Found Chem (2015) 17:137–151
DOI 10.1007/s10698-015-9220-5

Lavoisier's "Reflections on phlogiston" I: against phlogiston theory

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Abstract This seminal paper, which marks a turning point of the chemical revolution, is presented for the first time in a complete English translation. In this first half Lavoisier undermines phlogiston chemistry by arguing that his French contemporaries (particularly P.-J. Macquer and Baumé) had replaced Stahl's original theory with radically different systems that conceptualised the phlogiston principle in completely incompatible ways. He refutes their claims by showing that these later models were riddled with inconsistencies as to phlogiston's weight, its ability to penetrate glass and its role as a source of colour and odour in chemical compounds.

Keywords Chemical revolution · Phlogiston · Combustion

Translator's preface

The following article is a sequel to a paper Antoine Lavoisier had read to the Royal Academy of Sciences of Paris in 1777 in which he publicly attacked phlogiston theory for the first time. The present argument was meant to be the *coup de grâce*.

Lavoisier read this paper at the Academy over two nights, starting 28th June and concluding 13th July 1783. It is not explicitly stated which portions were read at which date but it is worth noting that there is a clear break in the paper where the argument

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changes course.[1] It is at that point that the present translation has been broken into two parts: the first, to which I have added the subtitle "Against Phlogiston" appears below; the second, which I have dubbed "On the Nature of Heat", will appear in the next issue of *Foundations of Chemistry*. This essay was first published in the *Mémoires* of the Academy in 1786 and republished in Jean-Baptiste Dumas's edition of Lavoisier's collected works.[2] Pagination given here in square brackets is that of the Dumas edition.

Dumas updated the French spellings according to the orthographical standards of his day (i.e. as promulgated by the *Académie française* in 1835). He did not, however, update Lavoisier's evolving nomenclature. I have modernised some terms in this translation, especially where not doing so would be misleading. Notably, at the time of writing this paper Lavoisier called his principle of combustion and acidity *oxygine*; he later re-spelt it *oxygène*. Dumas retains the original but I have used the English spelling "oxygen" throughout, since it is merely a change in spelling.[3] In modern French *acide nitreux* now refers to HNO_2 but in this work refers to HNO_3. Had Lavoisier written this paper a few years later, he would have written *acide nitrique*, so I have permitted myself the slight anachronism of translating it as "nitric acid", for the sake of preserving the correct reference.[4]

I have retained the more literal translation of *charbon* as "charcoal" in cases where Lavoisier refers to burning a solid substance. In just a few places I have used "carbon" for the same French term, when he is clearly speaking of the chemical behaviour of an element.[5] Nevertheless, the reader should be aware that both these terms correspond to a single French word, which can also mean "coal". Similarly, I have translated *corps* as "substance" in most instances, since the emphasis is usually on the substance of the sample, not its physical shape, but have used the more literal translation "body" where the context makes clear that Lavoisier means individuated bodies.

Some of the terms Lavoisier employs are translated into English expressions that may seem out-dated or unnecessarily prolix. I have retained the deprecated term "igneous fluid" and the cumbersome locution "the matter of heat", despite being sorely tempted to

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[1] Taken in isolation, the first half might lend itself to a triumphalist interpretation whereby Lavoisier demonstrates that phlogiston does not exist by a type of *reductio ad absurdum* (Chang 2009). However, these negative arguments should not be read without remembering Lavoisier's positive claims—that a caloric-like fluid plays as large a role in combustion as oxygen. With this in mind, it would be wise to give a more literal reading to Lavoisier's accusation that 'the same name has been given to very different things', which he makes repeatedly throughout the first half.

[2] As: Réflexions sur le phlogistique, pour servir de suite à la théorie de la combustion et de la calcination, publiée en 1777. Mém. Acad. R. Sci. Paris **année 1783**, pp. 505–538 (1786), republished in: Dumas, J.-B. (ed.) Œuvres de Lavoisier, vol. II, pp. 623–655. Imprimerie Impériale, Paris (1862).

[3] N.B. although the terms "pure air" and "vital air" refer to the gas we now call "oxygen" and consider an element, for Lavoisier, "the oxygen principle" is just one component of that gas, along with the matter of heat.

[4] The 2–3-year lag between reading an essay at the Academy and it coming out in print makes it difficult to pinpoint when Lavoisier changed his preferred nomenclature. Louis-Bernard Guyton de Morveau's 1787 *Method of Chemical Nomenclature* spells it *oxigène* and the 1788 English translation of that work spells it "oxygen". In a paper published in 1788 (read to the Academy in 1786) Lavoisier first spelt it *oxygène*, the modern French way (Réflexions sur la décomposition de l'eau par les substances végétales et animales. In: Dumas (ed.) Œuvres de Lavoisier, vol. II, pp. 656–670. Imprimerie Impériale, Paris ([1786] 1862)). In that same paper Lavoisier used the term *acide nitrique* without remark. The distinction between nitric and nitrous acids was first made explicitly around the same time by Guyton de Morveau (Guyton de Morveau 1788, 35).

