Antoine Laurent Lavoisier
26 August 1743—8 May 1794

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[Plates 10 and 11]

We have met to-day to honour the memory of a great Frenchman. Antoine Laurent Lavoisier is one of the immortals. In the whole history of science there is no transformation so swift and dramatic as when in 1789, in his great Treatise, he gave chemistry its modern form, sweeping away the cobwebs of centuries which obscured its progress. He was a child of his age. Bred in France at a time when the writings of Voltaire and Rousseau were stirring men’s minds, and Diderot and the Encyclopaedists were widening their vision, Lavoisier was a great reformer. It is difficult within the compass of an hour to do justice to his many-track mind. Ambition, curiosity, humanity and love of action took him into many fields, and in each his creative genius saw an opportunity for constructive work. The six great volumes of his collected writings display an amazing intellectual and practical achievement. In chemistry, in physics, in physiology, in chemical engineering, in agriculture, in geology, in education, in statistics and in finance he was a pioneer, and in each his contribution has the modern touch both in thought and phrase. The marvel is that with his widespread interests it was he alone, in a band of brilliant contemporaries like Black, Cavendish, Priestley and Scheele, who had the vision of modern chemistry and gave it life. Alone among the intellectuals Lavoisier was a man of affairs, skilled in administration and finance, and that is in some measure the secret of his success. For it can be said of him that he applied not only the balance but the principle of the balance sheet to chemistry and physiology.

Lavoisier’s life was such a tangled skein of occupations that they cannot be seen in their true perspective under separate headings. Their reactions on each other are the clue to so much that, even at the sacrifice of logical sequence, I shall try to picture the daily current of his life flowing in its many channels.

Lavoisier was a Foreign Member of the Royal Society and, although he never came to England, at many critical moments of his scientific work he was influenced directly or indirectly by Fellows of our Society. You will see that Robert Boyle, John Mayow, John Locke through his disciple Condillac, Stephen Hales, that most ingenious vicar of Teddington, Black, Priestley and Cavendish all had their influence on Lavoisier.

Early Life

He was born in Paris on 26 August 1743. His father was a lawyer, and his mother and grandmother came of legal stock, so that he had the law in his blood, and no one could draft an opinion more skilfully. After a classical education at the
Sir Harold Hartley

Mazarin College, he turned to science, and was fortunate in his teachers. Mathematics and astronomy he learnt from La Caille, chemistry from Rouelle, geology from Guettard, and botany from de Jussieu. From their teaching not only did he gain a broad general scientific background, but he was bitten with the idea of research.

He qualified as a lawyer, but he could afford to choose his own career, and his ambition turned to science. There was a touch of Francis Bacon in his make-up, a belief that by making systematic measurements the truth would emerge. He began like Dalton as a meteorologist, and his first published paper was on an aurora (1). Throughout his life he kept careful records of daily thermometric and barometric observations, made by himself and by correspondents in different parts of the world. He was always meaning to collate them, but that was never done, and his only meteorological paper was on forecasting, in which he suggested the value of a daily weather forecast (2). It was in meteorology that he served his apprenticeship in physical measurement, investigating the accuracy of the barometer and thermometer, and the best construction of the portable instruments which he sent to his correspondents.

GEOLGY

In 1763, when he was twenty, Guettard interested him in his project of a geological map of France, the first of its kind. It appealed to Lavoisier's systematic mind, and he threw himself into the scheme with characteristic energy, writing to ministers for support, and drawing up questionnaires to go to the provinces. For seven years Lavoisier was making geological tours to collect data for the survey, and his journeys gave him a cross-section of social conditions all over France that left its mark on his mind.

He travelled on horse-back with his servant carrying his barometer, thermometer, hydrometer, and box of reagents. His observations included both mineral deposits and the thickness and characteristics of the various strata at different exposures. He measured in each case their height above sea-level with his barometer, so that he knew the levels at which they occurred in different places. His material formed the basis of sixteen plates in the first geological map of France which was published in 1784 by Guettard's successor Monnet without proper acknowledgement of Lavoisier's work. His only substantial geological paper, on recent sedimentary rocks (3), was not published until 1788. In it he distinguishes between littoral and pelagic banks which were formed at different distances from the land and consisted of distinct kinds of sediments and organisms. His sections gave the first outline of a correct classification of the Tertiary deposits of the Paris region. Geikie said of Lavoisier that 'if he had not given himself up to chemistry, he might have become one of the most illustrious among the founders of geology'.

PUBLIC LIGHTING

Throughout his life Lavoisier's interests were divided between pure science and its application to practical problems. He had a deep sense of responsibility that science should be used in the service of man, and he was always ready to turn
Antoine Laurent Lavoisier
dside from his researches to some practical task. In 1765 the Academy offered a
prize for a paper on the lighting of the streets of a large city and Lavoisier decided
to compete. He made an elaborate investigation, both practical and theoretical,
of various methods of illumination; of the relative cost of lighting Paris with candle
or oil lamps, of the advantage of various types of reflexion, of the time of burning of
different kinds of oil, and of the use of dissolved resin to prevent the freezing of oil
in winter. The prize was divided between three manufacturers, but Lavoisier's
paper, an early and admirable piece of industrial research, was awarded a gold
medal given by the King and was published by the Academy(4).

Académie des Sciences

1768 was the fateful year of Lavoisier's life. In February the great promise he
had shown as an investigator was recognized by his election as a member of the
Academy of Sciences. From the day he joined that august body as 'adjoint
chimiste' his wide knowledge and experience, his diligence and his ability in
drafting memoranda made him one of its most active members. Throughout his
life a considerable portion of his time was devoted to its service, and Lavoisier
was a most staunch defender of its privileges. He became a full member in 1778,
director in 1785, and treasurer in 1791 until its suppression in 1793. The Govern-
ment was constantly remitting questions to the Academy for reports, and Lavoisier's
was the guiding hand in their preparation. He wrote over fifty memoranda on
subjects ranging over The Great Frost of 1776, Prison Reform, Mesmerism, Water-
Divining, the Creuzot Works, and The Development of Balloons(5).

The Ferme

A few days after he had joined the Academy he became a member of the Ferme,
the financial corporation that leased from the Government for periods of six years
the privilege of collecting the indirect taxes. The annual payments had to be made
in advance, so that membership of the Ferme involved a considerable investment
of capital, the return on which depended on the ability of the administration and
the state of trade. For Lavoisier it was not merely an investment, as he threw
himself into the task of administration with his usual energy. His practical ability
and his conscientious management soon made him one of the leading members of
the Corporation. Lavoisier's scientific friends shook their heads at his new venture,
but said cynically 'Well, at any rate he will give us better dinners'.

The collection of customs duties, octroi, and salt tax and the sale of tobacco,
involving an annual income approximating 200 million livres, required an organiza-
tion of nearly 30,000 officials working all over France. This was supervised by a
number of committees drawn from the sixty members of the Corporation, their
work involving a series of visits to the provinces. Lavoisier served on some of
these, and he was specially charged with inspection of the tobacco factories and of
the frontier guards to prevent smuggling. These journeys occupied a large part of his
time from 1769 to 1771.
Sir Harold Hartley

Marriage

In 1771 Lavoisier married the daughter of Jacques Paulze, one of his colleagues in the Ferme. His wife was only fourteen years old, but she was a girl of character and intelligence and devoted her life to helping her husband (see plate 10). She learnt languages and translated Priestley and Cavendish for him, and later she published a translation of the essays of Kirwan. She was constantly in the laboratory, and many pages of the records of his experiments are in her handwriting. She studied painting with David, and two drawings showing Lavoisier's experiments on respiration with Seguin are by her hand (see plate 11). She also drew and engraved all the plates for his Traité Élémentaire de Chimie. Benjamin Franklin, in writing to thank her for his portrait, said: 'It is allowed by those who have seen it to have great merit as a picture in every respect; but what particularly endears it to me is the hand that drew it.'

We get a glimpse of her in Arthur Young's Diary in 1787. 'To Monsieur Lavoisier by appointment. Madame Lavoisier, a lively, sensible, scientific lady, had prepared a déjeuner Anglais of tea and coffee, but her conversation on Mr Kirwan's Essay on Phlogiston, which she is translating from the English, and on other subjects, which a woman of understanding, that works with her husband in his laboratory knows how to adorn, was the best repast.'

Gouverneur Morris, the United States Minister in Paris, had to discuss with Lavoisier the price the Ferme should pay for Virginian tobacco and also the debt that was owing by his Government. His Diary of the French Revolution gives us a picture of Lavoisier as a business man and of Madame Lavoisier as his hostess:

2 June 1789: Return Home and then call on Monsr. Lavoisier....Talk of a future Contract. Thinks it should exist for a Part of the Supply. I agree with him and add that I would rather contract for the best Quality and leave the inferior Kinds to the Chance of Marketts. He asks at what Price. I tell him that what I say must not draw to any Consequence but be considered merely as Conversation. That it may be from 32 to 33. He thinks this much too high.

8 June 1789: Dine with Mr. de Lavoisier; as I am leaving he tells me that the Farm are determined to stand Suit and that he is sorry for it. Madame appears to be an agreeable Woman. She is tolerably handsome, but from her Manner it would seem that she thinks her forte is the Understanding rather than the Person.

