The Development of the Conservation of Mass Law:

Progress in Science is Rarely Straightforward or Linear

People often wrongly think of scientific ideas as being "discovered" — arising at some specific time from startling or new experimental evidence collected by a solitary scientist. This unfortunate view drives many talented individuals away from science thinking that it lacks the creativity and collaboration most people enjoy in a career. The story behind how our scientific understanding of mass and energy developed dispels these and other common myths about scientists and scientific work.

Our story begins with the work of the influential Greek philosopher Aristotle (384-322 BC). Aristotelian natural philosophy, which remained the dominant way of thinking about the world through the Scientific Revolution of the 16th and 17th centuries, was based not on rigorously acquired evidence but on contemplative observations and logic. For Aristotelian and earlier natural philosophers, the idea that matter could not be created out of nothing or vanish without a trace was simply logical. The philosophical argument, *nothing comes from nothing*, is attributed to Parmenides who lived approximately 150 years earlier.

After the Scientific Revolution, many practitioners of the new science of chemistry continued to accept the Aristotelian idea that matter could not be created or destroyed, and used this idea as a guiding principle for their work. For example, the Scottish chemist Joseph Black (1728–1799) weighed the reactants and products in chemical reactions. Any difference between the two he attributed to experimental error.

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Note how prevailing ideas influence how researchers interpret their work. Thinking entails working with prevailing ideas, and scientists during the scientific revolution made use of medieval ideas about the natural world that drew from Greek, Roman, and Islamic thinking about nature. That said, scientific thinking and practice did change in significant ways during the 16th and 17th centuries which is why this period is often referred to as the scientific revolution. One significant change included abandoning in many cases the common sense view of experience, at times setting aside observation in favor of other approaches that would, in the end, make more sense of natural phenomena.

1. Many people wrongly think that scientists should be totally objective in their work (i.e., not permitting prior thinking to influence their interpretations of new information or ideas).
A) Why is this not possible?
B) In what sense is it not even desirable?

But in the 18th century, a new chemical idea was put forward that cast doubt on the well accepted idea that mass is conserved in chemical reactions. The German chemist and physician Georg Ernst Stahl was seeking to explain why some materials burned, while others did not. Between 1718 and 1723 he developed and clarified the idea that a substance's ability to burn depended on whether or not it contained phlogiston, the "essence of combustibility." Stahl thought that phlogiston was a "subtle fluid" – something that could not be measured, but that nonetheless existed.

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The idea that phlogiston could not be massed or measured may appear silly. But at this time other things in nature, such as light and heat, were also classified as "subtle fluids" that could not be directly massed. Even today, the primary evidence for the existence of dark matter is based on mathematics and indirect lines of evidence.

According to Stahl, when an object burned, its phlogiston was released into the surrounding air. When the object lost all of its phlogiston, or when the air had absorbed all the phlogiston it could, the burning stopped. We might write Stahl's explanation for what happens when metal and wood are burned like this:

$$\text{Metal} \rightarrow \text{Metallic Ash} + \text{Phlogiston}$$

$$\text{Wood (or other organic substance)} \rightarrow \text{Ash} + \text{Phlogiston}$$

Thus, materials that burned consisted of the resulting physical product and phlogiston. Stahl's theory went a long way towards explaining why some objects changed when heated and others didn't, and also explained why the same object might burn more brightly in one location than

Georg Ernst Stahl, adapted from portrait by Johann Georg Mentzel (Public Domain) in another. But a problem arose with the explanation. The "metallic ash" resulting from the burning of some metals had a greater mass than that of the original metal while the burning of wood and other organic material resulted in ash that had less mass than the original material. If the mass of reactants and products were to be balanced, that would mean phlogiston could have a positive or a negative mass.

This was a puzzling idea, but those supporting the phlogiston explanation did not want to discard such a useful theory because of this problem. Some scientists thought this problem was the result of imprecise measuring equipment. They maintained that when more was learned about phlogiston and better balances were developed, the problem would be resolved. However, others began to question whether mass was always conserved as had been thought since the time of Aristotle.

After Stahl, the most famous advocate of the phlogiston theory was the English experimenter Joseph Priestley (1733–1804). Priestley, like most other natural philosophers of his time, did not make his living through science. Instead, Priestley was a well-known Dissenting minister (English Christians who did not agree with the teachings of the Anglican Church were known as Dissenters) and religious thinker who made his living as a preacher and also as a schoolmaster.

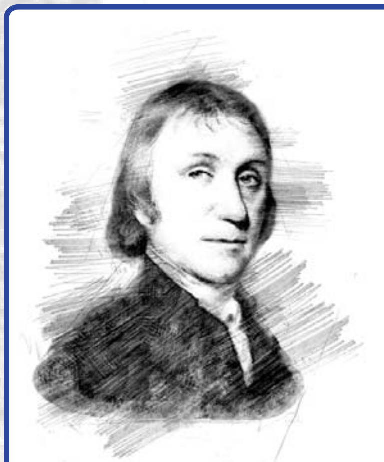
Throughout this story, notice how those working to understand the natural world are either pursuing their interest as a hobby outside their everyday job, are wealthy, or have the financial support of a benefactor. The word "scholar" comes from the Latin word "scholee" which means "leisure time." Today we hardly think of conducting scholarly work as "leisure." However, historically, doing science and other forms of scholarship was associated with leisure time.

