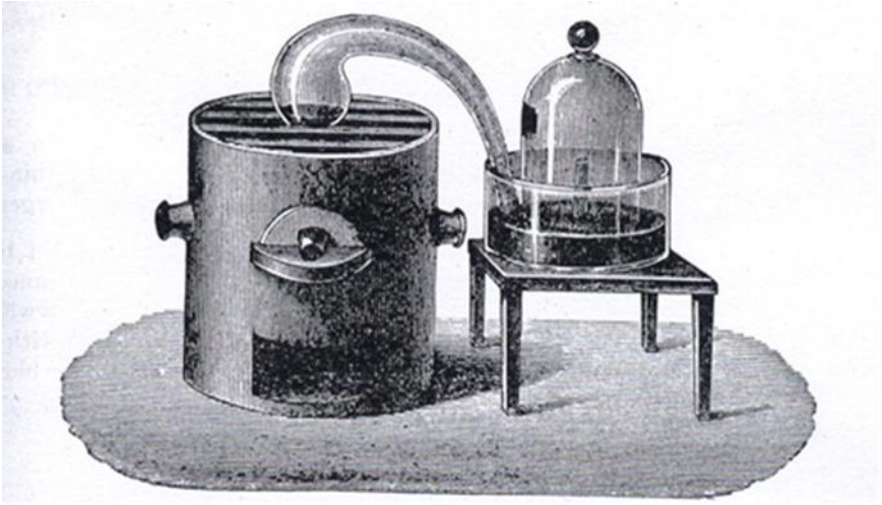


Figure 1. Lavoisier's apparatus for studying the composition of air.

(French) or Boyle's (English) law for pressure constancy and the then known expansion characteristics of a gas with temperature for temperature constancy. On the other hand this may not be so surprising given Lavoisier's respect for the Abbe de Condillac who promoted the use of algebra as an exact language and the experimental difficulties associated with such a requirement of constant temperature and pressure.

What conclusions did Lavoisier draw from his composition of air experiment? We suggest the conclusions may be categorized in four ways as follows.

1. Air can be divided, or decomposed (a term sometimes used by Lavoisier) into two elastic fluids, one that supports combustion and one that doesn't support combustion.

This conclusion appears to be consistent with Lavoisier's practical definition of elements and his endeavour to appeal to his experimental observations. One could argue, of course, that there could be more than one elastic fluid present that supports combustion and more than one that doesn't support combustion. This argument could be true, of course, but it is speculative, going beyond what Lavoisier's experiment revealed. Lavoisier gives no indication of this possibility in his text. Given that air consists predominantly of nitrogen and oxygen Lavoisier's conclusion was fairly close to what the composition of air turned out to be but of course things could have been different if argon had occupied say 30% of the air.

2. In Lavoisier's own words: "Although this experiment furnishes us with a very simple means of obtaining the two principal elastic fluids which compose our atmosphere separate from each other, yet it does not give us an exact idea of the proportion in which these two enter into its composition" (Lavoisier 1789, p.18).

From the quoted experimental values one would expect oxygen and nitrogen to constitute 16% and 84% of the atmosphere by volume respectively. Lavoisier does suggest later that the percentages are more like 27% and 73% respectively. While he does refer to some of the

experimental difficulties associated with this experiment and the need to repeat the procedure a number of times his main reason for inaccuracy appears to reside in a speculation about the relative attraction of the respirable part of air (oxygen) to mercury, to caloric, and to the non-respirable part of air (nitrogen). In other words, according to Lavoisier, not all the respirable or vital air was attracted to the mercury. Some remained attracted to its caloric and some remained attracted to the mephitic or non-respirable part of the air. This approach appears to be out of character with Lavoisier's insistence on referencing his ideas to his experimental results. Perhaps Joseph Priestley was partially justified in accusing Lavoisier of relying on metaphysical speculation (Hedley Brooke 1995, p.18).

3. If the base of respirable air is combined with mercury it follows that caloric must be disengaged during the process.

Because of the slowness of the mercury reaction and the close proximity of the furnace to the reaction chamber it was difficult to demonstrate that the reaction was exothermic. So Lavoisier chose a faster reaction, one with iron, to demonstrate this principle. A large amount of heat and light were detected from the iron reaction which confirmed Lavoisier's understanding of the role of caloric in the states of matter. It is interesting to note that $\Delta_r H^o$ for the mercury reaction is -181.7 kJ/mol while for the iron reaction it is -1648.4 kJ/mol.

