

CHAPTER 1

A Breath of Immoral Air

Joseph Priestley and the Discovery of Oxygen

Possibly no scientist has ever been more acutely aware of the role of chance in scientific discovery than Joseph Priestley, who stumbled on the existence of oxygen without having any real idea of what he was doing. The English chemist held that “more is owing to what we call *chance*, that is, philosophically speaking, to the observation of events arising from *unknown causes*, than to any proper design, or pre-conceived theory in this business.” Even the experiment that earned him an exalted place in scientific annals was unplanned. He confessed:

I know that I had no expectation of the real issue of it. For my own part, I will frankly acknowledge, that, at the commencement of the experiments . . . I was so far from having formed any hypothesis that led to the discoveries I made in pursuing them, that they would have appeared very improbable to me had I been told of them; and when the decisive facts did at length obtrude themselves upon my notice, it was very slowly, and with great hesitation, that I yielded to the evidence of my senses.

Even after making his historic discovery, however, he was unable to recognize its true significance. He still adhered to the received wisdom of his day that ordinary air—the air we breathe—became saturated with a substance called “phlogiston” when the air could no longer support combustion or life. Phlogiston was thought to be transferred during burning and respiration—a unifying idea in eighteenth-century chemistry. In an ironic twist in which the history of science abounds, Priestley had unwittingly paved the way for overthrowing the theory of phlogiston once and for all.

As a theoretical concept, phlogiston originated in the second half of the seventeenth century when an eighteenth-century German chemist named George Ernst Stahl theorized that when anything burned, its combustible part was given off to the air. This was the part that he called phlogiston, from the Greek word for “flammable.” Plants, he maintained, absorbed phlogiston from the air. Because the rusting of metals appeared to be analogous to combustion, Stahl reasoned, this rusting process, too, must involve loss of phlogiston. By the same token, heating metallic oxides—called the calx—with charcoal restored phlogiston to them. So he concluded that the calx must be an element and the metal a compound. Although some chemists were seduced by the theory of phlogiston, it exerted only minor influence until the latter part of the eighteenth century, when it came under attack by the famous French chemist Antoine-Laurent Lavoisier. In theory, metals should lose phlogiston when heated, but in fact, according to advocates of the phlogiston theory, they gained weight. So what, Lavoisier wondered, had happened to the elusive phlogiston?

A more promising avenue of scientific research involving the chemical reaction of gases opened up in the early 1700s when the British physiologist Stephen Hales invented a pneumatic

trough. For the first time chemists had a device to collect and measure the volume of gases released from various solids when they were heated. And since it was a closed system, the gases—which were called “airs”—remained uncontaminated by ordinary air. In 1756 the British chemist Joseph Black published his findings on the reactions of two salts—magnesium and calcium carbonates—when heated. What Black found was that they gave off a gas, leaving behind a residue of what he called “calcined magnesia,” or lime (the oxides). This residue, when combined with sodium carbonate—an alkali—regenerated the original salts. The most significant finding to emerge from Black’s work was that, contrary to what was previously believed, gases could in fact enter into a chemical reaction. Black’s research set the stage for the identification of several gases as separate substances.

A decade later, another British scientist, Henry Cavendish, isolated hydrogen, which he called “flammable air.” Hydrogen was only the third so-called air to be identified after ordinary air and carbon dioxide, which Black labeled “fixed air.” It seemed that many airs were left to be discovered, a challenge that was eagerly taken up by Joseph Priestley, a minister and a church dissenter who incidentally also happened to be a brilliant chemist.