Priestley had been interested in chemistry from an early age, and as an adult, he came to believe that investigations into the natural world could reveal truths that would overthrow unjust or tyrannical religious and political authorities. His chemical work was therefore strongly linked to his Dissenting beliefs. In 1767, Priestley had published a treatise on the history of electricity that gained him admission to the Royal Society of London.

In 1773, Priestley found a patron, Lord Shelburne, who was interested in Priestley's work and invited him to move to the Shelburne estate and pursue his research in chemistry. During his time as Shelburne's scientific colleague, Priestley pursued a series of studies on the chemistry of air. He isolated several different types of air with different properties, but the two most important were the substances Priestley called "fixed air" and "dephlogisticated air." Fixed air was air that already contained a great deal of phlogiston – for example, if a piece of wood was burned under a sealed glass dome, when the burning was complete, the air inside the dome would be fixed air. Priestley found that mice placed in domes filled with fixed air could not survive as long as mice placed in domes filled with regular air.

Priestley was therefore surprised to find that unlike mice, plants seemed to thrive in fixed air. In fact, if a mouse and a plant were placed in the same sealed dome, the mouse lived much longer than a mouse in a dome alone. Priestley concluded that plants were capable of removing phlogiston from the air. He called the improved air they left behind "dephlogisticated air." Priestley saw these findings as confirming evidence for the phlogiston theory.

However, in France, another chemist was also studying different types of air, and coming to a conclusion entirely different from Priestley's. Antoine Laurent de Lavoisier (1743-1794), like Priestley, did not make his living through his scientific interests. In 1768, Lavoisier had purchased shares in the *Ferme generale*, a private corporation of shareholders responsible for collecting taxes for the king. In 1771, Lavoisier married a young woman named Marie-Anne Paulze (1758-1836), the only daughter of a wealthy colleague at the *Ferme generale*. His wife's fortune and his own earnings as a shareholder in the *Ferme* made Lavoisier an extremely rich man, and Lavoisier used this money to pursue his interest in chemistry. Marie-Anne was well-educated and a skilled artist who not only assisted Lavoisier with his work, but also translated chemistry papers from English into French for Lavoisier. On a typical day, Lavoisier would rise at five in the morning and work in his laboratory from six until nine, and then return to the laboratory in the evening after his work at the *Ferme generale* was complete. On Saturdays he would work all day with his assistants (including his wife, who drew many of the illustrations we have of Lavoisier's laboratory) on his latest scientific project.


Joseph Priestley

Lavoisier's research was characterized by a determination to measure everything as precisely as possible. Unlike

Joseph Priestley, adapted from portrait by Ellen Sharples (Public Domain)

Priestley, who used simple experimental setups that anyone else could easily duplicate, Lavoisier put a great deal of his wealth into constructing sophisticated experimental equipment. He was especially interested in obtaining the best, most reliable balances he could in order to determine the mass of reactants and products as accurately as possible. Lavoisier knew about and accepted the phlogiston theory. But the negative mass problem troubled him a great deal, and in 1772 he set out to investigate the combustion of sulfur in air and also phosphorous in air, measuring everything as precisely as possible, to determine why some burned objects gained mass. As is often the case with research, Lavoisier encountered many technical problems in his work and much conceptual confusion ensued.

Lavoisier slowly came to the conclusion that the phlogiston theory was not viable – some substances gained too much mass during combustion. The explanation that they were losing an unmeasurable substance, phlogiston, simply didn't make sense any longer to Lavoisier. Instead, in a paper he submitted to the Académie des Sciences in November of 1772, Lavoisier argued that when sulfur and phosphorous were burned, the increase in their mass was due to these compounds combining with air. Lavoisier reached this conclusion in part by studying lead calx (what we now call lead oxide, or PbO), a compound that gave off bubbles when dropped into water. He had begun to speculate that lead calx was lead combined with air, and when placed in water the air was given off. This sparked an original idea that the calcination of metals, the combustion of sulfur and the combustion of phosphorous likely all involved these substances combining with air.

Priestley, however, was suspicious of Lavoisier's elaborate experimental setup and unconvinced by his arguments and novel explanation. Priestley thought the Aristotelian idea of conservation of mass might be wrong, and was not as troubled as Lavoisier by the mass gain during combustion and the "negative" mass of phlogiston. Priestley pointed to examples such as heat and light – chemists could not weigh them, but clearly they existed. Priestley thought immaterial substances like heat, light and phlogiston might possibly undergo a transformation and acquire mass, and thought this sort of transformation better explained the mysterious mass gain of some substances during combustion. Thus, Priestley never accepted Lavoisier's ideas, and the two never agreed on the question of combustion.