4. New language for the two elastic fluids can be based on their chemistry.

We know that Lavoisier was assisted by de Morveau, Berthollet, and de Fourcroy in the development of a new nomenclature for chemistry (Lavoisier 1789, p.4). As far as the elastic fluids associated with the composition of air experiment are concerned, Lavoisier retains "the word *air* to express that collection of elastic fluids which compose our atmosphere" and the term *gas* as "a generic term expressing the fullest degree of saturation in any body with caloric; being, in fact, a term expressive of a mode of existence" (Lavoisier 1789, p.21). He then draws attention to the two gases composing atmospheric air and defines the base of each gas according to its chemical properties. "We have given to the base of….the respirable portion of the air, the name *oxygen*, from …*acidum*, and…*gignor*; because, in reality, one of the most general properties of this base is to form acids by combining with many different substances. The union of this base with caloric we term *oxygen gas*, which is the same with what was formerly called *pure* or *vital* air" (Lavoisier 1789, p.22). This gas was also called *dephlogisticated air* by Priestley based on his use of the phlogiston theory which Lavoisier set out to replace with his oxygen theory of combustion. The term *oxide* was to be used to name substances formed by the binary combination of oxygen with simple substances or elements. So, oxygen combined with lead was to be called 'the grey oxide of lead'. Such a term reflected the fact that the name which was to be chosen for the base of the gas "had to be changeable into adjectives and verbs" (Lavoisier 1789, p.21).

As far as the non-respirable part of atmospheric air was concerned, Lavoisier says, "we have been satisfied to derive the name of its base from its known quality of killing such animals as are forced to breath it, giving it the name of *azote*, from the Greek privative particle *a* and *vita*; hence the name of the noxious part of atmospheric air is *azotic gas*" (Lavoisier 1789, p.22). Lavoisier indicates that there was some thought about calling this gas *nitrogen gas* given the fact that this element was known to be a part of *nitric acid*. However, the decision was finally made in favour of *azotic gas*. Binary substances formed from the combination of this element with simple substances were to be called *azides*. The common term used these days is, of course, nitrogen gas and its nitrides, although sodium nitride is also known as sodium azide, the substance used for filling the car air bag.

Significance of Lavoisier's composition of air experiment for studies in the nature of science

Lavoisier's self-confessed emphasis on facts derived from observation and experiment and his self-confessed avoidance of speculation sounds very much like Chalmers' definition of a widely held common-sense view of science.

> Scientific knowledge is proven knowledge. Scientific theories are derived in some rigorous way from the facts of experience acquired by observation and experiment. Science is based on what we can see and hear and touch, etc. Personal opinion or preferences and speculative imaginings have no place in science. Science is objective. Scientific knowledge is reliable knowledge because it is objectively proven knowledge (Chalmers 1982, p.1).

This is an example of scientific induction which implies that there is such a thing as a rigorous scientific method. Sir Peter Medawar expresses his opposition to this view in this way: "The essential point is that there is no logically rigorous procedure by which an inductive "truth" can be proved to be so", and, "there is no such thing as a calculus of discovery or a schedule of rules by following which we are conducted to a truth" (Medawar 1984, pp.14,16). While these statements refer to the impossibility of proving a universal law statement from some specific cases for which the law seems to apply, they also imply what philosophers refer to as the *theory-dependence of observation* and that *scientific ideas or theories are underdetermined by experiment.* Are these ideas relevant to Lavoisier's composition of air experiment?