[5] The list of simple substances given in the *Method of Chemical Nomenclature* gives *charbon pur* as the old name for *carbone*.

substitute "caloric".[6] In this text Lavoisier gives this hypothetical substance a name that is little more than a description of its role—'I name this fluid (whatever it is) *igneous fluid, the matter of heat and fire*.' (D641). This shows that despite the chemical revolution being well underway, chemical nomenclature was still in a transitional state, since Lavoisier chose to give this entity a name that resembles the definite descriptions by which earlier chemical principles were known but had already begun to baptise some chemical entities with proper names derived from classical languages e.g. the oxygen principle (Best 2015a, b).

Some of the terms used by Lavoisier have become false friends after generations of theory change e.g. *molécule* meant any small piece of matter, not a set of bonded atoms. Nevertheless, these seem to be meant as discrete corpuscles, as Lavoisier's explanation of macroscopic physical phenomena depends on their regular behaviour.[7] So *molécule* has been translated as "corpuscle", which has no such connotations of covalent bonding.

The units Lavoisier uses for the quantities he gives are now archaic—French royal inches, feet, pounds, grains and degrees Réaumur.[8] These have been translated into SI units (rounded to the same number of significant figures as the quantity quoted) with literal translations given in numbered footnotes.

Reflections on Phlogiston
to serve as a sequel to the theory of combustion and calcination published in 1777[9]

[*Œuvres* II.623] In the series of papers that I have submitted to the Academy, I reviewed the principal phenomena of chemistry, I emphasised those that accompany combustion, the calcination of metals and, in general, all the processes where there is absorption and fixation of air. I have deduced all explanations from one simple principle: that is, that pure air (vital air) is composed of a special characteristic principle—which forms its base and which I have named the *oxygen principle*—combined with the matter of fire and heat. Once this principle was accepted, the principal difficulties of chemistry seemed to fade and dissipate and all the phenomena were explained with astonishing simplicity.

But if all of chemistry is explained in a satisfactory manner without the help of phlogiston, it is by this fact alone infinitely probable that this principle does not exist, that it is a hypothetical entity, a gratuitous supposition and it is indeed a principle of a good logic to not multiply entities unless necessary. Perhaps I could have restricted myself to these negative proofs and contented myself with having proven that one can give a better account of the phenomena without phlogiston than with phlogiston. But it is time I explained in a more formal and precise manner an opinion that I regard as a disastrous error in chemistry and that seems to me to have retarded [624] its progress considerably by introducing a bad style of philosophising into the science.

In starting this essay, I beg my readers to shed themselves of all prejudices as far as possible, to see in the facts only what they show, to banish all that reasoning has assumed,

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[6] The French term *calorique* was not coined until 1787, the English equivalent appeared soon after (Guyton de Morveau 1788, 22).

[7] For an interpretation of such corpuscles as chemical atoms, especially in Lavoisier's later work, see Newman (2009, 259ff).

[8] Devised by René-Antoine Ferchault de Réaumur (1685–1757), long time director of the Academy. Standardly used in France from its invention in 1730 in until the switch to Celsius in 1790, the Réaumur scale divided the difference in water's freezing and boiling points into 80°.

[9] Lavoisier, A.L.: Mémoire sur la combustion en général. In: Dumas, J.-B. (ed.) Œuvres de Lavoisier, vol. II, pp. 225–233. Imprimerie Impériale, Paris ([1777] 1862). Originally published in: Mém. Acad. R. Sci. Paris **année 1777**, 592–600 (1780)

to transport themselves to a time before Stahl and to forget for a moment that his theory ever existed, if that is possible.

At the time when Stahl was writing,[10] the principal phenomena of combustion were still unknown. The only aspects of this process that were understood were those that stimulate the senses—the release of heat and light. From the fact that some substances burn and inflame, he concluded that there exists in them an inflammable principle—some fixed fire. However, as it was difficult to reconcile the fixity one observes in these substances with the mobility and subtlety that appears to characterise the element of fire, he supposed that an earthy principle served as an intermediary to unite the fire with the combustible substances. He called the result of this combustion the *inflammable principle* or *phlogiston*. Such is at least the manner in which Mr Macquer has presented Stahl's doctrine in his *Dictionary of Chemistry*.[11] It is true that the German chemist[12] did not always present it in that degree of simplicity—that he and Professor Becher[13] often regarded phlogiston as a purely earthy element—but I thought it would be pointless to follow these different opinions that he successively embraced and that I could restrict myself to that version of Stahl's doctrine that was conceived and presented by Macquer. If Stahl had restricted his study to this simple observation, undoubtedly his system would not have merited him the glory of becoming one of the patriarchs of chemistry and of making a kind of revolution in the science. Indeed, nothing was more natural than to say that combustible substances inflame because they contain an inflammable principle. But two important discoveries are owed to Stahl that are eternal truths, independent of any system and of any hypothesis: Firstly, that metals are combustible—that calcination is a true combustion, which [625] presents all the relevant phenomena. This unchanging fact, which Stahl appears to have recognised first, and that is today generally affirmed by everyone, necessitated that he admit an inflammable principle in metals. Indeed, if combustion is due to the release of an inflammable principle that had been fixed in these substances, making metals combustible, it follows necessarily that these substances contain an inflammable principle.