26 June 1789: Return Home and take a little Medicine and then go to Dinner at Mr. Lavoisier's. They are just returned from Versailles and Madame gives me the News.... At Dinner, Mr. Lavoisier, who seems to be a sensible and well informed Man, tells me that the usual Produce of France is from 5 to 6 Times the Seed sown.

25 September 1789: Go to the Opera according to my Promise and arrive towards the Close of the Piece at the Loge of Madame Lavoisier.... Go to the Arsenal and take Tea with Madame Lavoisier en attendant le Retour de Monsieur who is at the Hôtel de Ville. As Madame tells me that she has no Children I insist that she is une Parasseuse, but she declares it is only Misfortune.... Monsieur comes in and tells us of the Obstination of the Bakers. This Corps threatens the Municipality of Paris with a Discontinuance of their Occupation unless a Confrère, justly confined, is released. Thus the new Authority is already trampled on. I take Mr. Lavoisier apart and propose to him to negotiate with the Farm for the Debt of the United States. I offer him also a Concern. He will I think accept it, tho he rather objects. He wishes to know my Terms. I speak vaguely.
Antoine Laurent Lavoisier

25 July 1791: Call on Mr. Franklin and we go together to Made. de Lavoisier's to Dinner. As the Party is rather High-Flying they conclude Haphazard that the Riot at Birmingham has been occasioned by the Government. This is ridiculous enough.

7 November 1791: Mr. Franklin dines here, and we go together after Dinner to see Made. Lavoisier where there are a Number of Gens d'Esprit who are in general but so so Company.

Few men can have been more happily married than Lavoisier. His wife shared in all his activities, she helped him to fight his scientific battles, and in the dark days to come she risked everything to try and save him.

 EARLY CHEMICAL RESEARCHES

Even before his election to the Academy Lavoisier's interests were turning from geology to chemistry. His first two chemical papers were on gypsum, its composition and its solubility in water (8). Lavoisier used a hydrometer to show that the solution of gypsum was denser than water, and this led him to a systematic study of the subject of hydrometry in which he devised a new form of constant-immersion hydrometer, a small portable version of which he used to examine the densities of a large number of natural waters during his geological tour, in order to determine their content of dissolved salts. His practical mind saw the importance of water supplies to cities, and he was a strong supporter of de Parcieux's scheme for improving the water supply of Paris, on which he read papers to the Academy in 1769.

In order to standardize his hydrometers Lavoisier studied the effect of repeated distillation on its density and also the variation of density with temperature, in which he observed the increase of density to a maximum above the freezing-point. He was unaware that this had been discovered in Italy in the seventeenth century.

In 1768 he began to investigate the supposed conversion of water into earth which had been a matter of so much controversy since the time of Boyle. Lavoisier's method of attack is characteristic of his experimental methods (9). He weighed a retort, introduced into it a known amount of fresh rain water, and luted on a closed receiver to act as a reflux condenser, after heating the retort to expel some of the air. The whole apparatus was then carefully weighed and the retort heated for 110 days in an oil-bath to about 80° C. A deposit of earth slowly formed in the retort, but the weight of the apparatus at the end was unchanged, showing that it had gained no fire material nor lost any water through the glass. This must have had an important influence on Lavoisier's ideas by strengthening his tacit assumption of the conservation of mass, and by showing him that in chemical changes involving exposure to heat the 'fire material' did not necessarily, as was often supposed, cause any change of weight. The solid was then collected, the water evaporated and the weight of the total dry solid residue was compared with that of the loss of weight of the empty retort during the operation. The solid weighed 20.4 grains, while the retort had lost only 17.4 grains. Lavoisier could not explain the greater weight of the solid residue (caused, as Meldrum has pointed out, by the absorption
by alkali of carbon dioxide from the air), but he concluded rightly that in spite of this discrepancy the solid must have come from the glass and not from the water.

This was the most significant of Lavoisier’s early papers, and it was followed early in 1772 by an investigation with Macquer and Cadet of the effect of heat on diamonds (10). The varying resistance of gem stones to heat had excited the curiosity of experimenters for centuries, and the causes of the loss of weight of the diamond on heating had been continuously a matter for inquiry. Was it due to true volatilization as Boyle thought, or to a species of combustion as Macquer’s recent observations indicated, or to a decrepitation into small fragments caused by contact with cold air? Those were the rival views which Lavoisier and his friends set out to investigate by comparing the effects of heating diamonds in open and closed vessels. Heated in an open retort to a high temperature for some hours they were found to lose weight and become discoloured. On the other hand, diamonds heated in a clay pipe filled with charcoal and closed with a lute, the pipe itself being enclosed in a nest of three crucibles with a similar lute to exclude air, lost no weight and showed only a slight superficial darkening and no loss of polish after exposure to the highest temperature available. Hence they concluded that the loss of weight depends on contact with the air and is due either to combustion or to some mechanical effect of the air in causing decrepitation. These experiments were continued later by Lavoisier using the great burning glass of Tchirnhausen, but the paper was not printed until 1776, and it is not clear at what date it was presented to the Academy (11). Lavoisier’s notebook shows that these experiments were still in progress in 1773.

**Combustion**

The experiments on diamonds and probably papers by Sage and Cigna on the burning of phosphorus gave Lavoisier an interest in combustion, and his knowledge of the work of Boyle and Hales shows that he was studying the literature. At this time Stahl’s theory of phlogiston still held the field. It was generally accepted by chemists that substances are inflammable because they contain this mysterious principle, which was liberated with heat and light so long as air was there to remove it. Respiration was thought to be a similar process, the air removing phlogiston from the lungs. It was a looking-glass hypothesis, a relic of alchemy, but it had an astonishing hold on chemists’ minds until Lavoisier broke it.

The critical moment for Lavoisier came on 10 September 1772 (12) when, having bought an ounce of phosphorus, he found it could be burnt in glass vessels without breaking them and began to examine the absorption of air already noticed by Cigna and others during its combustion. On 20 October he sent a sealed note to the Secretary of the Academy giving the results of his experiments which showed that air is absorbed when phosphorus is burnt and that the phosphoric acid weighs more than the phosphorus (13). On 1 November he sent another note describing his discovery that sulphur, like phosphorus, gains in weight during combustion, and that this increase of weight is due to a prodigious quantity of air which is fixed during combustion (14).
Cette découverte, que j’ai constatée par des expériences que je regarde comme décisives, m’a fait penser que ce qui s’observait dans la combustion du soufre et du phosphore pouvait bien avoir lieu à l’égard de tous les corps qui acquièrent du poids par la combustion et la calcination;...L’expérience a complètement confirmé mes conjectures; j’ai fait la réduction

\[ \text{Expérience sur le Phosphore} \]

\[ \text{Du 10 Juin 1772} \]

J’ai acheté chez Mr. Marand une once de grosses perceuses d’où il me fallait absolument enlever la partie pure de la substance

J’ai mis une petite mèche dans un bocal de la phénacé et demarre l’incendie d’un brûleur de zinc. Les chaleur produite ont l’air approchant un feu de chemin et j’ai essayé avec peine mais la phénacé tenant aussi bien que la phénacé normale ou sans aucun

enhardi, puis à l’aide j’ai voulu par la même appuie vérifier si le phosphore absorbé

sur cette phénacé disparaissait à l’état pur. J’ai donc introduit une cuillère dans le brûleur et j’ai réduit l’expérience à un moment petit brûleur pour l’air et jamais comme tenu la chaleur à la même manière et même

\[ \text{Figure 1. The page from Lavoisier’s notebook, 10 September 1772, recording his experiments in burning phosphorus.} \]

de la \textit{litharge} dans les vaisseaux fermés, avec l’appareil de Hales, et j’ai observé qu’il se dégageait, au moment du passage de la chaux en métal, une quantité considérable d’air, et que cet air formait un volume mille fois plus grand que la quantité de \textit{litharge} employée. Cette découverte me paraissant une des plus intéressantes de celles qui aient été faites depuis Stahl, j’ai cru devoir m’en assurer la propriété, en faisant le présent dépôt entre les mains du secrétaire de l’Académie, pour demeurer secret jusqu’au moment où je publiera mes expériences.
Sir Harold Hartley

It was a moment of great elation for Lavoisier. To his practical mind increase in weight meant gaining something, not losing it, as the phlogistics argued. He saw a vision of something much bigger than a theory of combustion, 'a revolution in chemistry and physics'. He saw, too, that its realization depended on a detailed investigation of the gases that were given off or absorbed in the chemical changes. It was no easy task, as Lavoisier had had comparatively little chemical experience, but he attacked it with courage on a wide front, and the next twelve months saw the most concentrated and sustained scientific work of his career. He was confident of his objective, and that confidence kept him going through the perplexities and disappointments of twelve crowded years.

*Opuscules physiques et chimiques*

The record of his next year's work was published in a separate volume, *Opuscules physiques et chimiques*, as it was too long for the *Memoirs* of the Academy (15). It is described in the preface as the first of a series of investigations covering the wide field that he already had in view. It was Lavoisier's apprenticeship to the study of gases. He began with a careful study of the literature, and half the volume consists of a history of previous work. Hales, Black and Priestley are the three chemists to whom he pays special attention. Through Hales he learned the experimental methods of John Mayow, and his own apparatus, though more elaborate, is obviously based on that of Hales. His systematic mind appears in the tables in which he assembles all the quantitative results of Hales's ingenious but almost random experiments. From Black he learned perhaps more than he said. Black's paper on the alkalis was a quantitative study after his own heart, and broadly speaking he was to do for metals and oxides just what Black had done for mild and caustic alkalis.