Theory-dependence of Observation

During the course of his twelve-day experiment Lavoisier observed that the 'bulk of air' in contact with the mercury had decreased from 50 cubic inches to a value between 42 and 43 cubic inches and that the red particles formed on the surface of the mercury being heated by the furnace had amounted to 45 grains. Philosophers like Chalmers (1982) would argue that even seemingly precise observation statements like those made by Lavoisier pre-suppose theories about bulk and mass even though these are well-established theories. So, according to Chalmers, "Precise, clearly formulated theories are a pre-requisite for precise observation statements. In this sense theories precede observation" (Chalmers 1982, p.29). Such well-formulated theories are often classified as low-level theories probably because their formulation is such that they border on being classified as a fact. Godfrey-Smith addresses this point as follows: "For example, maybe observational reports assume 'theories' that are so low-level that the testing of real scientific theories will never be affected. We can think of the assumption that objects generally retain their shape when we are not looking at them as 'theoretical' in a sense, but the effect of this assumption on observation reports does not usually matter to testing in science" (Godfrey-Smith 2003, p.157). In this sense we would agree that Lavoisier's statements about the bulk of air and the mass of red matter are factual enough for our purposes here. The question is, is there any evidence that Lavoisier showed a commitment to theories or ideas which were not as well-established at the end of the 18th century to be classified as facts at the time he did his experiments on the composition of air?

Lavoisier was committed to a binary view of chemical substances in that they were classified as consisting of a *base* combined with the matter of heat known as *caloric.* While Lavoisier refused to speculate as to the constitution of a *base* and its *caloric* a commitment to

the binary nature of substances suggested that when mercury combined with a proportion of atmospheric air to produce the red solid product heat should be released since less caloric was associated with the solid state compared to the gas state. Here is Lavoisier's reasoning: "Since, during the calcination of mercury, air is decomposed, and the base of its respirable part is fixed and combined with the mercury, it follows, from the principles already established, that caloric and light must be disengaged during the process" (Lavoisier 1789, p.18). However, as already stated elsewhere in this paper, it was difficult to observe such a phenomenon in the case of the mercury reaction which turns out to be slow with a relatively small negative enthalpy compared with other metals. The close proximity of the furnace also compounded the problem. Lavoisier then describes a reaction with iron which illustrates a large release of heat and light to confirm his prediction. The desire to illustrate the importance of caloric in the combustion reaction seems to have been Lavoisier's motivation for the iron experiment. "It is, however, easy to render this disengagement of caloric and light evident to the senses, by causing the decomposition of air to take place in a more rapid manner. And for this purpose, iron is excellently adapted, as it possesses a much stronger affinity for the base of respirable air than mercury" (Lavoisier 1789, p.18).

During a description of the observations associated with the iron experiment, Lavoisier demonstrates a commitment to the law of conservation of mass without acknowledging such. This is how he describes his observations at one point:

> If all the attention has been paid to this experiment which it deserves, the air will be found diminished in weight exactly equal to what the iron has gained. Having therefore burnt 100 grains of iron, which has acquired an additional weight of 35 grains, the diminution of air will be found exactly 70 cubic inches; and it will be found, in the sequel, that the weight of vital air is pretty nearly half a grain for each cubic inch; so that, in effect, the augmentation of weight in the one exactly coincides with the loss of it in the other" (Lavoisier 1789, p.20).

However, it would appear that Lavoisier's use of the word 'exactly' is somewhat unwarranted given the results he himself reports. He reports an increase in the weight of iron as 35 or 36 grains and speaks of vital air as being 'pretty nearly' half a grain per cubic inch. Priestley tried to duplicate Lavoisier's work but without success and accused Lavoisier of over-estimating the accuracy of his measurements. In the case of the mercuric oxide experiment, , Brock claims that,

> Priestley's objections to Lavoisier's chemistry were often, indeed, usually, perfectly valid....For example, in the decomposition of mercuric oxide Priestley consistently got less mercury back than he started with. In any case, he observed, Lavoisier's pretence of measuring to four or five places of decimal was pure window dressing. To this Lavoisier replied that expensive and superior apparatus was needed to achieve precision which, of course, was anathema to Priestley's democratic approach to chemical experimentation (Brock 2008, p.75).

It would appear that Lavoisier's commitment to the law of conservation of mass guided his reporting of results. This seems to be particularly the case given the difficulty he experienced in obtaining consistent results for the percentage composition of respirable and non-respirable air in atmospheric air.