The second discovery for which we are indebted to Stahl (and which is more important still) is that the propensity to burn—to be inflammable—can be transmitted from one body to another. For example, if one mixes charcoal, which is combustible, with vitriolic acid, which is not, the vitriolic acid is converted to sulphur—it acquires the propensity to burn, whereas the charcoal loses it. It is the same for metallic substances—by calcination they lose their combustible quality but if they are put in contact with charcoal (or in general with substances that have the propensity to burn), they revivify. That is to say, metals reclaim the property of being combustible to the detriment of these other substances. Stahl concluded from these facts that phlogiston (the inflammable principle) can pass from one

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[10] Georg Ernst Stahl (1659–1734) professor of medicine at the University of Halle from 1694, court physician to King Frederick William I of Prussia from 1715.

[11] Macquer, P.-J.: A Dictionary of Chemistry. Cadell, Elmsly, Robson and Bladon, London (1771), 525. Lavoisier makes reference to both the first and second French editions of this work below (D626, D629). The second French edition was never fully translated into English; the second English edition of 1777 was prepared from a partial manuscript of the second French edition but contains much original work from the translator, James Keir. For details, see Neville and Smeaton (1981).

[12] I.e. Stahl.

[13] Johan Joachim Becher (1635–1682), professor of medicine at University of Mainz from 1657, often regarded as the true originator of the theory that Stahl perfected.

body to another and that it obeyed certain laws, to which the name "affinity" has since been given.[14]

According to Stahl, phlogiston (the inflammable principle) is a heavy substance. Indeed, one cannot form any other idea of an earthy principle or even of a composite containing an earthy element. He even tried to determine its weight in his treatise on sulphur.[15]

This theory of Stahl's on the calcination of metals and on combustion in general did not account for a very anciently observed phenomenon, verified by Boyle,[16] that has become today an incontrovertible truth—that all combustible substances increase in weight when they burn or calcine. This is what is observed in an especially striking manner in metals, sulphur, phosphorus etc. Conversely, in Stahl's system, phlogiston (which is a heavy principle) escapes from [626] metals when they are calcined and from combustible substances that burn; they must therefore lose a portion of their weight instead of gaining it.

The chemists who have written since Stahl and who have adopted his principles hid this difficulty from themselves as best they could. In the first edition of his *Dictionary of Chemistry*, Macquer said not a word, neither of the fact nor of any way to explain it. Mr Baumé, whose chemistry appeared soon after,[17] did sense that such a direct contradiction between the theory and the facts required reform within Stahl's system and he had the courage to undertake it. He believes in an inflammable principle composed of fiery matter combined with an earthy principle. He supposes that organised entities—vegetables and animals—have been charged by nature with the combination of these two principles and he claims that all phlogiston that exists in minerals owes its origin to the other two kingdoms. Up to that point Baumé's system greatly resembled Stahl's but a point on which he differed more explicitly is that he supposed that free fire and the earthy element that combine to make phlogiston can combine in an infinite number of proportions and that, consequently, there exists an infinity of intermediate states between free fire and phlogiston properly speaking. Even though this extension of Stahl's system makes a great number of facts easier to explain (and a principle able to thus take any of an infinity of forms as needed was extremely convenient for chemists), nevertheless Baumé was no more successful in the explanation he gave for the increase in weight of metallic calces. He claims (with Stahl) that metals lose their phlogiston during their calcination but that this phlogiston is replaced by pure fire—or at least by fire combined with less of the earthy element—and it is to the addition of that almost free fire that he attributes the increased weight of metallic calces.

In this hypothesis Baumé finds himself obliged to attribute [627] an extremely large weight to the element of fire because there are metals (like iron) that increase in weight by more than a third by simple calcination in the open air. Therefore, it would have to be the case that the pure iron had not only caused this increase but that it had also replaced the loss of weight caused by the volatilisation of the phlogiston (which is itself necessarily heavy, since it is composed of two heavy elements). Yet this supposition of the great weight of fire is contrary to all the facts: that element, that subtle fluid, most likely obeys

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[14] For Lavoisier's attempt to incorporate oxygen into an affinity framework, see his Mémoire sur l'affinité du principe oxygine avec les différentes substances auxquelles il est susceptible de s'unir. In: Dumas (ed.) Œuvres de Lavoisier, vol. II, pp. 546–556. Imprimerie Impériale, Paris ([1782] 1862).

[15] This was available to the French chemical community as Stahl, G.E.: Traité du soufre : ou remarques sur la dispute qui s'est élevée entre les chymistes, au sujet du soufre. Didot, Paris ([1718] 1766).

[16] Boyle, R.: New experiments, to make the parts of fire and flame stable & ponderable. In: Hunter, M., Davis, E.B. (eds.) The Works of Robert Boyle, vol. 7, pp. 299–322. Pickering & Chatto, London (1999).

[17] Baumé, A.: Chymie expérimentale et raisonnée. Didot, Paris (1773). The first edition of Macquer's dictionary appeared in 1766.

the laws of attraction like all the others but its weight is so small that it is not possible to detect it in any physical experiment.

I have elsewhere given an account of the forays I have made in that regard.[18] I have proven that the quantity of the matter of fire and of heat that is released when 4.9 g of phosphorus is burnt has no measurable weight, even with the most precise instruments.[19] Moreover, far from there having been free fire absorbed during the calcination of metals (as Baumé supposes), on the contrary, there is a great quantity of it that passes from the fixed state to the free state. This quantity of fire that is released is quite perceptible and even measurable when calcining iron or zinc in vital air.