Having finished his survey of the literature, on 22 February 1773 he began his laboratory notebook with a remarkable forecast of the work it was to record (16):

> Qui m'a paru fait pour occasionner une révolution en physique et en chimie. J'ai cru ne devoir ne regarder tout ce qui a été fait avant moi que comme des indications; je me suis proposé de tout répéter avec de nouvelles précautions, afin de lier ce que nous connaissons sur l'air qui se fixe, ou qui se dégage des corps, avec les autres connaissances acquises et de former une théorie.

Lavoisier's own experiments, which are described in the second half of the volume, consist mainly of careful measurements of the changes in weight and volume that accompany the evolution or absorption of gas in the formation or decomposition of carbonates, the neutralization of acids, the reduction of metallic oxides, and the calcination of metals. His observations were thus concerned only with carbon dioxide and oxygen, but at that time Lavoisier had formed no definite view as to the nature of different gases. He was convinced of their fundamental importance and his aim was to bring them all into a common theory.

The experimental part of the paper begins with a repetition and testing of Black's work, using the results to establish the composition of quicklime, slaked
lime and chalk. This was then extended to the carbonates and hydroxides of the alkali metals and ammonium, and to the precipitation of metallic solutions by alkalis. The amounts of gas evolved by heating metallic calces with charcoal were measured and the gas was shown to be identical with that from chalk, but owing to faulty experimental methods the gas in each case was mixed with air, which must have complicated Lavoisier's conclusions. Finally, he measured the absorption of air when metals are calcined or phosphorus burnt in bell-jars over water.

Lavoisier's most important conclusion was that in confined spaces only a limited amount of calcination takes place, the increase in weight being roughly proportional to the volume of air absorbed. Thus it followed that metals could only fix part of the air, and the same result was obtained with phosphorus. But no conclusion is hazarded as to the nature of the gas which supports combustion, and the last sentence of the paper reveals one of the difficulties that must have been puzzling Lavoisier's mind. He says:

J'ai été curieux, relativement à des vues dont je rendrai compte dans un autre temps, d'observer si le mélange d'un tiers de fluide élastique des effervescences corrigérait l'air qui avait servi à la combustion du phosphore, et lui rendrait la propriété d'entretenir les corps enflammés. Le mélange fait, j'en ai rempli un bocal étroit et j'y ai introduit une bougie, mais elle s'y est éteinte sur-le-champ.

The paper as a whole is such a clear exposition of a logical sequence of quantitative experiments that it is disappointing that it should end on so inconclusive a note. Luckily we have in Lavoisier's notebook the clue to his perplexities. Misled perhaps by Black's name of 'fixed air' for carbon dioxide (which he abandoned in the following year), Lavoisier thought that the gas which was 'fixed' in alkalis was identical with the gas 'fixed' by metals in their combustion to form calces. This is proved by several entries in his notebook; for example, on 1 July 1773 he wrote: 'Persuadé que la combustion du phosphore absorbe l’air fixe contenu dans l’air, ou plutôt le soupçonnant, j’ai pensé qu’en rendant de l’air fixe à cet air, on pourrait peut-être le rendre air commun.' He tries, of course, without success, but fails to push the matter further (17).

A comparison of the notebook with the paper is interesting in another way. The experiments seem to have been made without any planned sequence, but in the paper the results are marshalled in perfect order, showing the systematic grasp Lavoisier already had of the whole field, his doubts only being recorded in the last sentences. It was a remarkable pioneer achievement in experimental technique, but progress had to wait until Lavoisier knew the relationship between carbon dioxide and oxygen. He had still much to learn, despite his brilliant intuition.

Calcination of metals

Lavoisier was unshaken in his belief that increase in weight meant chemical combination, and immediately the Opuscules was published he began experiments on the calcination of tin and lead in sealed vessels. Boyle had done similar
Sir Harold Hartley

experiments but had only reweighed the vessels after opening them, when he found an increase in weight which he explained by the passage of fire material through the glass (18). Lavoisier saw the opportunity for a crucial experiment by weighing the vessels both before and after they were opened. A summary of his results was deposited with the Academy on 24 April 1774, but was not read until the public session on 14 November (19), following Lavoisier’s usual plan of keeping a tit-bit for that occasion. Without giving any numerical details Lavoisier said that in sealed vessels the calcination of lead and tin ceased after an hour’s heating, the amount of calx formed being greater in larger vessels. In every case the weight of the vessel was unaltered if it was weighed before it was opened. When the seal was broken, air was heard to rush in, and the weight of the vessel was then greater, the increase being ‘exactly proportional to its capacity’. Hence it was clear that the increase in weight was due not to the passage of fire-stuff through the glass but to something the metal had ‘borrowed’ from the air in the vessel which had converted it into a calx.

Lavoisier ended with a significant sentence about the nature of the air that remained after metal had been calcined in it:

Cet air ainsi dépouillé de sa partie fixable (je pourrais presque dire de la partie acide qu’il contenait); cet air, dis-je, est en quelque façon décomposé; et il m’a paru résulter de cette expérience un moyen d’analyser le fluidé qui constitue notre atmosphère; et d’examiner les principes qui le constituent. Quoique je ne sois pas arrivé à cet égard à des résultats entièrement satisfaisans, je crois cependant être en état d’assurer que l’air aussi pur qu’on puisse le supposer, dépouillé de toute humidité et de toute substance étrangère à son existence et à sa composition, loin d’être un être simple, un élément, comme on le pense communément, doit être rangé au contraire tout au moins dans la classe des mixtes, et peut-être même dans celle des composés.

Lavoisier found that his experiments were not as new as he had thought, and he added a note saying that Beccaria had made the same observations on tin fifteen years earlier, and that Priestley had pointed out the limited extent of calcination in sealed vessels. But the ultimate value of an observation lies in the deduction from it, and here Lavoisier alone saw the truth.

A full account of these experiments was not given until 1777, when Lavoisier had to admit that owing to their difficulty only two with tin were completely successful and none with lead (20). However, the numerical results of the two successful experiments showed the care and skill with which they had been carried out, and justified the conclusion that the weight of the sealed vessels was unaltered, within the errors of experiment, after calcination had occurred. By then Lavoisier had further evidence about the nature of air, which he describes as a mixture of a salubrious portion which combines with metals during calcination, leaving ‘une espèce de mofolette’ which will not support life or combustion, and is itself ‘fort composé’. From his results he suspected that the former is the denser of the two, air being intermediate. His experiments were, in fact, sufficiently accurate to justify this conclusion.
These experiments on the calcination of tin must have strengthened Lavoisier’s confidence in the correctness of his theory, and from March 1774 onwards his notebook shows that he was widening his front of attack, for combustion was only one aspect of the revolution he had in mind. This year saw the beginnings of work on a number of problems whose solution eluded him for the moment, as the background of his knowledge was as yet insufficient. In each there was a quantitative approach to determine both the composition of substances and the nature of the chemical changes that they undergo.

He begins by burning inflammable air (hydrogen) which ought on his theory to increase in weight, and he was puzzled to find a loss owing to the escape of water vapour. This was a problem that continued to perplex him for nine years.

Next came a study of the formation of nitrous ether, also abortive, then an attempt to determine the composition of nitre by exploding a mixture of it with charcoal, and analyzing the gaseous products. Knowing the percentage of caustic alkali in the nitre he tried to calculate its composition, but he did not know how much the charcoal contributed to the weight of fixed air.

In October he is repeating a number of Priestley’s experiments on various gases, including his production of an acid by passing electric sparks in air. But it was characteristic of Lavoisier’s lack of qualitative intuition that in spite of his interest in acids he does not follow up this clue, and the explanation had to wait for Cavendish ten years later.

Next come some revealing thoughts on ‘vegetable analysis’ and plans for future work, the birth of organic analysis.

Nous ignorons: 1° Quelle est la qualité de cette immense quantité d’air qui se dégage pendant la distillation: il y a probablement de l’air fixe et de l’air inflammable; 2° ce que c’est que l’huile; il paraît que par la combustion on peut la réduire en air et en eau; mais nous ne savons rien au-delà. Déterminer les proportions des deux en brûlant une lampe en un vase clos. 3° Ce que c’est que le charbon. Nous savons bien qu’en brûlant il convertit l’air évidemment en air fixe: mais nous ne savons pas s’il donne lui-même de l’air fixe.

Lavoisier is still not quite free from the incubus of phlogiston, and he suggests burning charcoal in a sealed vessel to see if any phlogiston escapes through the glass during combustion with a corresponding loss of weight.

**Priestley and oxygen**

Lavoisier’s notebooks show that in 1774 his mind was roving over a wide range of problems of great significance but too complex to be solved with his present knowledge. He was still puzzled about the relation of fixed air to the air absorbed in calcination, and had tried to find a calx which could be reduced and give up this air in the absence of charcoal. It seems clear that Priestley gave him the clue he needed when he was in Paris in 1774. On 1 October he told Lavoisier that by heating the calx of mercury he had got a gas in which a candle burnt particularly brightly. It was not until the following 1 March that Priestley realized the remarkable properties of this gas and thus discovered oxygen. Lavoisier got some
Sir Harold Hartley

calx of mercury from Cadet, and after some preliminary experiments in November
three months elapsed until he completed them in three days’ work with Trudaine
at Montigny. He described the results at the public session of the Academy in
April 1775 in a paper on ‘The nature of the principle that combines with metals
during their calcination and augments their weight’ (22).