In order to add experimental justification to his proposition that atmospheric air consists of two elastic fluids, Lavoisier uses the principle of analysis and synthesis, the belief that adding together the products of analysis would lead to the synthesis of the original

material. Referring to his mercury experiment he offers a proof of the 'two elastic fluids' proposition as follows:

> As a proof of this important truth, if we recombine these two elastic fluids, which we have separately obtained in the above experiment, viz., the 42 cubic inches of mephitis, with the 8 cubic inches of respirable air, we reproduce an air precisely similar to that of the atmosphere and possessing nearly the same power of supporting combustion and respiration, and of contributing to the calcination of metals (Lavoisier 1789, p.18).

This kind of analysis looks appropriate but didn't convince chemists such as Priestley and Cavendish (Gillispie 1960, p.217) probably because of the opportunistic way Lavoisier seemed to combine his results, particularly given the fact that he earlier reports his volume of mephitis as between 42 and 43 cubic inches.

Scientific ideas or theories underdetermined by experiment

Using modern terminology the main finding of Lavoisier's composition of air experiment was that atmospheric air consists of the two gases oxygen and nitrogen. However, Lavoisier's conclusion was based on the application of just one experimental test, that of support or non-support of combustion. Nowhere in his *Elements of Chemistry* does Lavoisier suggest the possibility that two or more gases could be responsible for supporting combustion or conversely the possibility of two or more gases being responsible for not supporting combustion. Of course, we must remember that Lavoisier did not have at his disposal the atomic-molecular view of matter which was to come with Dalton in the early 19^{th} century. Lavoisier distinguished matter on the basis of its 'principles' rather than on the weight of its atoms. Since two different 'principles', that of supporting or not supporting combustion, were evident from his experiment this signified two different gases or elastic fluids. However, from a modern perspective, given the more complicated composition of the atmosphere (see Table 1), we could say that Lavoisier's experiment did not grant him a complete picture of the atmosphere's composition. That is, the composition of the atmosphere was underdetermined by his experiment. In a section dealing with underdetermination Godfrey-Smith notes that, "Over time, structures and objects in the world can move from being so inaccessible that only speculative model-building can be applied to them, to being so accessible that their study is routine" (Godfrey-Smith 2003, p.223). While a study of the noble gases in the atmosphere could be considered routine today, it certainly wasn't the case in the 18^{th} century. As noted, Lavoisier refused to speculate on the possible existence of more than two gases in the atmosphere, probably because this went beyond his immediate experimental results, yet he did not hesitate to speculate on mercury's incapacity to attract all the base of vital air in the atmosphere as a possible reason for inconsistent results in the air experiment.

What is rather fortuitous is that Lavoisier was amazingly close in his estimate of two elastic fluids composing the atmosphere as can be seen from Table 1. According to Table 1 nitrogen and oxygen combined constitute 99.03% of the atmosphere. It took nearly 100 years for chemists to determine that other gases were present. In 1894 Rayleigh observed that the density of nitrogen obtained from iron reduction of nitrogen oxides was 1.2505 g/cm^3 whereas the nitrogen density in the atmosphere appeared to be 1.2572 g/cm^3 (Rayleigh 1894). While one might conclude that experimental error was responsible for this small difference in density value, careful experimentation by Rayleigh and Ramsay led to the discovery of argon which is nearly 1% by volume (Rayleigh & Ramsay 1895). Imagine what the implications

would have been for Lavoisier's experiment if argon had been 10% by volume. The composition of air would have been even more underdetermined.

Relevance of the study of air composition for current chemistry education

Today we have much more sophisticated techniques at our disposal for analysing air, such as mass spectrometry, which was not available to Lavoisier. Air composition has become a central component of environmental chemistry so there is no question about its usefulness in current chemistry education. However, does a historical approach to air composition have any relevance to a chemistry education which currently has a multitude of techniques at its disposal already for a student to learn? What is interesting is that Lavoisier has rendered us his opinion on this subject in the preface to his *Elements of Chemistry*:

> …if I had allowed myself to enter into long dissertations on the history of the science and the works of those who have studied it, I must have lost sight of the true object I had in view and produced a work the reading of which must have been extremely tiresome to beginners. It is not to the history of the science, or of the human mind, that we are to attend in an elementary treatise: our only aim ought to be ease and perspicuity and with the utmost care to keep everything out of view which might draw aside the attention of the student.. (Lavoisier 1789, p.6).