Experiments on heat performed recently in England,[20] France and Sweden[21] provide even more new objections against Baumé's system. If free (or almost free) fire really had the property of combining with metallic substances and reducing their calces to the metallic state, the substances that would contain the most free fire (or at least in a state very close to being free) should also be the most apt to perform this reduction. Today it is known that vaporised fluids, steam for example, are such a case: this substance stays in an aeriform state, while it is kept at a temperature over 100 °C,[22] only because it is combined with a portion of fiery matter in an almost free state, which gives it elasticity. Steam, particularly at the temperatures near where it recondenses to water, [628] should then revivify the metallic calces, convert sulphur into vitriolic or sulphurous acid, phosphorus into phosphoric acid, give the property of inflammability to a great number of bodies and itself be inflammable. Nevertheless, one observes nothing of the sort; whence it follows that the revivification of metals and the formation of sulphur and phosphorus are not due to the combination of free (or almost free) fire with metallic substances. Finally, in Baumé's view, when metals are calcined in hermetically sealed glass vessels, there should be an increase in weight; whereas the fact of the matter is that, if one weighs a vessel (without opening it) before and after calcination, one finds no difference in weight, even with the most sensitive balances.

While Baumé occupied himself with the writing and publishing of his chemistry, a phenomenon that takes place constantly in all metallic reductions drove me to undertake some research on this subject. I noticed that in all these processes there was considerable effervescence at the moment when the metal passed from its calx to the metallic state. It was natural to conclude from this that a gas was released and I designed an apparatus appropriate for collecting and harvesting it.[23] In November 1772, I deposited with the

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[18] Lavoisier, A.L.: Nouvelles réflexions sur l'augmentation de poids qu'acquièrent, en brûlant, le souffre et le phosphore, et sur la cause à laquelle on doit l'attribuer. In: Dumas, J.-B. (ed.) Œuvres de Lavoisier, vol. II, pp. 616–622. Imprimerie Impériale, Paris ([1783] 1862), 621.

[19] Original reads '92 [French] grains'.

[20] Priestley, J.: Experiments and Observations on Different Kinds of Air. Johnson, London (1774–7); Experiments and Observations Relating to Various Branches of Natural Philosophy with a Continuation of the Observations on Air. Johnson, London (1779–86).

[21] Scheele, C.W.: Chemical Treatise on Air and Fire. In: The Discovery of Oxygen, vol. 2. Alebmic Club Reprints, vol. 8. The Alembic Club, Edinburgh ([1777] 1912).

[22] Original reads '80° [Réaumur]'.

[23] Guerlac (1961, 29ff) argues that the apparatus that Lavoisier used was a setup designed by his mentor, Guillaume-François Rouelle (1703–1770), itself a combination of two apparatus described and illustrated in Hales, S.: Vegetable Staticks. Innys and Woodward, London (1727). Guerlac suggests that it was a combination of Hales's "pedestal apparatus" (p. 206, fig. 35) and a proto-pneumatic trough (p. 262, fig. 38). But Guerlac's reproduction of the Rouelle/Lavoisier device more closely resembles a combination of Hales's fig. 33 and 34 (p. 160).

secretary of the Academy a note in which I give an account of my experiments.[24] I showed there that a great quantity of an elastic fluid (very much like the one that is drawn from chalk, calcareous earths, effervescent fixed alkalis, vats of fermenting liquors etc.) was released from a *minium* during its reduction, that is to say, during its transition into lead.[25] I repeated these experiments many times in 1773, notably in the presence of many members of the Academy.[26]

During the summer of that same year I occupied myself with experiments in the opposite direction—on the calcination of metals by burning glass in known quantities of air.[27] I observed that in these processes the volume of air diminished as the metal calcined and the weight by which the metal increased was exactly equal to that of the quantity of air that had disappeared. It was impossible not to conclude from [629] these facts that the increase in weight of metallic calces was due to the fixation of a portion of the air that combines with the metal as it calcines. The detail of these experiments has been the subject of many papers that I have to the Academy in 1773 and that I have assembled in an octavo volume, under the title of *Essays Physical and Chemical*, which appeared in December of that year.[28]

As conclusive as those experiments upon which I based my arguments were, following established practice, any facts in doubt were rejected at first. Next, those who seek to persuade the public that all that is new is untrue, or that all that is true is not new, succeeded in finding the seed of that discovery in a most ancient author. Without examining here the authenticity of the work of which a new edition was hurriedly provided at that time, I have seen with some pleasure that the impartial public has judged this a vague assertion, hurled at random, that was not based on any experiment, which was ignored by all scholars, not preventing me from being regarded as the true discoverer of the cause of the increase in weight of metallic calces.[29]

Not only did I then demonstrate that the increase in weight was one of the preconditions of all metallic calcinations, but I also proved that that same law took place in combustions—that sulphur, phosphorus and all combustible substances in general increase in weight while burning and that that increase was due to combination with (fixation of) the air.

These new facts upset both Stahl's system and Baumé's. Macquer senses this, but at the same time he believes that it is not impossible to reconcile modern experiments with the phlogiston doctrine. The new theory that he devises to fulfil that objective can be found learnedly expounded in the second edition of his *Dictionary of Chemistry*, under the headings "Phlogiston", "Calcination" and in a great number of articles. One is astonished to see there Mr Macquer quite seeming to defend Stahl's doctrine (preserving the name

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[24] This note is reproduced as an appendix to Guerlac (1961, 227–228).