His main interest was to compare the fixed air he got by heating the calx of
mercury with charcoal with the gas he got by heating it alone, which to his surprise
was quite different and ‘more respirable, more combustible and consequently
purser than ordinary air’. His difficulty about the relation of these two gases was
therefore solved. But qualitative experiments were never Lavoisier’s strong suit,
and in this paper for once he is inconsistent. Perhaps it was written hurriedly for
the public session. At one point he describes the ‘principle’ absorbed in calcination
as ‘neither one of the constituents of the air, nor a particular acid existing in it,
but the air itself without alteration or decomposition’. And he has the curious
idea that the air can be purified whenever it is absorbed in a calx and then set free
again. In another part of the paper he says that the ‘principle’ is the purest part
of the air. Lavoisier is rarely guilty of such inconsistency, but in this paper he
clearly failed to realize the full significance of the facts he had observed.

The paper was published in Rozier’s Journal and soon drew a criticism from
Priestley (23), whose observations were much more accurate:

Having mentioned the paper of Mr Lavoisier’s,… I would observe, that it appears by it,
that, after I left Paris, where I procured the mercurius calcinatus abovementioned, and had
spoken of the experiments that I had made, and that I intended to make with it, he began
his experiments upon the same substance, and presently found what I have called depillogisti-
cated air, but without investigating the nature of it, and indeed, without being fully apprised
of the degree of its purity…. He therefore inferred, as I have said that I myself had once
done, that this substance had, during the process of calcination, imbibed atmospheric air,
not in part, but in whole… As a concurrence of unforeseen and undesigned circumstances
has favoured me in this inquiry, a like happy concurrence may favour Mr Lavoisier in another;
and as, in this case, truth has been the means of leading him into error, error may, in its turn,
lead him into truth.

It is curious that Lavoisier failed to see at once that the experiments with the
calx of mercury gave the support he needed for his theory, and that he was so slow
to complete them. From May until September 1775 his laboratory notebook is a
blank. The reason for all this was a new preoccupation in his mind.

RÉGIE DES POUDRES

Turgot, a friend of Lavoisier, had just been made Controller-General, the one
man who might perhaps have saved France from a Revolution, if vested interests
had not been too strong. Lavoisier was in touch with every side of the administra-
tion, and his critical eye had noted the inefficiency of the national production of
gunpowder which was made under contract by a financial company. Lavoisier
saw that their methods of collecting nitre and of making gunpowder were costly
Antoine Laurent Lavoisier

and wasteful, and that production was insufficient. He remembered, too, that the prohibitive cost to France of imported powder during the Seven Years’ War was one cause that had led to the peace of 1763. He succeeded in persuading Turgot that it would not only pay the government to cancel the existing contracts with compensation and take over the manufacture itself, but that it was essential for the national safety. This was done by a decree in March 1775, and Lavoisier and three of the former officials were put in charge of the powder factories.

Lavoisier at once concentrated all his energies on the new task. He moved to the Arsenal, where he lived and had his laboratory until 1792. He then began a thorough investigation into the methods of making and collecting nitre, nitrification being the only source of saltpetre apart from some deposits which he spent three months in surveying. His laboratory notebooks for 1775 and 1776 are full of records of various investigations into the manufacture of nitre and gunpowder.

In 1777 he drew up comprehensive instructions for the construction and operation of nitrification plants embodying many improvements, which represented a fine piece of chemical engineering. With his usual eye to finance he calculated that the plants should yield a net revenue of 15% on the capital. Great care was taken to select suitable staff, who had to pass an examination in chemistry, mathematics and the construction of powder mills.

The results were even better than Lavoisier had predicted. In three years the improvement of the powder had increased the range of French weapons by 60%. Production increased steadily, and by 1788 there was a reserve of five million pounds in the magazines, and the economies had amounted to 20 million livres.

However, the effect of Lavoisier’s work did not end with the Napoleonic wars. He had interested young Irénée Du Pont, the son of the physiocrat, in chemistry, and later he became Lavoisier’s assistant at the Arsenal. Irénée and his father were constitutionalists, and in 1792 they were fighting beside the Swiss Guard at the Tuileries. Saved by a miracle, they emigrated later to America. There on the banks of the Brandywine River at Wilmington, Irénée Du Pont built another powder factory destined twice to become a great arsenal of the Allied Nations.

THE DISCOVERIES OF 1776 AND 1777

In September 1775 experiments in the laboratory were resumed, though most of the work in the autumn was concerned with the manufacture of nitre. But gradually Lavoisier began to take up his scientific work again. He dissolves mercury in nitric acid, evaporating the solution to dryness and measuring the gases evolved when the mercuric nitrate is heated. This he uses as a method of analyzing nitric acid, as the experiment ends with the same weight of mercury as at the start. From the proportions of nitrous gas and pure air he calculates the percentage composition of nitric acid, assuming the other component to be water. The results were read to the Academy in 1776 in a paper ‘On the existence of air in nitric acid’(25), which he takes as an illustration of his general thesis that ‘non-seulement
Sir Harold Hartley

l'air, mais encore la portion la plus pure de l'air, entre dans la composition de tous les acides sans exception; que c'est cette substance qui constitue leur acidité'. He shows how he gets a mixture of nitrous air and pure air from nitric acid, and how by recombining them he gets nitric acid back again. He always tried to verify his conclusions both by analysis and synthesis.

In this paper he twice pays a tribute to Priestley as the original discoverer of many of the facts he describes: 'comme les mêmes faits nous ont conduits à des conséquences diamétralement opposées, j'espère que, si on me reproche d'avoir emprunté des preuves des ouvrages de ce célèbre physicien, on ne me contestera pas au moins la propriété des conséquences'.

This was the only paper he published in 1776, but it was a very busy year in the laboratory. Many of Priestley's experiments were repeated. Work was in progress on the analysis of air by the calcination of mercury, on the composition of various acids, on respiration, on the burning of a candle, on the latent heat of vaporization, and on the heat produced in the neutralization of acids.

Lavoisier is now quite clear about the nature of the air and of combustion, and for the first time he openly challenges the theory of phlogiston. During 1777 the evidence he had accumulated in support of his theory was presented to the Academy in nine papers, one of which was not read until 1779, and none was printed until 1780. Air, he says, is a mixture, four-fifths being an inert gas 'mofette' which takes no part in respiration or combustion, and one-fifth a gas 'eminently respirable', a constituent of all acids, which he therefore named oxygen. The compositions of carbonic acid, nitric acid, phosphoric acid, sulphuric and sulphurous acids had been determined. Respiration and the burning of a candle both convert oxygen into carbonic acid or 'acide crayeux aeriforme', the name Lavoisier has substituted for fixed air. Slow combustion in the lungs is suggested as the source of animal heat. Finally, the existence of the three states of matter is shown to depend on their heat content, and the heat of combustion is explained by the heat given out by gaseous oxygen in its change of state and combination.

Supported by this evidence Lavoisier attacks the theory of phlogiston, and shows that his own explanation is much simpler, involving no unwarranted assumptions such as the presence of an immense quantity of fire material in solids like the diamond, or that substances gain in weight while losing part of their contents.

It was a year of great achievement; the problem of combustion was solved, but Lavoisier's theory gained no adherents. It was incomplete, and there were many other simple reactions he could not explain. He was still puzzled by inflammable air, and he had not tried to discover the nature of the inert constituent of the atmosphere.

Lavoisier's experimental farm

The clue to both problems was to come eventually from Cavendish, and Lavoisier's notebooks of 1778–82 contain no records of new and important discoveries. His hands must have been full enough with the Arsenal, the collection of
taxes and the business of the Academy. To these he now added a fresh activity—an experimental farm. On his many journeys through France Lavoisier, like Arthur Young, had seen the poor state of French agriculture and the hard lot of the peasants. The staple crop was wheat grown three years out of four, and the head of livestock was too small to yield the manure required for good cultivation. Lavoisier saw the advantages of the British system of mixed farming, with its larger capital investment, more livestock, and wheat grown only one year in four.

So in 1778 he started an experimental farm at Fréchines near Blois, in a district where the standard of farming was low, in order to investigate and demonstrate the possibilities of improvement. Lavoisier always took the big view, and his aim now was to increase the wealth of France and to ease the life of the peasants.

The experiments were carried out as far as possible with the same strict control as if they had been made in the laboratory. He kept records at Paris of every field, its size, soil, crop and yield, with an annual debit and credit account.

His main objective was to increase the amount of fodder crops and raise the number and quality of his livestock. He had some disappointments at the start—lucerne failed and clover did badly in dry years, but sainfoin was a success. He introduced ley farming on the fallows, catch crops and root crops, and gradually increased his livestock. The folding of sheep was another successful innovation. No point was too small for Lavoisier, and one of his papers describes in great detail a simple way of making hurdles.

After nine years’ development the farm was in much better shape, but Lavoisier was disappointed at the slowness of progress, and he saw no prospect of getting a 5% return on his investment. This and the shortness of the leases explained why French farming suffered so badly from a lack of capital. However, that was not the end, as by 1793 his wheat crop had doubled, his stock had multiplied five times, and his neighbours were copying his improved methods of farming.

