EUREKA!

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Scientific Breakthroughs that Changed the World

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Introduction

A Sudden Flash of Light

Scientific progress comes in fits and starts—years of toil in a laboratory may prove fruitless but a contemplative walk in the countryside can yield an astonishing breakthrough. That's what the nineteenth-century French mathematician Henri Poincaré found out when previous efforts to solve a particularly thorny mathematical problem had come to naught. "One morning, walking on the bluff," he wrote, "the idea came to me, with . . . brevity, suddenness and immediate certainty. . . . Most striking at first is this appearance of sudden illumination, a manifest sign of long, unconscious prior work. The role of unconscious work in mathematical invention appears to me incontestable."

As mysterious and unpredictable as such bursts of creative insight are, their occurrence is frequent enough that the phenomenon has been well chronicled. Another French mathematician, Jacques Hadamard described the experience: "On being very abruptly awakened by an external noise, a solution long searched for appeared to me at once without the slightest instant of reflection on my part . . . and in a quite different direction from any of those which I had previously tried to follow." The German mathematician, Carl Friedrich Gauss, offers a similarly arresting account of how he solved a problem that had resisted him for four years: "As a sudden flash of light, the enigma was solved. . . . For my part I am unable to name the nature of the thread which connected what I previously knew with that which made my success possible."

Creativity, whether in mathematics, the sciences, or the arts, is a funny business. You can spend long years of struggle in fruitless effort, banging your head against a wall as if it were possible to force an idea to come, only to hit upon a solution all at once, out of the blue so to speak, in the course of an idle stroll. The twelve scientists who make their appearance in this book all experienced the kind of sudden illumination that Poincaré, Gauss, and Hadamard are referring to. Almost invariably their insights came about in a moment of distraction or else burst forth from their unconscious while they slept. Religious epiphanies, by most accounts, appear to represent a similar phenomenon, where inspiration seems to strike like a lightning bolt.

There seems no accounting for when lightning will strike (or whether it will at all). "I have had my solutions for a long time, but I do not yet know how I am to arrive at them," lamented Gauss. What he's saying is that he knows he knows the solution but it remains infuriatingly unreachable, hiding out in some dark corner of his brain. And even if lightning does strike, the revelation may produce a solution for which proof is impossible to come by. André-Marie Ampère, the early nineteenth-century French physicist, remarked:

> I gave a shout of joy. . . . It was seven years ago I proposed to myself a problem which I have not been able to solve directly, but for which I had found by chance a solution, and knew that it was correct, without being able to prove it. The matter often returned to my mind and I had sought

> twenty times unsuccessfully for this solution. For some days I had carried the idea about with me continually. At last, I do not know how, I found it, together with a large number of curious and new considerations concerning the theory of probability.

Sometimes, of course, genius outstrips technology, with the result that the idea may wither and die on the vine, derided and mocked—or worse, simply ignored—for years, only to be rediscovered when science catches up to it. When Alfred Wegener, the German astronomer and meteorologist, proposed the theory of continental drift in 1912—which states that hundreds of millions of years ago the continents had made up one great landmass that has since split apart—he provoked a storm of outrage from fellow geologists. That the theory was largely correct had to wait until the early 1960s—more than thirty years after Wegener's death—before the technology was available to substantiate it. But Wegener never lost faith in the theory. That's another thing the scientists in this book have in common: however intense their opposition, they remained convinced that they were correct. The proof of their theories, they assumed, would eventually be found. As one mathematician explained, "When you have satisfied yourself that the theorem is true, you start proving it." That could be called the aesthetic approach—something that looks good and feels right, strangely enough, has a good chance of being right, even if you can't immediately figure out how to convince anyone of its truth.

The development of technology also often prods the mind into new ways of thinking. Without the refinement of X-ray diffraction techniques at the end of World War II, biophyisicists James Watson and Francis Crick could have had the most brilliant theories in the world, but they still would never have gotten any-where in their efforts to fathom the structure of the DNA molecule. But the catch phrase of the movie *Field of Dreams* is also apt in this context: “Build it and they will come.” Invent an instrument that can do something earlier devices could not and some researcher somewhere will want to experiment with it. Take the invention in the eighteenth century of an enclosed chamber that allowed the researcher to heat up various substances in order to study the gases they emitted. Using this device, the eighteenth-century English chemist Joseph Priestley tested several different compounds, just to find out what would happen, with no idea as to what kind of gases he might produce. In the process he discovered oxygen.