Table 1. The current values for the chemical composition of air.

Name	Symbol	% by volume
Nitrogen	N_2	78.084 %
Oxygen	O_2	20.9476 %
Argon	Ar	0.934 %
Carbon Dioxide	CO_2	0.0314 %
Neon	Ne	0.001818 %
Methane	CH_4	0.0002 %
Helium	He	0.000524 %
Krypton	Kr	0.000114 %
Hydrogen	H_2	0.00005 %
Xenon	Xe	0.0000087 %

Lavoisier, then, implies that there are a "sufficient number of difficulties" already in the science without burdening students with the history of the subject. The concern expressed

here appears to be in the use of extended historical accounts for beginning students of chemistry. However, Lavoisier admits that the criticism of his lack of a historical treatment in the *Elements of Chemistry* is perhaps better founded than the criticism of his new nomenclature. So it would appear that his criticism does not relate to history of science as such but to its extended use in introductory chemistry. This remains a challenge for chemistry educators.

The Lavoisier air composition study is used with our students in first-year tertiary BSc study. These students have already studied chemistry to the end of year 12. However, the historical component is administered in the form of an assignment and is embedded within the chemistry topic on the gas laws. The assignment does not draw upon Lavoisier's air composition study exclusively but includes a treatment of the principles of the mass spectrometer and concludes with an analysis of the operation of the car air bag: the emphasis being on how history informs the way we go about doing and understanding chemistry today. Students typically struggle with units of measurement, for example, and it has been found that an historical treatment is well-placed to communicate the *arbitrary* nature of our units of measurement.

It so happens that Lavoisier used old French units of measurement in his reporting of results. These units prevailed predominantly before the 19^{th} century with the decimal system being adopted somewhat later on. In *Elements of Chemistry* mass is given in *grains* where 1 French grain is equivalent to 53.11 mg; volume is given in cubic inches where 1 French cubic inch is equivalent to 19.836 cm^3; length is given in inches where 1 French inch is equivalent to 2.707 cm; and temperature is quoted in Reaumur degrees where 1 Reaumur degree is equivalent to 4/5 of a Celsius degree. The Reaumur thermometer was based on the freezing point of water taken as 0^o and the boiling point of water taken as 80^0. To form a connection with the ideal gas law of modern chemistry, one can get students to evaluate the gas constant *R* using the data associated with Lavoisier's experiment. Lavoisier quotes his oxygen sample as weighing 0.5 grains per cubic inch and the temperature and pressure conditions as being 10^o and 28 inches on the barometer. Converting these units into the Standard International (SI) units, assuming ideal gas behaviour, and taking the molar mass of oxygen as 32 g/mol, leads to a value of *R* of 8.48 J $K^{-1}mol^{-1}$ which is within 2% of the known value (8.314 J K^{-1} mol^{-1}). One could do this kind of calculation in other ways such as using the known *R* value to calculate the molar mass of oxygen and so on.

Stoichiometric calculations can also be done using Lavoisier's data. For example, the following questions could be asked in the context of the ideal gas law and units of measurement.

1. **What was the mass in grams of mercuric oxide (HgO) (red calx) produced in Lavoisier's experiment? Show calculations.**

2. **Write down a balanced chemical equation for the reaction between mercury and oxygen to produce mercuric oxide. Use subscripts (s, l, g) to indicate state.**

3. **Use the guidance above (about unit conversions, mole calculations, use of the ideal gas law) to determine how many cubic inches (French) of oxygen would theoretically have been required to produce 45 grains of red calx (mercuric oxide).**

4. **Deviations from the experimental volume (assuming this volume to be correct) could be due to our assumptions of temperature and atmospheric pressure. The deviation could also be due to an inaccurate measurement of the mass of calx (HgO) produced. Considering these three variables separately what changes to temperature,**

atmospheric pressure, and amount of calx would bring the theoretical volume closer to the experimental volume [8 cu.in]?

The use of the historical assignment has shown that students have difficulty in interpreting what an experiment has achieved and what it has not achieved. They are not familiar with the following style of question used to assess an understanding of Lavoisier's air experiment.