[25] "Minium" usually refers to Pb_3O_4, sometimes known as "red lead" in English. Here Lavoisier assumes that the reader is aware that such a reduction would have to take place in the presence of a carbonaceous substance (which he explains explicitly below, D635).

[26] A number of Lavoisier's manuscripts on this work are reproduced in Perrin (1986).

[27] Détail des expériences exécutées au moyen du grand verre ardent. In: Dumas (ed.) Œuvres de Lavoisier, vol. III, pp. 284–342. Imprimerie Impériale, Paris (1864). For a detailed description of these and other burning lenses, see Smeaton (1987).

[28] Thomas Henry's English translation of that volume appeared 3 years later as Lavoisier, A.L.: Essays Physical and Chemical. Johnson, London (1776).

[29] In 1775 Pierre Bayern told Lavoisier of Jean Rey's *Essays* and their remarkable similarity to his work. Lavoisier at first believed that the new edition that appeared (Gobet 1777) was a forgery but by 1792 would come to speak positively of Rey's work (see McKie 1951, xl).

"phlogiston") but presenting a completely new theory, which [630] is not Stahl's. He substitutes the pure matter of light for phlogiston (the inflammable principle, that weighty principle, composed of the fiery element and the earthy element). Thus, Macquer has preserved the word without preserving the thing and so appeared to defend Stahl's doctrine—here he has truly done him a disservice. But to get a better feeling for this new system—which is no longer that of Stahl, nor that of any other chemist or physicist, and which belongs exclusively to Macquer—I must enter into details.

Macquer conceives of metals, sulphur, carbon, phosphorus and all combustible substances in nature as containing contain a great abundance of the matter of light combined in such a way that it does not readily evaporate, and it is to this material combined in this way that he gives the name "phlogiston". Consequently, he no longer believes the earthy element is a constitutive principle of phlogiston—neither in a fixed proportion as Stahl declared, nor in variable proportions as Baumé claimed. According to Macquer, when phlogiston (or the matter of light) unites with naturally solid substances, it does not make them fluid but it does decrease their hardness and always increases their subtlety. It is the same for fixity: the compounds that result from the combination of the inflammable principle with a fixed substance have less fixity than that substance had before its union with this principle. According to him, phlogiston increases the absolute weight (often even the specific weight) of the substances with which it unites and it commonly makes them opaque. Substances that in their natural state have neither odour nor colour almost always acquire one or the other of these qualities (often even both) by their union with the inflammable principle.

According to Macquer, phlogiston cannot combine with either air or water. In general, only with difficulty does it combine with volatile, light, fluid substances. Conversely, it does combine with fixed, solid, heavy substances, such as earths. Finally, it is identical in all bodies.

[631] Up to this point, Macquer was still not explaining the cause of the increase in weight as metals calcine for, since a heavy principle is lost, they should lose weight rather than gain it. The objection would remain even when it is admitted that phlogiston does not have a perceptible weight, for in that case metals should neither increase nor decrease in weight during their calcination. To explain this phenomenon, Macquer admits, agreeing with my experiments, that air (rather, the most pure portion of the air) combines with metals during their calcination and with combustible substances during their combustion, and that each increases in weight in proportion to the amount of air absorbed. But he thinks that the matter of light that was united with the body separates as this union proceeds, so that in this system all calcination, all combustion is a combination with air and at the same time a precipitation—a separation of phlogiston (or, what is the same thing, of the matter of light).

Furthermore, Macquer finds himself obliged to reject the element of fire and to suppose that there does not exist a specific matter of heat, that heat consists of a very fast movement impressed upon the elementary corpuscles of matter and, since light is the subtlest of all materials, he regards it as more prone than any other to adopt the movement that constitutes heat.

Such is more or less the picture of Stahl's theory presented by Macquer in his *Dictionary of Chemistry* (or, rather, the one that he has substituted for Stahl's). It is certain that a great number of objections that were completely unresolvable by Stahl's hypothesis are explained in a simple and natural way with the modifications introduced by Macquer: such as, as we have just seen, the increase in weight of metallic calces and the sort of combustion that they undergo by their calcination; or such as the property of some metallic calces (like those of gold, silver and mercury) to revivify without the addition of phlogiston, nor by being put in contact with a body that contains phlogiston. [632] Given that the matter of heat and light has the property of penetration (the ability to pass through vessels), to revivify these calces it suffices to expose them to a certain degree of heat and ensure contact with the air. Macquer explains in no less elegant a manner what happens in the formation of nitrous gas. As we know, this gas is released by the dissolution of iron, copper, mercury etc. in nitric acid. Macquer supposes that in these processes the vital air contained in the nitric acid combines with the metal, that it drives out the phlogiston from the metal, which combines with a portion of the nitric acid, depleted of vital air, to form nitrous air. And when the vital air and nitrous air are later recombined, they reform nitric acid and phlogiston, which becomes free, escaping through the pores of the vessel.