Joseph Priestley was born on March 13, 1733, in Yorkshire, England, the son of a wool merchant and his wife. Joseph was only six years old when his mother died, apparently worn out after giving birth to six children in as many years. Unable to care for his oldest child, his father decided to pack the boy off to live with his sister-in-law, Sarah Keighley, and her husband. The Keighleys were both Dissenters and as such were to have a lasting influence over Priestley’s life. (Dissenters did not believe in the doctrines of the Anglican Church, the denomination to which most of England adhered. The Keighleys would be called Unitarians to-

day.) There was no question that Priestley was a prodigy. By the age of 16 he had already mastered Greek, Latin, and Hebrew. Then he went on to teach himself French, Italian, and German. After his graduation from a college catering to Dissenters, he decided to try his hand at the ministry, but at the same time he was drawn to academia, taking up a position as a professor of languages at a school in Warrington. Until this point Priestley had displayed no interest in science.

What prompted Priestley to attend a series of lectures on practical chemistry given by a prominent surgeon in Warrington is uncertain. Clearly, though, they made an impression on him, sparking a fascination for all things scientific. There were only so many knowledgeable people to talk with about science in Warrington, and so he began to make annual pilgrimages to London. There he had the opportunity to meet some of the leading intellectual and scientific lights of his age, one of whom was Benjamin Franklin. He told Franklin that he wanted to write a book about electricity. That he knew little about the subject failed to daunt him. Evidently Franklin perceived in him a kindred spirit—someone whose audacity equaled his own—for he proceeded to encourage Priestley to pursue the project. Franklin's faith was amply rewarded. The result was *The History and Present State of Electricity*, published in 1767. It was breathtaking in scope, summing up just about everything that was known about electricity at the time. Priestley also offered original contributions, based on his own experiments, noting, for example, that when he electrified a hollow sphere there was no charge inside, anticipating the inverse square law of electrical attraction.

Yet it was his ministry, and not science, that Priestley considered his most important work. Invited to assume the ministry of Mill Hill Chapel in Leeds, he seized the opportunity eagerly, welcoming a chance to preside over a congregation he described

as “liberal, friendly and harmonious.” But his decision to relocate to Leeds, barely six miles from where he grew up, also turned out to be a felicitous choice for reasons that had nothing to do with religion.

Priestley found lodging in Leeds next door to a brewery. Others might have been repelled by the odor that hung over the place. Not Priestley. He became curious to learn more about the “air” that effervesced from vats of fermenting liquor. The air, he observed, was capable of extinguishing lighted chips of wood. Mixed with smoke, the air descended to the ground, an indication that it must be heavier than ordinary or common air. The air released by fermentation was actually carbon dioxide—what Black had dubbed “fixed air.” While Priestley knew no more about airs than he had about electricity, he immediately embarked on learning about them. The only way to find out the properties of fixed air, he believed, was to experiment with it. By dissolving the air in water, he found, it made bubbles. The idea occurred to him that this fizzy water might be useful for making sparkling wines and that it might also have a therapeutic purpose as well, because, he believed mistakenly, it might prevent scurvy in sailors on long voyages. In the course of these experiments he succeeded in inventing soda water, making him, in effect, the father of the soft drink industry. His achievement was recognized by the Royal Society, which gave him a medal for it in 1773.

Encouraged by this initial success, he turned his attention to other “airs” given off when various substances were heated. As he had become more interested in chemistry, he had begun to reflect on the similarity between the processes of burning and respiration. Investigating the properties of airs offered him a chance to explore these processes in a laboratory setting. To carry out his experiments, he constructed a simple but ingenious apparatus, consisting of a trough full of mercury over which glass vessels

could be inverted to collect the gas. (This device, the invention of which is credited by some historians to Henry Cavendish, had an advantage over the one invented by Stephen Hales, which relied on water. Priestley's trough allowed the experimenter to collect and measure water-soluble gases, which Hales's could not do.) The substance to be heated was placed in a second, smaller glass vessel within the larger one. Priestley would then proceed to heat the substance by focusing the sun's rays on it using a twelve-inch lens. Between 1767 and 1773 he discovered four new "airs," including nitric oxide (nitrous air), nitrogen dioxide (red nitrous vapor), nitrous oxide (diminished nitrous air, more commonly known to dental patients as "laughing gas"), and hydrogen chloride (marine acid air). His account of his gas experiments, "On Different Kinds of Air," published in his opus *Philosophical Transactions* in 1772, attracted the attention of another scientist across the English Channel who was to play a crucial role in Priestley's own scientific endeavors—Antoine-Laurent Lavoisier, the same French chemist who had made a stir in scientific circles by blasting the whole notion of phlogiston.