Assess your understanding of this topic by selecting <u>one or more</u> alternatives for the following question by circling the appropriate letter(s). In each case you are asked to justify your choice(s). Keep in mind that in the late 18th century when Lavoisier and Priestley did most of their work scientists had little idea of the composition of air and formulae and atomic weights were not known as we know them today. Think of the enormous task this presented to chemists of the 18th century.

Lavoisier's experiment on the heating of mercury in air

(a) categorically proved that air consisted of a mixture of only two gases.

(b) showed that air does participate in combustion reactions.

(c) demonstrated that air consists of a part that supports combustion and a part that doesn't.

(d) proved that mercury and oxygen react in the ratio of two parts mercury to one part oxygen.

Justify your choice(s) from the incidents in this story.

While we may be expecting too much of students to transport themselves into an 18th century context, the kind of analytical skills required to answer the question are just the kind of skills necessary to interpret their own experience in a current laboratory.

A consideration of Lavoisier's air composition experiment also gives one an opportunity to address other ways of determining the composition of air. With internet services at their disposal students are quite capable of locating other ways of determining air composition. There are a range of experiments, for example, in the *Journal of Chemical Education* for determining the oxygen content of the air ranging from the use of pyrogallol (Munro 1928), nitric oxide (Najdoski et al 2000), and steel wool (Vera et al 2011). Adaptations of some of the original historical experiments can be found in Fowles (1937). Thinking about what is common or different about these approaches to that used by Lavoisier can be quite instructive.

Conclusion

What can one say about Lavoisier's use of facts, ideas, and language in his air composition experiment? We have seen how Lavoisier expected thermal energy to be released in his mercury-air reaction based on his commitment to the role of caloric in nature. While this release of thermal energy could not be observed in the case of mercury due to the slowness of reaction and close proximity of the furnace, it was confirmed in the case of the burning of iron. Also, the reporting of results seemed to mirror a commitment to the law of conservation

of mass in chemical processes although this was not stipulated. Lavoisier was committed to using a language for describing the components of air that was related to their chemical properties. Thus was selected *oxygen* and *oxide* (acid producer and product of combustion respectively) for the component of air that supported combustion and respiration. This was considered superior to the former names of *dephlogisticated air* and *calx. Azote* and *azide* were chosen for mephitic or noxious air and the product of burning an element in this air respectively. Thus, with some small variations, we owe much to Lavoisier for our current chemical nomenclature.

However, the language used in *Elements of Chemistry* to describe a chemical process is sometimes used in a different sense to that used in modern chemistry texts. When we speak about *decomposition* in a current setting we are usually referring to the breaking down of a compound into simpler components. However, Lavoisier speaks about air (a mixture in modern terminology) being decomposed into two elastic fluids and oxygen gas being decomposed by phosphorous. Here, decomposition is being used in the sense of separating a mixture into its components and separating an element as a base from its caloric respectively. The sense of separation, however, is common to both usages although the confusion in terminology is a typical feature of reading historical documents.

Lavoisier argued that the language and concepts of chemistry were already difficult enough for a neophyte in chemistry without introducing the added complications associated with the history of the subject. Therefore, how can those of us committed to the history of chemistry justify our use of it in the teaching and learning of chemistry? Isn't the language and conceptual structure of even upper-level chemistry difficult enough without adding components of history to the mixture? I have argued in this paper that there are benefits in using history if it is embedded within or amidst current concepts and informs those concepts. Of course, philosophers and historians may argue reasonably that this is too pragmatic an approach. What about the place of our chemistry in the grand scheme of intellectual and cultural life, of its place in the history of ideas? In the introduction to his four-volume treatise on the history of ideas, Peter Watson (2009, p. xl) observes that many philosophers have divided human intellectual history into three stages. While there is nothing sacrosanct about a threesome, Watson chose the *Soul*, *Europe*, and the *Experiment* as his three stages. While Francis Bacon (1561-1626) was one of the first in the modern period to give a clarion call to the important role of observation and experiment in science, Lavoisier, along with others, championed the call in the 18th century. Granting our students the opportunity to witness a big picture approach to chemistry, that is, one which positions chemistry in the broader context of the history of ideas, remains a challenge but one we envisage will be ultimately rewarding.

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