When Calonne appointed a Consultative Committee on Agriculture in 1785, Lavoisier was its secretary and drafted its reports. Among its schemes were projects for experimental farms, a museum of agricultural implements, and a school of textiles made from home-grown materials, which was actually started in Paris. Among Lavoisier’s friends were the leading physiocrats, including Du Pont de Nemours and Malesherbes. While he sympathized with their views on freedom of trade, and regarded agriculture as the primary source of national wealth, he recognized that industry, too, had its place in the national economy. One of his memoranda dealt with the bad effects of restrictive regulations on agriculture. Another, dealing with the many relics of feudalism which handicapped the French farmer, reads like pages from Arthur Young’s Diary. A third, ‘Instructions to the Provincial Assemblies for improving agriculture’, recommends many of the new practices Lavoisier had tried himself at Fréchines. In the end, however, little was done owing to the lack of interest of the ministers.
Sir Harold Hartley

Lavoisier's day

Lavoisier's immense output of work in so many fields during this period was only made possible by his quickness of mind and memory, his power of concentration on the matter in hand and his methodical habits. While he was living at the Arsenal six hours a day were given to science, in the early morning from 6 o'clock to 9 and from 7 o'clock to 10 after dinner. The rest of the day was spent in dealing with the business of the Ferme or the powder factories, in the meetings of the Academy or of the many Commissions of which Lavoisier was a member. Sunday was the happiest day of the week, as he spent the whole of it in his laboratory, which soon became a rendezvous for intellectual society in Paris. Scientists, ministers, economists and distinguished visitors from abroad went there to see Lavoisier's latest experiment and to join in the discussion of its significance. This was the usual preliminary to one of his papers at the Academy. The younger men interested in science were equally welcome with their seniors, and they often helped Lavoisier with his experiments. The memories of those brilliant gatherings in his laboratory, which played no unimportant part in scientific history, remained fresh in the minds of those who shared in them.

Thermochemistry

One of Lavoisier's great services to chemistry was to disentangle the chemical and physical aspects of chemical change. The phlogiston theory had been responsible for much loose thinking, since it assumed that this mythical principle could modify both the chemical and the physical properties of matter. Lavoisier concentrated first on the alterations in weight accompanying chemical change, particularly combustion. His belief in the conservation of matter was strengthened by his experiments in sealed vessels which showed no evidence of changes in weight due to the gain or loss of fire material. This was confirmed by unpublished experiments which proved that the weight of sealed tubes of water remained unchanged when they were frozen. The distinction between chemical and physical changes simplified his task greatly, and by 1777 his evidence on the gravimetric side was sufficient to enable him to give a satisfactory explanation of the nature of air and its role in the chemical changes involved in combustion and respiration.

Lavoisier was now striving to give a similar picture of the physical changes accompanying chemical action. He recognized the dependence of the three states of matter on their heat content, and he explained the heat of combustion by the change in the heat content of the oxygen concerned. He had no idea of the conception of energy, and he did not connect the evolution of heat with the affinities of the elements for each other. The difference in the heat of neutralization of caustic and mild alkalis (hydroxides and carbonates) he explained by the absorption of heat in the liberation of carbon dioxide as a gas.

Lavoisier had always been interested in thermometry and heat changes since the start of his scientific work. In 1772, when Desmarest told the Academy of Black's
Portrait of Lavoisier and his wife by David, 1788.
Lavoisier and Laplace’s ice calorimeter.

Madame Lavoisier’s drawing of an experiment on respiration; Seguin is wearing a mask, Lavoisier directing the experiment, and Madame Lavoisier taking notes.
Antoine Laurent Lavoisier

work on latent heat, Lavoisier described an experiment made the preceding year in which he had discovered independently the same phenomenon, finding to his surprise that on mixing water and crushed ice the temperature of the water remained at zero until all the ice was melted (37). In 1773, when studying the crystallization of sodium sulphate by cooling solutions, he observed the temperature arrest which occurred when crystallization began and lasted until it had finished. This he explained correctly by the heat of crystallization of the salt (38).

In his physical work he had the advantage of partnership with Laplace, who worked in his laboratory at intervals from 1777 to 1785. In 1777 they were measuring the vapour pressure of liquids, and determining latent and specific heats by the method of mixtures. Black's unpublished work was known to them, and de Luc and Crawford were working in the same field. In 1782, finding the method of mixtures unsatisfactory for measuring heats of reactions, they invented a new method, the ice calorimeter, in which the amount of heat given out is measured by the amount of ice melted (plate 11). The calorimeter consisted of two concentric vessels each containing crushed ice, the purpose of the outer vessel being to insulate the inner one against any gain or loss of heat from outside. There was a space in the inner vessel to hold the substance or reaction under examination, the amount of heat enclosed being measured by the amount of water that ran down from the ice as it melted. It was a beautifully simple and accurate apparatus which they used to measure specific heats, including the specific heats of gases by a flow method, heats of reaction, heats of combustion of phosphorus, carbon, ether and oil, and the heats of detonation of nitre mixed with charcoal or sulphur.

Thermochemistry dates from Lavoisier and Laplace's great paper 'Sur la Chaleur' of 1783 (39), and one of their generalizations is a partial anticipation of Le Chatelier’s Theorem which came a century later: 'Dans les changements causés par la chaleur à l'état d'un système de corps, il y a toujours absorption de chaleur; en sorte que l'état qui succède immédiatement à un autre, par une addition suffisante de chaleur, absorbe cette chaleur sans que le degré de température du système augmente.'

More measurements were made in the following winter, including the heats of combustion of hydrogen and of wax, which Lavoisier showed was nearly equal to the sum of the heats of combustion of the hydrogen and carbon it contained.

The ice calorimeter thus gave Lavoisier precise data for the heat changes involved in the chemical reactions in which he had already determined the weight changes involved. He now had a complete picture of these two different aspects which enabled him to show how unnecessary it was to assume the existence of phlogiston, as everything could be explained much more simply without its aid.

In 1777 Lavoisier had explained the source of animal heat as being the heat evolved when carbonic acid (air crayeux) is produced in the lungs from the oxygen of the air during respiration. This was an entirely new point of view, as Haller had accepted Stahl's explanation that the heat of the body was due to the friction of the blood in the arteries, though he was baffled by the constancy of body
Sir Harold Hartley

temperature. The ice calorimeter gave the opportunity to verify this speculation by measuring the heat given out by a guinea-pig and comparing it with the heat evolved in the formation of the volume of carbonic acid which an animal of similar weight expired during the same period.

First the amount of carbonic acid expired by guinea-pigs in a period of ten hours was measured by absorbing it in potash bulbs. From the mean of their experiments Lavoisier and Laplace calculated that the combustion of the corresponding amount of carbon would have melted 10.38 oz. of ice. A guinea-pig was then kept in a calorimeter for the same period and the heat given out by it melted 13 oz. of ice. Part of the excess, they said, might have been due to the cooling of its extremities—it might well have had cold feet! From the results they concluded: 'la conservation de la chaleur (animale) est due, au moins en grande partie, à la chaleur que produit la combinaison de l'air pur respiré par les animaux avec la base de l'air fixe que le sang lui fournit'. The maintenance of a constant body temperature under different climatic conditions they ascribed to differences in the rate of evaporation of moisture rather than to differences in the amount of carbonic acid formed during respiration.

This was one of Lavoisier's most brilliant papers, remarkable for the beauty of the experimental technique, for the directness of attack, and for its verification of his theory of animal heat, which gave a new significance to metabolism. No doubt the paper owed much to Laplace, who was the first convert to Lavoisier's theories. The full significance of their eight years of partnership has not had the attention it deserves.

THE NATURE AND COMPOSITION OF WATER

His notebooks show repeatedly how puzzled Lavoisier still was as to the nature of the inflammable air he got in various ways, by the solution of metals in acids, or the distillation of vegetable substances. In 1774 he had tried and failed to ascertain the increase in weight when inflammable air was burnt. He expected inflammable air to give an acid on combustion but could find none. Since the inflammable air came from sulphuric acid and metals Lavoisier thought it should give sulphuric acid. Bucquet thought it should give fixed air. Experiments in 1774 and 1777 showed that neither acid was produced. He returned to the problem again in 1781 and 1782, when he and Gingembre burnt a jet of oxygen in inflammable air and found neither carbon dioxide nor any acidity, which still surprised Lavoisier 'que l'analogie m'avait porté invinciblement à conclure que la combustion de l'air inflammable devait également produire un acide'. Hence in 1782 he had no idea that water was the product.

Meanwhile other chemists were busy with the same problem, and Cavendish had found that when a mixture of inflammable air and common air is exploded in a closed vessel water is formed without any change in weight. When Blagden, the Secretary of the Royal Society, was in Paris, he told Lavoisier of Cavendish's experiments. On 23 June 1783, Lavoisier took two gas holders containing in-
flamable air and oxygen and joined them up to a jet at which the mixture could be burnt for a considerable time in a bell-jar over mercury. The first experiment was made by Lavoisier and Laplace in the presence of Blagden and a number of other scientists. A considerable quantity of pure water collected on the surface of the mercury, and although it was not possible to establish directly that the weight of the water found was equal to that of the two gases Lavoisier had no doubt of it. He wrote ‘comme il n’est pas moins vrai en physique qu’en géométrie que le tout est égal à ses parties, de ce que nous n’avions obtenu que de l’eau pure dans cette expérience, sans aucun autre résidu, nous nous sommes crus droit d’en conclure que le poids de cette eau étoit égal à celui des deux airs qui avoient servi à la former’ (30).