Over the next few years, Priestley discovered ammonia (alkaline air), sulfur dioxide (vitriolic acid air), silicon tetrafluoride (fluor acid air), nitrogen (also discovered by British chemist Daniel Rutherford in 1772), and a gas later identified as carbon monoxide. In these experiments Priestley observed that light was important for plant growth and that green plants gave off a substance he called "dephlogisticated air." His findings set the stage subsequently for the systematic work on photosynthesis begun in 1779 by the Dutch physician Jan Ingenhousz and by the Swiss cleric-naturalist Jean Senebier.

As if this were not enough, Priestley somehow found the time to make an original contribution to the understanding of optics with the publication in 1772 of *History and Present State of Dis-*

coveries Relating to Vision, Light, and Colours, a book that brought him an invitation to join Captain James Cook's second voyage of exploration (1773–1775) as an astronomer. He was forced to decline, however, because of conservative opposition to his Unitarian views.

In December 1772, Priestley found new employment at the country estate of William Petty, Earl of Shelburne, as his librarian, literary companion, and tutor to his two young sons. The terms were generous. Shelburne gave him the freedom to preach and write as he wished and to continue to investigate airs to his heart's content.

On the first day of August 1774, Priestley decided to see what would happen if he extracted air from mercurius calcinatus (red mercuric oxide). Why this substance in particular? Even the chemist himself was uncertain. In his account of the experiment, written several years later, he wrote: "I cannot, at this distance of time, recollect what it was that I had in view in making this experiment: but I know that I had no expectation of the real issue of it." The only reason he could think of was that, having done so many similar experiments, he was always prepared to do another. It was almost as if he had nothing better to do. But there was one unusual aspect to this particular experiment that he would only appreciate later. "If, however, I had not happened, for some other purpose, to have lighted a candle before me," he wrote, "I would probably never have made the trial; and the whole train of my future experiments relating to this kind of air might have been prevented." Here was where chance intruded itself into the equation.

He followed the same routine that he had established with his earlier experiments on airs, first showering the substance with sunlight, intensified by his lens, until it was sufficiently heated to

give off a gas. He then added water to see if it would dissolve. It did not. "But what surprised me more than I can well express," he remarked, "was, that a candle burned in this air with a remarkably vigorous air."

Priestley had discovered an air—that much was obvious—but what kind of an air exactly? He had no idea. Eager to further investigate the mysterious gas, he chose to find out what would occur if he exposed it to a living creature. In March 1775 he introduced an adult mouse into a glass apparatus filled with air from mercurius calcinatus. He expected it to survive for no more than fifteen minutes, by which time the air would be depleted. By air he meant so-called common air, which both mice and men depend on to live. But in this air, he noted with astonishment, the mouse lived for half an hour. When Priestley removed the creature and held it to the fire, it at once revived, apparently none the worse for wear. "By this I was confirmed in my conclusion, that the air extracted from mercurius calcinatus . . . was, *at least, as good* as common air; but I did not conclude that it was any *better*."

All the same, he concluded that "from the greater strength and vivacity of the flame of a candle," this pure air "might be peculiarly salutary in the lungs in certain medical cases." He offered a caveat: "But, perhaps, we may also infer from these experiments, that though pure dephlogisticated air might be very useful as medicine, it might not be proper for us in the usual healthy state of the body . . . so we might . . . *live out too fast*, and the animal powers be too soon exhausted in this kind of pure air." He even went so far as to wonder whether he had overstepped certain ethical limits by his discovery. "A moralist, at least, may say, that the air which nature has provided for us is as good as we deserve."