There is, of course, no way to be sure that an epiphany will ever occur. Deserving scientists can struggle with a problem for a lifetime and never experience a flash of insight that will result in a solution. But it would be a mistake to think of the scientists discussed here as passive vessels, moved to action only after being seized by a burst of illumination. On the contrary, these scientists were preparing themselves for their eureka moment for years in advance, even if they didn’t realize it at the time.

Fortune favors the prepared mind, said French chemist Louis Pasteur, and the French scientist Bernard Fontenelle observed: “These strokes of good fortune are only for those who play well!” But what kind of preparation exactly, you might ask?

For one, a prepared mind is a curious mind, open even to possibilities that experts consider outlandish, impractical, or simply foolish. Fortune seems to favor scientists who love to rummage around for ideas in places no one else would think to look—“the trash cans of science,” as the French mathematician Benoit Mandelbrot (b. 1924) puts it. Almost without exception, these scientists were and are indifferent to boundaries and have little compunction about poaching on territory claimed by another discipline if it suits their purposes. These men are generalists, and as such they are impossible to pigeonhole. Wegener, for instance, was trained as an astronomer and meteorologist (he was also a champion balloonist), yet it was as a geological theorist that he made his mark. (Was it any wonder that geologists of the day resented him?) Friedrich Kekulé the German chemist, who unraveled the mysteries of how carbon molecules bond, studied to be an architect. Priestley considered the ministry his primary calling; science was something he did in his spare time. Watson, codiscoverer of the double-helix structure of DNA, had been an ornithologist before he turned to genetics. Mandelbrot, trained as a mathematician, tackled engineering and economic problems. These scientists all share a capacity to draw from many diverse—and seemingly unrelated—sources. (To come up with his theory of continental drift, Wegener amassed data from fields as varied as meteorology, seismology, paleontology, and zoology, as well as geology.) In other words, these men are all great synthesizers. "The sudden activation of an effective link between two concepts or percepts, at first unrelated, is a simple case of 'insight,' " noted the psychologist D. O. Hebb. "The insightful act is an excellent example of something that is not learned, but still depends on learning."

These scientists are also distinguished by their penchant for looking at something in a way that may seem counterintuitive. Even what may appear, on the surface, to be a mistake or a botched effort can have unexpected, and profitable, consequences, as illustrated by an invention of a scientist named Spencer Silver. Silver, who worked for the 3M Corporation, had developed a polymer adhesive that formed microscopic spheres instead of a uniform coating, with the result that it took years to set. Here, you'd assume, was a product that would seem to have no commercial viability. What use after all is an adhesive that takes forever to bind? Enter another 3M scientist, Arthur Fry. Fry was looking for a better bookmark for his church hymnal—a bookmark that wouldn't fall out, but that wouldn't damage its pages, either. That's when he thought of Silver's adhesive. Sure enough, it worked excellently as a bookmark: it stuck to the page when needed and was easily removed, leaving the paper unharmed. From this observation Fry came up with the idea for the Post-it. Conventional wisdom would say that all adhesives must be strong, but obviously that isn't true. It's just that it took a prepared mind to see how a weak adhesive could have an eminently practical use as well.

It is helpful to recall, too, that until the twentieth century, the boundaries between disciplines were far more blurred than they are today, and in some cases, disciplines that are now a standard part of any curriculum simply did not exist as such. That made it easier for scientists to roam far afield without worrying about whether they had the requisite credentials. Chemistry, for example, didn't come into its own until late in the nineteenth century. Moreover, some fields were so new—paleontology, for example—that practically anyone with enough curiosity and gumption could have the opportunity to make a significant contribution. No one, for instance, questioned Priestley when he decided to write a book about electricity, even though he wasn't an authority on the subject. That was because no one else was, either. In a sense, these scientists are explorers, venturing into little-known territory with unreliable maps, unafraid of risking humiliation or professional disgrace, and endowed with frightening self-confidence. They are also unafraid to ask questions—questions that sometimes seem so obvious that no one before thought them worth posing. For instance, just how long is the coast of Britain? And why is the length of the border between Spain and Portugal one length as measured by the Spanish and another as measured by the Portuguese, even though both nations use the same metric system? (See chapter 12.)