The next day the experiment was described to the Academy. ‘Nous ne balançâmes pas à en conclure que l’eau n’est point une substance simple, et qu’elle est composée poids pour poids d’air inflammable et d’air vital.’ Lavoisier then heard that Monge had made similar experiments. Having determined the combining volumes of the two gases he had found that the weight of the water was almost equal to that of the two gases, the specific gravities of which he had determined.

Lavoisier must have seen in a flash the wide significance of this new view of the nature of water, which gave him the clue to so many of his unsolved problems. It explained the source of the water he got in organic combustions, and he saw the possibility of using them to determine the composition of organic bodies.

Additional evidence was obtained by studying the decomposition of water by long standing over cold iron, and by passing steam over hot iron or charcoal, as well as from experiments on its formation by passing inflammable air over heated metallic calces, thus extending some observations made by Priestley.

Lavoisier was naturally anxious to know the percentage composition of water, as it would enter into so many of his calculations. In his first paper to the Academy he gives the following figures based on experiments made with Meusnier to determine the combining volumes of the two gases and their densities:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air vital, ou plutôt principe oxygine</td>
<td>0.86866273</td>
</tr>
<tr>
<td>Air inflammable, ou plutôt principe inflammable de l'eau</td>
<td>0.13133727</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.00000000</strong></td>
</tr>
</tbody>
</table>

Lavoisier at this stage has a preference, like Boyle, for the word ‘principle’ rather than ‘element’. The name of hydrogen was not adopted until the whole nomenclature was revised four years later.

There are numerous references to a new apparatus that was constructed to prove that the weight of water was equal to that of the gases from which it was formed, and to determine its composition. Arthur Young saw it in Lavoisier’s laboratory in 1787. ‘In the apparatus for aerial experiments’, he writes in his Diary (31) ‘nothing makes so great a figure as the machine for burning inflammable and vital
Sir Harold Hartley

air, to make or deposit water; it is a splendid machine. Three vessels are held in suspension with indexes for marking the immediate variations of their weights; two that are as large as half hogsheads contain the one inflammable, the other the vital air, and a tube of communication passes to the third, where the two airs unite and burn;...If accurate (of which I confess I have little conception) it is a noble machine.'

It has been questioned whether Lavoisier ever used this apparatus successfully, as the results were never published by him. The experimental details, however, are given in the *Traité*. Hydrogen was burnt at a fine jet in a glass globe containing oxygen, both gases having been dried by passing over potash (Lavoisier says that calcium nitrate or chloride would have been better). The increase in weight of the globe together with measurements of the volumes of the gases consumed, and a knowledge of their densities, gave Lavoisier the data he needed. Details of one experiment were published in an unsigned article in the *Journal Polytype* (32), an ephemeral scientific journal in which Lavoisier was interested. The weight of water found was within 1% of that of the two gases, and its composition is given as 85% oxygen and 15% hydrogen, which are the figures Lavoisier used subsequently in all his calculations. The hydrogen content was too high owing to errors in the determination of its density.

It was a very difficult experiment and a great test of Lavoisier’s skill. The final solution had to wait until Morley’s classical investigations just a century later.

Lavoisier lost no time in exploiting this new view of the composition of water. He saw that it explained the formation of water in organic combustions, and he was now able to use them to determine the composition of organic bodies. He determined the heat of combustion of hydrogen and saw that the oxidation of hydrogen as well as carbon in the body would account for more oxygen being consumed in respiration than the expired carbonic acid could account for. This would also explain why the amount of heat produced by an animal was greater than that calculated from its output of carbonic acid.

**The New Chemistry and the Reform of Nomenclature**

The recognition of hydrogen as an element was a great advance. It explained many of Lavoisier's perplexities, and shortly afterwards Cavendish discovered that the inert part of the atmosphere, Lavoisier’s 'mofette', gave nitric acid when sparked with oxygen, and Berthollet found that ammonia is a compound of 'mofette' with hydrogen.

The way was now clear. With the recognition of the elements oxygen, hydrogen, nitrogen (or azote as the French chemists called it), carbon, sulphur, phosphorus and the metals, Lavoisier could explain quite simply the composition of chemical compounds, their reactions and their quantitative relations. There were no longer obscurities to serve as a stronghold for phlogiston. Laplace and some of the younger physicists were already on his side. Of the chemists, Berthollet announced
Antoine Laurent Lavoisier

his conversion at the Academy in August 1785, followed soon by Fourcroy and Guyton de Morveau. The latter had published proposals for a reform of chemical nomenclature in 1782, but these were based on phlogiston. Discussions between the four chemists in 1786 led to their publication jointly of a new method of chemical nomenclature based on Lavoisier’s theory\(^{(33)}\). In the introduction Lavoisier acknowledges his debt to Condillac, the disciple of John Locke. From Condillac’s *Logic* he had learnt the value of clarity of expression, of language as an instrument of analysis, of words as the symbols in the algebra of thought.

Till then phlogiston had been the only common basis. Names had had little reference to the nature or relationships of the substances that bore them, and many were relics of alchemy. Lavoisier’s work had made a system possible, in which the names of elements like hydrogen and oxygen told something about them, and the names of compounds like sulphates and sulphites indicated their composition. The system devised by the four chemists, with few exceptions, is the one we use to-day, and its adoption helped greatly towards the general acceptance of the new theory.

*Traité élémentaire*

The nomenclature having been agreed upon, Lavoisier was drawn irresistibly, as he tells us, to use it to give a logical account of his new theory. His *Traité élémentaire de chimie*\(^{(34)}\) was finished early in 1789. Its publication marks the birth of modern chemistry, and it threw a new light on all the related sciences. It was no ordinary textbook, as the first person singular appears on every page. It was in fact an autobiography of Lavoisier’s work since 1772. The discoveries of seventeen years were compressed into a few pages, and the experimental basis of the new chemistry presented in such a clear compelling fashion that it won immediate acceptance. It was chemistry as Lavoisier saw it without any history or even a mention of phlogiston.

The first part outlines Lavoisier’s theory of chemistry and gives the results of the crucial experiments on which it was based. ‘C’est elle seule qui contient l’ensemble de la doctrine que j’ai adoptée; c’est à elle seule que j’ai cherché à donner la forme véritablement élémentaire.’

After giving his views on the nature of heat, he describes the experiments which established the composition and chemical nature of the atmosphere, water and a number of acids, gradually building up his picture on experimental results. He then sets out his views on organic chemistry, his experiments on fermentation, and his work on the analysis of organic compounds by combustion.

Oxygen is the central element, a constituent, Lavoisier thought, of all acids and all bases. Hence he predicted rightly the existence of the alkali metals isolated twenty years later by Davy. But his assumption of the presence of oxygen in all acids was less happy, and here again Davy established the facts.

The *Traité* was the forerunner of the textbooks of the nineteenth century, and some of Lavoisier’s views, the dualistic nature of salts and the conception of
compound radicals, were to have a profound influence on chemical thought and to be the issues on which many battles were to be fought.

The idea of the chemical equation had been implicit in all Lavoisier’s quantitative work:

Car rien ne se créve, ni dans les opérations de l’art, ni dans celles de la nature, et l’on peut poser en principe que dans toute opération, il y a une égale quantité de matière avant et après l’opération; que la qualité et la quantité des principes est la même, et qu’il n’y a que des changemens, des modifications... je puis considérer les matières mises à fermenter et le résultat obtenu après la fermentation, comme une équation algébrique.

**TRAITE ÉLÉMENTAIRE DE CHIMIE, PRÉSENTÉ DANS UN ORDRE NOUVEAU ET D’APRÈS LES DÉCOUVERTES MODERNES;**

**Avec Figures:**

*Par M. Lavoisier, de l’Académie des Sciences, de la Société Royale de Médecine, des Sociétés d’Agriculture de Paris & d’Orléans, de la Société Royale de Londres, de l’institut de Bologne, de la Société Helvétique de Basle, de celles de Philadelphie, Har’em, Manchester, Padoue, &c.*

**TOME PREMIER.**

*APARIS,*

Chez Cuchet, Libraire, rue & hôtel Serpente.

M. DCC. LXXXIX. *Sous le Privilège de l’Académie des Sciences & de la Société Royale de Médecine.*

**Figure 2.** Frontispiece of the *Traité*, 1789.
The first time that Lavoisier actually used the familiar form of the chemical equation was in the chapter on alcoholic fermentation when he wrote:

\[ \text{Le moût de raisin} = \text{acide carbonique} + \text{alkool}. \]

The second part of the *Traité* contains lists of salts with general methods for their preparation from each acid. It is a useful summary containing nothing ‘qui me soit propre’.

The first part gave few experimental details: ‘J’ai reconnu...que des descriptions minutieuses...figuroient mal dans un ouvrage de raisonnement; qu’elles interrompoient la marche des idées, et qu’elles rendoient la lecture de l’ouvrage fastidieuse et difficile.’ In the third part Lavoisier gives a full account of the construction of the apparatus and the experimental methods which he had gradually developed. It is of intense interest in revealing the care and skill he devoted to his experiments, most of which were made with his own hands. Its value is enhanced by many illustrations drawn and engraved with loving care by Madame Lavoisier who had so often seen the apparatus in use in the laboratory. The book has the same individual quality as Faraday’s *Chemical Manipulation*. It begins with an appeal for the use of the decimal system and ends with the prototype of future tables of physico-chemical constants.