Stahl's system (either accepted without modification or the version adopted by Mr Priestley) was unable to adequately explain the phenomena of this experiment. Therefore, since in this system phlogiston is a substance incapable of penetrating and passing through vessels, it must be found in the receptacles where the process of combination was happening. Indeed, Priestley has claimed that a residue of phlogisticated air remains but the fact is that, when the nitrous air and the vital air that one uses are pure, the two airs react and are entirely converted into nitric acid, weight for weight, without excess.[30] Therefore, one must to either renounce phlogiston in the explanation of this experiment or (like Macquer) say that it passes through the vessels.

But if the new system envisaged by Macquer to reconcile Stahl's doctrine with modern discoveries satisfies a large enough number of phenomena, there is just as large a number of circumstances in which it is absolutely faulty. At first, Macquer believes (like all of Stahl's school) that phlogiston is a heavy substance. However, all natural phenomena, the unanimous consent of all physicists and a number of decisive experiments all disallow the supposition that light has an [633] appreciable (or even perceptible) weight.

But, even if we were to grant Macquer this supposition—when we accept, contrary to all appearances, contrary to the evidence of facts—that enough light can combine with and accumulate in bodies to become an integral part of their weight, there would still remain no shortage of phenomena that his system cannot explain. If phlogiston were the pure matter of light, all metallic calces should be revivified by burning glass as they are revivified by contact with charcoal. However, all metallic substances (with the exception of gold, silver and mercury) calcine by burning glass. Their calces, far from reclaiming the metallic state, melt into a type of glass under these conditions; whereas, these same calces quickly reclaim their metallic state after they are put in contact with charcoal at an appropriate level of heat. The matter that exists in charcoal is therefore not the same as what the sun's rays are composed of; therefore, phlogiston is not the pure matter of light.

Macquer believed that he had evaded this objection by saying that the revivification of metals cannot take place while they are in contact with the air, because they recalcine at the same rate that they revivify, and that it is for this reason that metallic calces vitrify by burning glass without passing into a metallic state. But this response of Macquer's can be eliminated by a decisive experiment. Metallic calces do not revivify with the aid of solar rays, even when one exposes them to those rays under bell-jars filled with mephitic air from the atmosphere.[31] However, there is no principle that can recalcine metals while they

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[30] Of the nitrous acid extracted from nitrous air, by a decomposition with common, or dephlogisticated air. In: Experiments and Observations on Different Kinds of Air, vol. III, §XV. London, Johnson (1777).

[31] The French term *mofette* and its English equivalent "mephitic air" can refer to any gas that does not support combustion or respiration. Hence Lavoisier here means air stripped of its oxygen.

revivify, they are in circumstances exactly like those that take place in closed vessels. And since they remain constantly in the state of calx, one must conclude that solar rays (the matter of light) do not act in the same manner as charcoal and, consequently, that phlogiston is not the pure matter of light.

[634] These objections against Macquer's system have been more or less intuited by chemists, and no doubt it is for that reason that it has not been completely adopted by any other chemist. He has established a great number of unique doctrines in which only the name phlogiston is conserved—each of them has attached a vague idea to this word, which no one has defined rigorously, and irreconcilable and contradictory properties have been united in the same entity without realising it. Some examples will make this easier to appreciate.

When very pure charcoal is burnt in vital air, all of the charcoal disappears and the vital air is converted into fixed air. If the process is conducted in a closed vessel, weighed precisely before and after the combustion, neither increase nor decrease in weight can be detected. But the air inside the vessel in which combustion takes place, instead of weighing 1.2670 g per litre, weighs 1.86 g.[32] The increase in absolute weight of this air is found to be exactly equal to the weight of charcoal that was used.

If one asks the majority of chemists—partisans of Stahl's doctrine—for an explanation of what happens in this experiment, they will be forced to recognise: Firstly, that it releases the matter of heat and light, which escapes through the vessels and dissipates. Yet, since the weight of the vessels in which one works neither increases nor decreases, they are obliged to admit that the matter of heat and light has no detectable weight. Secondly, they will be forced to recognise that a certain acid—fixed air—forms during combustion. Yet, as the weight of this acid is equal to the combined weight of the vital air and the charcoal, it obviously follows (independently of any system) that a heavy material exists in charcoal that cannot escape through glass vessels and that, consequently, is not the matter of heat and light. One sees therefore that in the combustion of charcoal Stahl's disciples give the name "phlogiston" to two very different materials—the weightless matter that escapes through the pores of vessels and the weighty matter that unites with [635] vital air to form fixed air. Therefore, we have two quite distinct substances, which Stahl's disciples conflate: a weightless phlogiston and a weighty phlogiston; one that is the matter of heat, the other that is not. It is by borrowing the properties of one of these substances then the other that they succeed in explaining everything.

Stahl's disciples also accept (without realising it) two types of phlogiston in metallic reductions. It is well known that reduction of the calces of gold, silver and mercury proceed by simple heat and without addition. On the one hand, we get revivified metal; on the other, the vital air that had combined with it, and the combined weight of the air and of the metal is equal to that of the calx before reduction. These sorts of reductions cannot be explained by Stahl's system except by saying (like Macquer) that the matter of light that is released from charcoal burning in the furnace sifts through the pores of vessels and combines with the metal. Since in this experiment the weight of the air obtained and that of the metal does not exceed the weight of the metallic calx, it is clear that, if phlogiston has combined with metal, this phlogiston weighs nothing.