As explorers, most of the scientists profiled in this book are highly adaptable. If the path they had initially chosen turned out to be blocked, rather than give up, they would look for another. As a result, they might end up straying far from their intended destination. As so often happens, though, the destination that they had in mind to begin with was not the destination that they were meant to achieve. The English naturalist Charles Darwin did not set sail on the *Beagle* to find evidence that would account for the origin of species. He merely saw it as an opportunity for adventure; yet it was the observations that he made along the way that ultimately put him on the path that would lead him to propose the theory of evolution. The experience of American physicist Steven Weinberg, a Nobel Prize winner in physics, offers another telling example. He was trying to come up with particle descriptions that would explain the strong nuclear force (the force that binds atoms together), but was getting nowhere. "At some point in the fall of 1967, I think while driving to my office at MIT," he said, "it occurred to me that I had been applying the right ideas to the wrong problems." He realized suddenly that his particle descriptions were in fact correct, and that while they were irrelevant to the strong force, they could be applied perfectly to the weak nuclear force (the force that produces radioactivity) and electromagnetism. The prepared mind must be prepared to be surprised.

Serendipity as well plays a role in some of the discoveries described in the pages that follow. British bacteriologist Alexander Fleming goes on holiday one summer, neglecting to put away a bacterial culture he had been working on. In the lab below, a researcher, specializing in fungi, leaves the door open to the hallway because of the stifling heat. The spores from the fungi drift up into Fleming's lab and alight on the petri dish containing the culture. Fleming returns to find that something remarkable has happened to the contaminated culture that he could not have predicted. (See chapter 7). Or take another example: Joseph Priestley sits down one day to conduct an experiment on an unknown gas. A lit candle is nearby. To his surprise, when the gas is exposed to the flame, it burns more brightly and vigorously. (See chaper 1.) Yet if Fleming and Priestley hadn't been such acute observers, they might not have recognized the implications of these happy accidents, and the discoveries of penicillin and oxygen would have had to wait for another day. It does you no good if an opportunity is staring you in the face and you don't see it for what it is, or don't know how to take advantage of it. That is something only a prepared mind can do.

Finally, we come to what might be called the ripeness or zeitgeist theory. Or to put it another way: Why does a scientific breakthrough occur at one time and not at another? Clearly, a certain body of knowledge has to be acquired and disseminated beforehand: in other words, a foundation of data from observations and experiments has to be there to build upon. If Russian chemist Dmitry Mendeleyev had been doing his research in 1840, for example, rather than in the 1860s, he would not have been able to invent the periodic table for the simple reason that not enough elements were known, making it impossible to organize them according to their properties. Further, the problem has to be defined—not always as easy a task as it may seem. Why do a bowling ball and a feather fall at the same rate? What is the purpose of DNA? Why does the eastern coast of Africa seem to fit so well into the western coast of South America? Without a grasp on the problem, it's difficult to find a solution. (Though a solution sometimes does materialize and then the scientist has to go hunting for the problem to which it belongs.)

A scientific body of knowledge need not consist only of established facts. False starts, wrong turns, and discredited theories also have an instructive value. Once you know the mistakes your predecessors have made, you can avoid repeating them. But in many instances, the mistakes may suggest avenues that could have been profitably pursued but were not, for whatever reason. Many scientists have failed, not because they were moving in the wrong direction but rather because they didn't go far enough. Without an awareness of all the missteps and blind alleys engineers had taken in the past, for instance, American engineer Philo Farnsworth wouldn't have been able to develop a television system that worked where its precursors had failed.

That said, it does seem that some ideas manifest themselves at certain times and often to several scientists at once. It's almost as if there's something in the air—a germ of an idea—that you can reach up and grab if you are clever or intuitive enough. The notion that the time is "ripe" for an idea, be it the periodic table, continental drift, a theory of gravity, or fractal geometry, may not be possible to prove, but you could make a good case for it. Joseph Priestley wasn't the only scientist to "discover" oxygen. So did a Swedish chemist named Carl Wilhelm Scheele. Archibald Couper, a Scottish chemist, put forward a theory about the structure of carbon compounds that was uncannily like the one advanced by Friedrich Kekulé. Julius Lothar Meyer, a German chemist, came up with a periodic table practically identical to Mendeleyev's. And, in the best-known example of this kind of coincidence, the English botanist Alfred Russel Wallace proposed a theory of evolution that was little different from the one Darwin was working on. In each of these instances, the discoveries were made almost simultaneously.

Why, then, do we know so much about Priestley, Kekulé, Mendeleyev, and Darwin, and so little about Scheele, Couper, Meyer, and Wallace? The explanations vary. In some instances, it was a matter of luck; in others, an accident of geography. And it should go without saying that scientists who were self-promoters were more likely to gain a place in the history books than their more self-effacing rivals. Fortune, it seems, may well favor the person with a prepared mind and grant him or her the chance to make a great discovery, but fortune is not always so willing to award that person the credit he or she deserves for having done so.

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 today.) 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