The publication of the *Traité* marks the end of the phlogistic period and the beginning of modern chemistry. The clear logic of its presentation won immediately almost general acceptance. It was translated into several languages and became the accepted method of teaching. It had been a long fight, but in the end Lavoisier won an almost bloodless victory. In 1791 he wrote to Chaptal: ‘Toute la jeunesse adopte la nouvelle théorie et j’en conclus que la révolution est faite en chimie.’ Even Kirwan in 1792 wrote to Berthollet: ‘Enfin, je mets bas les armes et j’abandonne la phlogistique.’

Respiration and metabolism

After the publication of the *Traité* Lavoisier’s interests turned to organic and physiological chemistry. Almost his last scientific work was on respiration and metabolism. In 1785, in a brilliant lecture to the Society of Medicine, he described experiments on birds and guinea-pigs, showing that they could live for long periods in pure oxygen and that, to his astonishment, the rate of production of carbon dioxide was practically unaltered. He found later that they could live equally well in an atmosphere in which hydrogen was substituted for the nitrogen of the air. He saw that water was formed as well as carbon dioxide in the process of metabolism, thus accounting for what is now called the ‘respiratory quotient’, and he was able to calculate the amount of water produced. The heat evolved in its formation explained why his measurements with Laplace had shown that an animal gave out more heat than could be accounted for by the heat of formation of the carbon dioxide it expired.

From his observations on the distress of animals breathing in confined spaces as the concentration of oxygen diminished and that of carbon dioxide increased,
Lavoisier's practical mind travelled to the state of the atmosphere in crowded rooms. He measured its composition in hospital wards and in the Comédie Française. Finding a deficit of oxygen and an increase of 2 or 3% of carbon dioxide, he urged the need for better ventilation. He calculated the rate at which the atmosphere deteriorated, producing that 'impatience machinale' in an audience which was such a sad handicap to the last speaker at a meeting of the Academy.

Finally, he saw the danger that emanations from the lungs might spread disease in crowded places, and he urged the need for knowledge of the ways in which infection spreads in order to protect the health of people in large towns. The lecture was a brilliant forecast of the problems of ventilation.

Experiments on a human being were the culmination of Lavoisier's work on respiration and the subject of his last two communications at public sessions of the Academy in 1789 and 1790 (36). Seguin, his co-author, was the experimental subject. Measurements were made of his consumption of oxygen, his output of carbon dioxide, his rate of respiration and his pulse rate under different conditions. We know from sketches made by Madame Lavoisier the general experimental arrangement (plate 11). The results revealed the main factors regulating metabolism: the temperature of the environment, the output of work, and the digestion of food. Lowering the room temperature from 80 to 61°F raised the absorption of oxygen by a man at rest by 11%, the digestion of food raised it by 50%, doing work at the rate of 37,000 ft.lbs. an hour raised it by 160%, and the digestion of food simultaneously with work at the rate of 39,000 ft.lbs. an hour raised it by 280%. Lavoisier showed also that the increase in the pulse rate was proportional to the amount of work done, and that the amount of oxygen absorbed was proportional to the product of the pulse rate and the number of inhalations.

He saw at once the secret of the constancy of the body temperature under varying conditions of climate and occupation that had so long remained a mystery. It is regulated automatically by three balancing factors—respiration which produces heat by oxidation of carbon and hydrogen, transpiration which increases and diminishes as needed to remove any excess of heat by evaporation of water from the skin, and digestion which replaces the matter lost in the first two processes. The directness of the attack, the swift recognition of the wide implications of the results, are characteristic of Lavoisier at his best.

Finally, he discusses their bearing on the state of the body in health or disease. Fevers he thought were nature's method of restoring any disturbance of the equilibrium. The art of the doctor, he said, often consists in letting nature deal with herself, helped by suitable diet and purgatives. Contaminated atmospheres were, he thought, the cause of endemic disease and hospital and prison fevers. The best remedies were open air, freer breathing and a change of environment.

He left open the question as to whether oxidation actually took place in the lungs or in the course of circulation. Investigations already in hand on digestion and transpiration would throw further light on this.
Antoine Laurent Lavoisier

The first paper with Seguin on transpiration\(^{(37)}\) described an attempt to get a complete balance of the respiratory processes and ascertain the amounts of water lost through the skin and through the lungs. During the experiment Seguin was enclosed in a rubber bag, and his loss of weight was measured both with and without the bag. In addition, his absorption of oxygen and output of carbon dioxide were determined. Lavoisier could then calculate the loss of weight due to each cause on the assumption that all the oxygen absorbed formed carbon dioxide or water. If oxidation took place in the circulatory system he was uncertain whether this assumption was justified, and regarded the results as provisional.

A second paper on transpiration published after Lavoisier's death deals specially with the moisture content of air as determining comfort conditions, as to which, he said, a thermometer reading may be quite misleading\(^{(38)}\). The paper deals also with the purpose and design of clothing.

The trend of Lavoisier's thoughts at this time are shown by the programme drafted by him for the Academy Prize of 1794\(^{(39)}\). His introduction deals with the problem of nutrition, the animalization, as he calls it, of vegetable and animal food. He points out the lack of knowledge of the changes that take place in the various stages of digestion, which had led the Academy to choose an investigation into the functions of the liver and bile as the subject of the Prize. A broad treatment was suggested, including the comparative anatomy of the liver and gall bladder, the chemical nature of the bile, and the pathology of the liver. The investigations were to cover chemical researches, especially the new methods of organic analysis, Lavoisier's own invention. The programme was almost a forecast of some of the major developments in physiological chemistry in the nineteenth century.

Lavoisier was the first to submit the vital functions to an exact physico-chemical analysis. He laid the foundations of physiological chemistry. His investigations into the source of animal heat first disclosed the full significance of metabolism. If he had lived on, what contributions he might still have made! But it was not to be.

Politics and the revolution

No Frenchman saw more clearly than Lavoisier the dangers that were gathering for France—the state of her finances, her outworn social structure with all its inequalities and injustice, and the selfishness of privilege with its lack of patriotism. No one had done more than Lavoisier to forecast the reforms that had to come, and when Necker in 1787 set up the Provincial Assemblies to replace the effete local Governors he saw a great opportunity. Chosen to represent the Third Estate at Orleans he was soon its outstanding figure. 'It is Lavoisier who does everything, enlivens everything, and is everywhere', said Léonce de Lavergne. We still have his memoranda—clear, practical, convincing, and amazingly modern in outlook—on the state of agriculture, the freedom of commerce, old age insurance, savings banks, infant mortality, the need for a geological survey, and above all the reform
of taxation on an equitable basis\textsuperscript{(40)}. But privilege stood in the way and little was done.

The tide was running swiftly, and when the Estates General were summoned by the King in 1789 Lavoisier had fresh hopes. To his great disappointment he was only elected as a substitute deputy, but again he threw himself into the battle. He was a leading member of the Club of ’89 which stood for constitutional monarchy. His memoir on the \textit{Territorial Wealth of France} was ordered to be printed by the National Assembly\textsuperscript{(41)}. It was an attempt to estimate the national income and its taxable capacity, a pioneer effort in statistics, made possible by the information Lavoisier had collected from every province through the organization of the Ferme.

Many of the reforms Lavoisier had foreseen were soon accomplished, but early in 1790 there is already an anxious note in a letter to Benjamin Franklin:\textsuperscript{(42)}

\begin{quote}
Après vous avoir entretenu de ce qui se passe dans la chimie, ce serait bien le cas de vous parler de notre révolution politique; nous la regardons comme faite et bien faite sans retour;… Les personnes modérées et qui ont conservé leur sang-froid dans cette effervescence générale, pensent que les circonstances nous ont entraînés trop loin… et qu’il est à craindre que l’établissement de la nouvelle constitution n’éprouve des obstacles de la part de ceux mêmes en faveur de qui elle a été faite…. Nous regrettons bien dans ce moment votre éloignement de France; vous auriez été notre guide et vous nous auriez marqué les bornes qui nous n’aurions pas dû franchir.
\end{quote}

In almost the last of Lavoisier’s scientific papers there was a strangely prophetic passage:

\begin{quote}
Faisons des vœux surtout pour que l’enthousiasme et l’exagération qui s’emparent si facilement des hommes réunis en assemblées nombreuses, pour que les passions humaines qui entraînent la multitude si souvent contre son propre intérêt, et qui comprennent dans leur tourbillon le sage et le philosophe comme les autres hommes, ne renversent pas un ouvrage entrepris dans si belles vues, et ne détruisent pas l’espérance de la patrie.
\end{quote}

The violence Lavoisier feared came quickly. Members of the Club of ’89 were marked men because of their moderation. He himself was attacked by Marat, whose ridiculous pamphlet, \textit{Traité du Feu}, he had criticized. One by one he had to give up the offices which he had served so long and ably. In 1791 the administration of taxes was taken from the Ferme, and in 1792 he resigned from the Arsenal. Even the Academy was not safe. Lavoisier as its treasurer fought hard for its existence, but some of its own members turned against it, and it was suppressed in 1793.