But moral considerations aside, Priestley knew that people

would be curious to know just how far he carried his experiment. “My reader will not wonder, that, after having ascertained the superior goodness of dephlogisticated air by mice living in it . . . I would have the curiosity to taste it myself.” Priestley admitted that he had and then went on to describe what it felt like: “The feeling of it to my lungs was not sensibly different from that of common air; but I fancied that my breast felt peculiarly light and easy for sometime afterwards. Who can tell but that, in time, this pure air may become a fashionable article in luxury. Hitherto only two mice and myself have had the privilege of breathing it.”

Priestley quickly realized that this gas was the component of common air that made combustion and animal respiration possible. However, he reasoned that combustible substances burned more energetically in this gas, and metals formed calxes (or oxides) more readily because all the phlogiston had been expelled. Common air, by contrast, was partially filled with phlogiston. Air in which things had burned became less able to support combustion because, it was thought, it was saturated with phlogiston. Accordingly Priestley called the gas in which a candle flame burned with such “splendour and heat” dephlogisticated air. In fact, what Priestley had discovered was oxygen.

Priestley wasn’t alone in his discovery, though he did not know it at the time. In 1775, the same year that Priestley was carrying out his experiments with mice, Swedish pharmacist Carl Wilhelm Scheele (1742–1786) also isolated oxygen. Like Priestley, Scheele had no formal training in chemistry and studied the elements of science while apprenticed to an apothecary. An absence of a university education, however, was no obstacle to his discovering several compounds and elements, including chlorine and barium. And like Priestley, Scheele discovered oxygen by experimenting

on various oxides. But occupying an unassuming position as the proprietor of a pharmacy in Köping, Sweden, he never achieved the recognition that history has accorded the British chemist.

In October 1774, Priestley accompanied Shelburne on a journey through Europe. When the two arrived in Paris, Priestley took the opportunity to meet Lavoisier to tell him about his new dephlogisticated air. The meeting was a watershed event for the future of chemistry. Lavoisier was quick to appreciate the significance of Priestley's experiments. In fact, he understood the theoretical implications of the discovery, which Priestley did not. Lavoisier was not a modest man: two years prior to Priestley's visit, in 1772, he declared that he was "destined to bring about a revolution in physics and chemistry." Indeed he was as good as his word. Unlike older scientists, he realized that common air, as Priestley called it, was not an "element," but a component of air for which he had been searching. Now Priestley had brought him the missing piece of the puzzle.

Lavoisier wasted no time in repeating Priestley's experiments, carrying out intensive investigations all through 1775–1780. The results convinced him that Priestley's air was the active "principle" of the atmosphere. In a series of brilliant experiments, Lavoisier showed that air contains 20 percent oxygen and that combustion is due to the combination of a combustible substance with oxygen. He additionally interpreted its role in respiration. It was Lavoisier who in 1789 gave the substance the name oxygen. He derived the name from the Greek for "acid former," in the belief that all acids contained it.

Where Lavoisier parted ways with Priestley was in his repudiation of the phlogiston theory. In place of the phlogiston theory, Lavoisier demonstrated that oxygen from the air combines with the components of the combustible substance to form oxides of the component elements. In his "Discours preliminaire," a preface

to his major work, *Traité élémentaire de chimie* (Treatise of Chemical Elements, 1789), Lavoisier put forth his theory that substances that could not be decomposed by chemical means were *substances simples*—the basic elements out of which matter was composed. His conception of elements is little different from the way in which elements are regarded today. In the *Traite*, Lavoisier again anticipated modern science by declaring that matter cannot be either created or destroyed, but only altered and modified in chemical reactions. An equal quantity (no matter how greatly transformed) of the material remains before and after the operation. This theory—which would later find its echo in Einstein’s theory about the equivalence of matter and energy—is known as the law of conservation of mass.