Around that same time the existence of a substance we today call "oxygen gas" was independently isolated, first by the Swede Carl Wilhelm Scheele, and later by Priestley, although neither of them understood that the substance they had identified consisted solely of one element. Priestley had used a lens to focus sunlight on what we today know is HgO. A gas was emitted that he claimed was "five or six times as good as common air." This gas would cause a flame to burn far more intensely and would also keep a mouse alive much longer than an equal volume of air. Priestley is given credit for isolating this previously unknown gas because he published his work in 1774, three years before Scheele. But Priestley interpreted his work as supporting the phlogiston theory, referring to the gas as "dephlogisticated air." He maintained that the gas he had isolated had the impacts he reported because it had little or no phlogiston in it, and thus could absorb more of it. Soon after publishing his work, Priestley shared his accomplishment with Lavoisier.

2. Some people wrongly think that data tell scientists what to think and that science requires little creativity. How does the work of Lavoisier and Priestley, as well as other scientists, illustrate that rather than data telling scientists what to think, scientists develop ideas to account for or make sense of data?

After several more years of studying combustion and the chemistry of air, Lavoisier became convinced that Priestley's dephlogisticated air was instead air that contained an element that he named "oxygen." Lavoisier argued that the increase in mass when some substances (such as phosphorus, sulfur, and some metals) were burned was due to their combining with the oxygen in the air. Lavoisier was far more successful spreading his ideas than was Priestley in spreading his own. He began promoting his own system of chemistry; one that rejected phlogiston and employed a new chemical nomenclature that Lavoisier said was more rational than the old names.

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Priestley isolated what we now know is oxygen gas, but interpreted this as supporting phlogiston theory. Lavoisier, on the other hand, interpreted this newly isolated gas as a convincing refutation of phlogiston theory. Data does not tell scientists what to think. Rather, it must be interpreted and this involves both reason and creative insight.

In 1783, Lavoisier published *Les Reflexions sur le phlogistique,* where he firmly denied the existence of phlogiston. For some time, Lavoisier's claims were difficult for most in England and France to accept. Others who tried to recreate his laboratory equipment reported difficulties. Not until after Lavoisier's 1785 work separating water into its component gases did many French chemists accept his ideas. In a 1789 paper on the chemistry of fermentation, Lavoisier explicitly stated the principle of the conservation of mass: the reagents in a chemical reaction had to have the same mass, and the same elements, as the products.

This principle became an underlying assumption of the transformed science of chemistry that Lavoisier helped create.

3. Although Lavoisier is often credited with formulating the law of conservation of mass, note how early natural philosophers, including many chemists and physicists during the 18th century accepted and used the idea that matter would not spontaneously arise or vanish. What then was Lavoisier's important contribution?

In England, however, phlogiston underwent a resurgence in the 1770s and 1780s, and was a central feature of pneumatic chemistry. Thus, many chemists in England regarded the existence of phlogiston as beyond dispute. Even Joseph Black, who had always accepted that matter could not be created or destroyed, was very slow to accept Lavoisier's idea of oxygen's involvement in burning. However, by 1790, in a letter to Lavoisier, he wrote that he had:

> been habituated 30 years to believe and teach the doctrine of Phlogiston… I felt much aversion to the new system… This aversion however proceeded from the powers of habit alone has gradually subsided… Your plan… is infinitely better supported than the former Doctrine.

The conservation of mass law would remain well-established until the early 20th-century when it was modified to account for the theory of special relativity. Today we understand that while conservation of mass holds for chemical reactions, in nuclear reactions a very small amount of mass is converted into energy. The mass-energy equivalence law takes into account both chemical and nuclear reactions.

4. The idea that mass is conserved was once accepted by those studying the natural world, later abandoned, re-established, and then modified.
A) What does this illustrate about scientific work and progress?
B) How do scientists ever know that they have the absolute truth of a matter?
C) Why is well-established scientific knowledge trustworthy, even though it is open to revision?
D) How is the possibility of revisiting and revising previously established ideas a strength of science?

The final years of Priestley and Lavoisier's lives were marked by political unrest. During a series of riots in England in 1790 against Dissenters, Priestley's home was burned to the ground and he barely escaped with his life. He and his wife moved to Pennsylvania, where Priestley died in 1804. Lavoisier was even less fortunate. In 1789, the same year Lavoisier published his paper stating the principle of the conservation of mass, the French overthrew their king and the country was plunged into a revolution. When the Committee of Public Safety came to power under the leadership of Maximilien Robespierre, they began ordering the executions of people they saw as supporters of the old regime. According to the Committee, Lavoisier's participation in pre-Revolutionary tax collection made him an enemy of the Revolution, and he was executed in May 1794. Later exonerated by the government, Marie-Anne organized the publication of Lavoisier's work which assisted in ensuring his legacy in chemistry.

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