Knowing the financial difficulties of France he offered his services in various capacities, but was refused. In 1792, however, the King wished to nominate him as Minister of the Public Funds, an office Lavoisier would have occupied so gladly in happier days. He knew it was too late, that he was suspect as a member of the old regime, and no politician. He refused, saying, ‘je ne suis ni jacobin, ni feuillant’.

Lavoisier found another outlet for his activities in these difficult years. In 1791 the National Assembly had set up a Consultative Committee on Arts and Crafts to advise the government on various questions, including useful inventions.
Lavoisier, as usual, seems to have drafted all the reports, the most important of which was entirely his own. It was on a system of public education, a subject to which he had given much thought, having started at his own expense a primary school at Villefrancœur.

The report dealt with the general principles of education, and its national importance. It proposed a scheme covering the whole field from the primary school to the Lycée. Under his plan all children at the age of six were to enter a primary school, and at eleven were to go on to an elementary school teaching either the arts or the arts and sciences. Finally, there were to be twelve lycées giving the highest form of public education with a wide choice of subjects. Lavoisier had an eye to practical subjects like hygiene, the weather and simple surveying. Country schools were to teach the elements of agriculture and town schools the elements of commerce.

Lavoisier is emphatic as to the importance of education in every walk of life.

Le mot industrie n'exprime pas toujours un emploi de forces, ni même d'adresse, il exprime le plus souvent un emploi des facultés de l'esprit. . . . Le cultivateur qui prospère le plus n'est pas toujours celui qui est physiquement le plus fort et le plus adroit; c'est celui qui est le plus intelligent. . . . Organisiez l'instruction publique dans toutes ses parties; donnez du mouvement aux arts, aux sciences, à l'industrie, au commerce.

In 1791 the National Assembly had entrusted to the Academy the task of establishing a uniform system of weights and measures, a very necessary reform which resulted in the metric system. A commission was set up consisting of Borda, Lagrange, Laplace, Monge and Condorcet with Lavoisier as secretary and treasurer. The work was divided between various groups; Lavoisier and Hauy were to determine the density of distilled water at zero temperature. Lavoisier was also responsible for the administration of the commission, which continued after the suppression of the Academy. It was his last scientific task.

Meanwhile, in the general attack on the ancien régime, feeling was running high against the members of the Ferme, and in 1793 they were arrested on charges of maladministration. Lavoisier asked to be allowed to continue his work on the standards, and Hauy and Borda pleaded for him in vain to the Convention, risking their own lives. All his wife's efforts, too, were unsuccessful.

When the charges against the Ferme were formulated, it was Lavoisier who drew up their defence. He gave a masterly review of their financial transactions, showing that they had done their work efficiently and without undue profit to themselves. But it was the height of the Terror, the trial was a mockery of justice, and Lavoisier and twenty-seven of his colleagues were guillotined a few hours later. Lavoisier followed his father-in-law, Paulze, to the scaffold, and met death with the courage and philosophy of his generation.

Thus died this great Frenchman in his fifty-first year at the height of his achievements. The loss to France and to the world was immeasurable. The Terror had nearly run its course; within a few years came reconstruction, when under Napoleon science once more came into its own. What a contribution Lavoisier might have
made to the Industrial Revolution in France, with his vision of her needs, his imaginative use of science in industry, agriculture and hygiene, and his administrative skill and experience.

If in the fields of politics and economics he was cut off before his work came to fruition, he had foreseen the changes soon to come in industry, in social legislation and in education. His eloquence and writings must have left their mark on the minds of those who were to remake France.

In science it was otherwise. There his work was done with almost incredible effectiveness and speed. No other revolution in scientific thought has ever been so complete, so swift, or has done so much to clear men’s minds of the cobwebs of centuries. He quickened the advance of science over its whole front. Not only chemists, but workers in physics, biology, medicine and agriculture were given for the first time a clear view of the various forms of matter we call elements, and of the distinction between chemical and physical changes. Lavoisier put new and potent weapons into their hands, just when they were needed for science to play its full part in the nineteenth century. Compare the clear-cut vision of Lavoisier’s great treatise, based on quantitative measurement, on the methods of analysis and synthesis, and on the notion of the chemical equation, with the confused picture of chemistry in Macquer’s textbook, with no general conception but the theory of phlogiston. It was no wonder that progress was quickened. Dalton’s atomic theory, Davy’s discovery of the alkali metals, his recognition of the halogens as elements, and the massive contributions of Berzelius followed swiftly, completing the picture and giving chemistry its modern form.

It was, indeed, a revolution, and I have tried to show how Lavoisier fought the battle for the New Chemistry almost single-handed, for he had no school, with many other preoccupations in one of the busiest of lives. He was fortunate in his great contemporaries, Black, Priestley and Cavendish, who so often gave him the clue he was searching for, but he alone saw the significance of their discoveries.

What was the secret of his greatness? Lavoisier was above all things a reformer with an intense desire to improve everything he saw around him, whether it was the confused state of chemistry, the system of taxation, the lot of the peasant, the making of gunpowder or the methods of agriculture. He had the logical systematic mind of his countrymen, joined with great constructive power and a creative urge. Burning curiosity made him a born researcher. Every problem was to him a challenge for research and experiment, and for him research meant measurement, the method of modern science. He had an essentially modern outlook. He was not bound by tradition or authority. He looked his problems squarely in the face, and judged them on evidence with the shrewd common sense he showed as a man of affairs.

Lavoisier’s great strength was his realism. He saw each problem in its smallest details; and no one examined them with greater care, for he was a great experimenter; but he also had great vision and saw his problems in their widest implications. He gave his visions quantitative form, in chemistry with the balance, in
finance with statistics. He applied to any practical problem the same analysis and measurement that he used in the laboratory. It is often said that scientists are too remote from real life. Lavoisier is the outstanding example of the value of the laboratory mind in action. That is his lesson for us to-day.

I am greatly indebted to previous biographers of Lavoisier, and especially to the late Professor A. N. Meldrum for his scholarly researches on Lavoisier's early work. I have to thank also my secretary, Miss Josephine Wasse, without whose never-failing help the preparation of this lecture during wartime would have been impossible.

NOTES

(2) Œuvres, 3, 765.
(3) Œuvres, 5, 187.
(4) Œuvres, 3, 1.
(5) Œuvres, 3 and 4.
(8) Œuvres, 3, 106, 128.
(9) Œuvres, 2, 1.
(10) Œuvres, 2, 38.
(11) Œuvres, 2, 64.
(13) A. N. Meldrum, op. cit.
(14) Œuvres, 2, 103.
(15) Œuvres, 1, 439.
(17) Berthelot, op. cit. p. 246.
(18) Robert Boyle, Essays of the Strange Subtity

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\begin{align*}
\text{Great Efficacy} & \\
\text{Determinate Nature of Effluviums} & \\
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To which are annexed New Experiments to make fire and flame ponderable: together with a Discovery of the perviousness of glass, 1673, passim. London: W. G. for M. Pitt.
(19) Lavoisier, Observations sur la Physique, edited Abbé Rozier, 1774, 4, 448.
(20) Œuvres, 2, 105.
(21) Berthelot, op. cit. p. 257.
(22) Œuvres, 2, 122.
(24) Œuvres, 5, 391.
(25) Œuvres, 2, 129.
(26) Œuvres, 2, 812.
(27) Lavoisier, Observations sur la Physique, 1772, 2, 510.
(28) Lavoisier, Observations sur la Physique, 1773, 1, 10.
(29) Œuvres, 2, 283.
(30) Œuvres, 2, 334.
(31) Arthur Young, op. cit. p. 78.
(32) Journal Polytype, 5 February 1786.
Determination of the velocity coefficients for polymerization processes.

I. The direct photopolymerization of vinyl acetate

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This paper describes a method whereby the individual velocity coefficients of a vinyl polymerization reaction have been determined by a detailed analysis of the kinetics of the photo-polymerization of liquid vinyl acetate. The evaluation of the coefficients is made by the development of an accurate method for measuring the lifetime of the active polymeric molecules employing intermittent radiation. In addition, the kinetic chain length and the number average molecular weight of the polymers have been measured. It is shown that each absorbed quantum of radiation activates one vinyl acetate molecule probably as a diradical. The chain terminates by a disproportionation reaction between the polymer radicals. The size of the growth or propagation bimolecular coefficient decreases only slightly as the molecule grows, the energy of activation is 4400 cal. and the steric factor of the growth reaction is $10^{-2}$. In the termination reaction there is likewise only a small decrease of velocity coefficient with increasing molecular size—no energy of activation is required and the steric factor has the surprisingly large value of $10^{-2}$.

INTRODUCTION

The three fundamental reactions controlling the velocity of a chain polymerization process are: (a) initiation reaction, (b) growth reaction, and (c) termination of growth. Hitherto the kinetic analysis has made use of two measurable quantities, namely, (i) the overall rate of reaction, and (ii) the rate of initiation. The ratio of (i) to (ii) will give the kinetic chain length which is, in some cases, equal to the degree of polymerization of the polymer. There are, however, three unknowns involved in the analysis. Until a third parameter can be measured, further analysis is impossible, and, in particular, the values of the individual growth and termination coefficients cannot be obtained. The third parameter which requires to be measured is the
Portrait of Lavoisier and his wife by David, 1788.
Lavoisier and Laplace's ice calorimeter.
Madame Lavoisier’s drawing of an experiment on respiration; Seguin is wearing a mask, Lavoisier directing the experiment, and Madame Lavoisier taking notes.