Conversely, in the reduction of other metals we are obliged to add an ordinary carbonaceous substance. We thus obtain fixed air and reduced metal but the total product is found to have increased by the whole weight of the carbon that was used. Thus here we

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[32] Original reads, "instead of weighing 0.47317 [French] grains per cubic [French] inch, weighs 0.695 grains".

have again a material and weighty phlogiston and the disciples of Stahl who are again obliged to give the name "phlogiston" to two very different substances: to the matter of light (or the element fire), which weighs nothing; and to the carbonaceous matter, which does weigh something.

The reduction of metallic calces provides another disconcerting argument against them. There can be no doubt that the substance that is combined with the metal to form the metallic calx is vital air, the oxygen principle. However, this principle escapes in the form of fixed air when charcoal is added. Has the phlogiston from the charcoal united with the vital air to form fixed air, then? [636] Indeed, the weight of the vital air and charcoal that had been used is found in the fixed air. But, if all the weight of the charcoal had entered into the composition of the fixed air, then none of it combined with the metal, or at least what combined with the metal has no weight. Therefore, one must here accept a phlogiston with weight and that, combined with vital air, constitutes fixed air and a weightless phlogiston that, combined with a calx, gives it metallic properties. Whence it again follows that the disciples of Stahl give the same name to two different substances. Independently of these difficulties, which are common to the different modifications that have been introduced to the phlogiston doctrine, Macquer's system presents one that is unique to him. If, as he claims, phlogiston is nothing but the pure matter of heat and light, it follows that metals (in their metallic state) must contain much more matter of heat than metallic calces. Yet the experiments of Mr Crawford,[33] those of Mr Wilcke[34] and my own experiments with Mr Laplace[35] prove the contrary. Thus, only one of the two can be true: either phlogiston is not the pure matter of heat and light (as Macquer suggests) or metals contain less phlogiston than their calces. Yet these two consequences—and one must accept either one or the other—are equally destructive of Macquer's system and the doctrine of phlogiston in general.

The partisans of Stahl's doctrine are constantly in the same awkward position. If one asks them what happens when mercury is calcined in vital air, the English physicists respond that as the phlogiston escapes from the metal it combines with the air that surrounds it, which it changes into fixed air (or phlogisticated air). But this assertion is absolutely contrary to the facts. When one works with absolutely pure vital air it can be absorbed to the last drop. And, if one interrupts the operation before the absorption has been completed, the portion of vital air that remains is not at all altered—it only contains the exact same quantity of mephitic air [637] that was originally contained in the whole volume of air that was employed. Therefore, in this experiment the phlogiston is not combined with the air (as the English physicists claim) and so one must admit (like Mr Macquer) that it escapes through the pores of the vessel in the form of free fire (the matter of light). But if phlogiston can thus pass freely through the pores of vessels (if during the calcination of metals in vital air it has the propensity to penetrate the glass), if it has this same property in the revivification of the calces of gold, silver and mercury, then why does it not work with regard to these other metallic calces? Thus the partisans of Stahl's

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[33] Adair Crawford (1748–95)'s book (1779) sold out immediately and became very rare, so it is more likely that Lavoisier learnt of his work from de Magellan (1781), a précis in French (Guerlac 1976, 231ff).

[34] Johan Karl Wilcke (1732–96). The work in question was published in the *New Memoirs of the Royal Academy of Sciences* of Sweden for the year 1781(1783) (Guerlac 1976, 228ff).

[35] Lavoisier worked on calorimetry with his colleague Pierre-Simon de Laplace (1749–1827) over the winter of 1782–3. They read their paper to the Academy over two sessions—18th and 25th June 1783—and it was published the same year as a pamphlet (and again the next year with the *Mémoires* for the year 1780). In the published version they acknowledge the ingenuity of Wilcke's work, having seen it only after reading their own paper to the Academy (Memoir on Heat. Watson, New York ([1783] 1982), 14).

doctrine, after having been forced to say that phlogiston sometimes has weight and is sometimes weightless, are again obliged to believe that (even in its state of liberty) sometimes it penetrates the most compact pores of vessels, sometimes it does not penetrate—all incompatible qualities in the same entity, which proves more and more that the same name has been given to very different things.

A similar argument can be made with regard to the formation and destruction of nitrous air. According to the partisans of Stahl's doctrine, this results from the combination of nitric acid and phlogiston; but they do not realise that they are again obliged to attribute two incompatible qualities to phlogiston.

When nitrous air and vital air in their most pure states are combined in the appropriate proportions, the two airs penetrate each other and are reciprocally absorbed—they lose their aeriform state and are converted entirely into a liquid, which is nitric acid.[36] The partisans of Stahl's opinion are obliged to agree that there is a release of phlogiston in this experiment but, since only nitric acid is obtained and nothing else remains in the vessels after the combination, they are forced to admit that the phlogiston has passed through the pores of the vessel and has escaped. The phlogiston in question is therefore Macquer's phlogiston, the matter of light. But then, in combining nitric acid [638] with the pure matter of light (simply by heating it) nitrous air must be formed. Whereas, on the contrary, the body containing phlogiston must be in immediate contact with the nitric acid. Therefore, in sustaining this hypothesis we find ourselves forced to accept a phlogiston that does not pass through vessels for the formation of nitrous air and a phlogiston that does pass through the vessels for the composition of nitric acid.