In 1783 Lavoisier published his complete overhaul of chemical theory (he even introduced a new nomenclature to replace one that still used alchemy as its basis). To drive home the point that phlogiston was dead and buried, his wife ceremoniously burned books propounding the discredited theory. Unfortunately, Lavoisier’s luminous career in chemistry came to an abrupt and bloody end on the guillotine during the French Revolution: he was beheaded for having served the ousted monarchy as a tax collector.

The French Revolution was to make itself felt in Priestley’s life as well. Even while he was exploring the properties of atmospheric gases, he continued to espouse his belief in human progress and perfectibility, gaining renown as a political theorist. His *Essay on the First Principles of Government, and on the Nature of Political, Civil, and Religious Liberty* (1769), emphasizing individual rights, inspired the English economist and utilitarian Jeremy Bentham to coin the famous phrase “the greatest happiness of the greatest number.” In 1779, for reasons not entirely clear, Priestley left Shelburne’s employ and settled in the industrial town of Bir-

mingham as minister of the New Meeting congregation. While in Birmingham he continued to churn out a steady stream of books on religion and theology, sermons, tracts, and catechisms. Never one to shy away from controversy, he wrote a book that repudiated most of the fundamental doctrines of Christianity. It's possible that Priestley would have remained in Birmingham for the rest of his life, but in July 1791, on Bastille Day, a riot broke out—instigated by conservative elements opposed to freethinkers like Priestley—and in the ensuing rampage a mob destroyed Priestley's church, his home, and his laboratory. Priestley and his family barely survived a lynching, escaping the inflamed mob with only minutes to spare. While the incident is usually referred to as the Birmingham Riot, evidence suggests that the events were carefully orchestrated. All the victims were members of the dissenting religions and supporters of the French Revolution.

With the destruction of Priestley's library and the loss of his manuscripts, future biographers have been deprived of much of the material that could shed light on the chemist's life and work. A definitive biography of Priestley's early years exists (Robert Schofield's *The Enlightenment of Joseph Priestley: A Study of His Life and Work from 1733 to 1773*, published in 1998), but a comprehensive biography of his polymath in his later years is still to be written. Priestley may be simply too complex a figure to pin down. Here was a man, after all, who was equally at home in the laboratory, investigating electricity and discovering gases, as he was in the church, puzzling out the mysteries of the Book of Revelation.

Priestley's attempt to pick up the pieces and resume work in the aftermath of the riot proved fruitless. When efforts to rebuild his library and lab foundered, Priestley left England for good. In August 1793 the Priestleys set sail for America. A year later they

decided to make their home on a farm in Northumberland, Pennsylvania. Although he seemed a bit lost without his laboratory and library, he declined the offer to take up a Unitarian ministry in Philadelphia, preferring to stay put with his family on his farm. But even though he chose a life of relative obscurity, his admirers didn't forget him. One of them was Benjamin Franklin, who wrote in a letter to one of the chemist's students, "Remember me affectionately to the honest heretic, Dr. Priestley." Priestley's change of circumstances did not, however, cause him to alter his routine (though he did give up wearing his wig). He continued to write, devoting most of his time to the completion of his theological works, particularly his *General History of the Christian Church*. And as always he continued to conduct scientific experiments. When, for example, Erasmus Darwin (grandfather of Charles) proposed a theory of spontaneous generation, which stated that organisms could arise from inorganic material like sand, Priestley began to experiment with algae in an effort to prove Darwin mistaken. Priestley also kept up with the work being done by a new generation of British chemists, like John Dalton (1766–1844), who developed the basis for modern atomic theory, and Humphry Davy (1778–1879), who, among other achievements, discovered that diamonds are made of carbon. Ironically, the last scientific paper Priestley was to publish—in June 1797—took the form of a pamphlet titled *The Doctrine of Phlogiston Established*. This was at a time when the entire scientific community had dismissed phlogiston as a myth. Even as Priestley lay dying seven years later, he still clung to his belief in the very theory that his discovery of oxygen had done so much to demolish.