The doctrine of phlogiston is also in contradiction with itself in the majority of chemical explanations. We are taught that phlogiston is the principle of colour and nevertheless metallic calces become more coloured in proportion to their lack of phlogiston. The calx of lead is firstly grey, as it loses its phlogiston it becomes yellow and red; the calx of iron is firstly yellow, it passes then to red and brown; the calx of mercury is red; those of copper are green and blue, etc. Therefore, if phlogiston is the principle of colours, these calces contain phlogiston. Therefore, metallic calces are not metals stripped of phlogiston.

It is true that many metallic substances—such as antimony, tin and some others—give perfectly white calces. But this is not the majority and it is more often the exception than the rule itself. Moreover, I shall observe that the partisans of Stahl's doctrine do not have reasonable ideas on what should be understood by a colourless substance. White, far from being the absence of all colour (as they suppose it to be) is, on the contrary, the union of all colours. Therefore, if phlogiston is the principle of colour, one must accept that all metallic calces contain phlogiston, since some of them unite all the colours and others display distinctive ones. The same difficulties follow us if we pass from metallic substances to animal and vegetable substances. Burning paper and cloth allows phlogiston to escape in Stahl's system—and in great abundance, as these [639] are just about the most combustible substances we know of. Both are converted into a black carbonaceous substance by burning. Therefore, if the colour black is characteristic of the presence of phlogiston, if the colour white is characteristic of its absence, the partisans of Stahl's doctrine cannot avoid

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[36] Indeed, Lavoisier believes nitric acid to be composed of highly oxygenated nitrogen (and nothing else)—Lavoisier, A.L.: On the existence of air in the nitrous acid, and on the means of decomposing and recomposing that acid. In: Henry, T. (ed.) Essays on the Effects Produced by Various Processes on Atmospheric Air. pp. 129–138. Johnson, London ([1776] 1783). For his general theory of oxygen as the principle of acidity, see his General Considerations on the Nature of Acids, and on the Principles of which they are composed. In: Henry (ed.) Essays on the Effects Produced by Various Processes on Atmospheric Air, pp. 96–118. Johnson, London ([1781] 1783).

admitting that the burnt paper contains more phlogiston than the white paper, which is contrary to the evidence of the facts as, the greater part of the matter of fire having escaped through combustion, there must remain that much less in the residue.

It is almost the same for causticity: phlogiston, in Stahl's system, is the principle of flavour and of causticity. Metals, which are abundantly supplied with phlogiston, must therefore be eminently caustic, however the majority are without taste. Metallic calces, on the other hand, being deprived of phlogiston, should be in an earthy state, insoluble in water and without any flavour. Yet by a completely opposite effect, the calcination of metals brings them closer to the saline state, gives them the property of solubility in water and makes them corrosive. It is true that in recent times the causticity that metallic substances acquire when they are deprived of phlogiston has been explained in quite a convenient way: this causticity, it was said, is the effect of the tendency they have to reclaim that principle wherever it is found. But this explanation is still an example of the ease with which the phlogiston hypothesis lends itself to everything, as causticity is explained equally well by the absence and by the presence of phlogiston, by the great quantity that substances contain and by the tendency they have to reabsorb it.

The effects of the matter of fire manifest themselves most clearly with respect to odours. In general three types of odorous substances can be distinguished: volatile substances, substances dissolved in the air and those whose corpuscles are so finely divided that they float in the air and are carried by it. Yet, it is quite certain that vaporised substances, even those dissolved in air, are combined with the matter of fire. One can [640] therefore say in this sense, not that the fire is the principle of odour, but that it is its vehicle, which comes close to the opinion of the partisans of Stahl up to a certain point.

All these reflections confirm what I have proposed, what I had aimed to prove, which I am going to repeat again—that the chemists have made phlogiston a vague principle that is not rigorously defined and that, consequently, adapts itself to all the explanations into which one wants it to force it. Sometimes this principle is heavy, sometimes it is not; sometimes it is free fire, sometimes it is fire combined with an earthy element; sometimes it passes through the pores of vessels, sometimes they are impervious to it. It explains at the same time causticity and non-causticity, transparency and opacity, colours and the absence of colour. It is a veritable Proteus[37] that changes form at each instant.

Acknowledgments The translator would like to thank Florence Greffe, chief archivist at the Académie des Sciences of Paris, and her staff for allowing him to consult handwritten drafts of Lavoisier's paper. He is also grateful to the Department of History & Philosophy of Science at Indiana University for the award of a Richard S. Westfall Fellowship, which enabled him to take that trip. Parts of this work were completed while on short-term fellowships from the Chemical Heritage Foundation and the Philadelphia Area Center for the History of Science (now the Consortium for History of Science, Technology and Medicine). He thanks both these organisations for their financial support, for access to many pertinent documents and for sharing the expertise of their library staff (particularly Jim Voelkel of the CHF). Cindy Elbaz and Bill Newman provided invaluable advice on various aspects of this translation but the translator takes full responsibility for any mistakes that may remain.

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[37] An early Greek god, herdsman of sea beasts, who was said to be able to take any form. A number of early-modern natural philosophers used this metaphor for the mutability of nature (Burns 2001), including Francis Bacon who used "proteus" as a name for prime matter ([1609] 1858, 725ff).

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