Timberlane High School Science Summer Reading Assignment:

Course: Chemistry Accelerated

Instructions

- Please read the following selection(s) from the book A Short History of Nearly Everything by Bill Bryson.
- Please provide written answers (short essay style) to the questions at the end of the reading

  •Questions adapted from Random House Publishing Inc.
  https://www.randomhouse.com/catalog/teachers_guides/9780767908184.pdf
- The written assignment is to be turned into your teacher by **Thursday, September 5th and Friday, September 6th,** for potential full credit. Accepted until Sept 12th with 10% deduction in grade per day. Not accepted after Sept 12th.
- This is a graded assignment worth up to 3% of your quarter 1 grade.
- **□ll work must be your own and copying will result in a grade of zero.**

Grading Rubric:

The writing will be assessed on the following 0 to 3 scales

- Each answer should be in a short essay style (minimum one paragraph).
  - 1: most answers are short one word answers.
  - 3: complete thoughts and sentences that fully convey the answers.
- Each answer should demonstrate evidence of reading to comprehension.
  - 1: answers indicate that the reading was not completed o 3: answers show clear comprehension of the reading
- Each answer should be correct, relevant to the topic, should strive for detail and completeness.
  - 1: answers are not relative to question or reading o 3: Answers demonstrate clear relevancy to passage and get to the heart of the rationale for question in relation to subject area.
- Each answer should refer to a specific statement or include a quote from the reading.
  - 1: the writing is vague, incomplete and contains little detail o 3: writing is detailed, complete and references specific statements or quotes from the reading passage.
- Each answer should be original (no plagiarism)

Tips on how to read science text for comprehension:

Break the reading into more than one session (2 to 4 pages per day). This should take about 15 minutes each time. Read slowly! Understand each sentence before reading the next. Be sure to examine unfamiliar words and concepts; try to determine meaning from the reading (or look them up). Make notes on each paragraph! It is OK to reread as you go or even reread the entire text. Read to understand, think about the ideas as you read and relate to what you already know, and what you may want to find out.

7 ELEMENTAL MATTERS

CHEMISTRY AS AN earnest and respectable science is often said to date from 1661, when Robert Boyle of Oxford published The Sceptical Chymist —the first work to distinguish between chemists and alchemists—but it was a slow and often erratic transition. Into the eighteenth century scholars could feel oddly comfortable in both camps—like the German Johann Becher, who produced an unexceptionable work on mineralogy called Physica Subterranea , but who also was certain that, given the right materials, he could make himself invisible.

Perhaps nothing better typifies the strange and often accidental nature of chemical science in its early days than a discovery made by a German named Hennig Brand in 1675. Brand became convinced that gold could somehow be distilled from human urine. (The similarity of color seems to have been a factor in his conclusion.) He assembled fifty buckets of human urine, which he kept for months in his cellar. By various recondite processes, he converted the urine first into a noxious paste and then into a translucent waxy substance. None of it yielded gold, of course, but a strange and interesting thing did happen. After a time, the substance began to glow. Moreover, when exposed to air, it often spontaneously burst into flame.

The commercial potential for the stuff—which soon became known as phosphorus, from Greek and Latin roots meaning "light bearing"—was not lost on eager businesspeople, but the difficulties of manufacture made it too costly to exploit. An ounce of phosphorus retailed for six guineas—perhaps five hundred dollars in today's money—or more than gold.

At first, soldiers were called on to provide the raw material, but such an arrangement was hardly conducive to industrial-scale production. In the 1750s a Swedish chemist named Karl (or Carl) Scheele devised a way to manufacture phosphorus in bulk without the slop or smell of urine. It was largely because of this mastery of phosphorus that Sweden became, and remains, a leading producer of matches.

Scheele was both an extraordinary and extraordinarily luckless fellow. A poor pharmacist with little in the way of advanced apparatus, he discovered eight elements—chlorine, fluorine, manganese, barium, molybdenum, tungsten, nitrogen, and oxygen—and got credit for none of them. In every case, his finds were either overlooked or made it into publication after someone else had made the same discovery independently. He also discovered many useful compounds, among them ammonia, glycerin, and tannic acid, and was the first to see the commercial potential of chlorine as a bleach—all breakthroughs that made other people extremely wealthy.

Scheele's one notable shortcoming was a curious insistence on tasting a little of everything he worked with, including such notoriously disagreeable substances as mercury, prussic acid (another of his discoveries), and hydrocyanic acid—a compound so famously poisonous that 150 years later Erwin Schrödinger chose it as his toxin of choice in a famous thought experiment (see page 146). Scheele's rashness eventually caught up with him. In 1786, aged just forty-three, he was found dead at his workbench surrounded by an array of toxic chemicals, any one of which could have accounted for the stunned and terminal look on his face.

Were the world just and Swedish-speaking, Scheele would have enjoyed universal acclaim. Instead credit has tended to lodge with more celebrated chemists, mostly from the English-speaking world. Scheele discovered oxygen in 1772, but for various heartbreakingly complicated reasons could not get his paper published in a timely manner. Instead credit went to Joseph Priestley, who discovered the same element independently, but latterly, in the summer of 1774. Even more remarkable was Scheele's failure to receive credit for the discovery of chlorine. Nearly all textbooks still attribute chlorine's discovery to Humphry Davy, who did indeed find it, but thirty-six years after Scheele had.

Although chemistry had come a long way in the century that separated Newton and Boyle from Scheele and Priestley and Henry Cavendish, it still had a long way to go. Right up to the closing years of the eighteenth century (and in Priestley's case a little beyond) scientists everywhere searched for, and sometimes believed they had actually found, things that just weren't there: vitiated airs, dephlogisticated marine acids, phloxes, calxes, terraqueous exhalations, and, above all, phlogiston, the substance that was thought to be the active agent in combustion. Somewhere in all this, it was thought, there also resided a mysterious élan vital, the force that brought inanimate objects to life. No one knew where this ethereal essence lay, but two things seemed probable: that you could enliven it with a jolt of electricity (a notion Mary Shelley exploited to full effect in her novel Frankenstein) and that it existed in some substances but not others, which is why we ended up with two branches of chemistry: organic (for those substances that were thought to have it) and inorganic (for those that did not).

Someone of insight was needed to thrust chemistry into the modern age, and it was the French who provided him. His name was Antoine-Laurent Lavoisier. Born in 1743, Lavoisier was a member of the minor nobility (his father had purchased a title for the family). In 1768, he bought a practicing share in a deeply despised institution called the Ferme Générale (or General Farm), which collected taxes and fees on behalf of the government. Although Lavoisier himself was by all accounts mild and fair-minded, the company he worked for was neither. For one thing, it did not tax the rich but only the poor, and then often arbitrarily. For Lavoisier, the appeal of the institution was that it provided him with the wealth to follow his principal devotion, science. At his peak, his personal earnings reached 150,000 livres a year—perhaps $20 million in today's money.

Three years after embarking on this lucrative career path, he married the fourteen-year-old daughter of one of his bosses. The marriage was a meeting of hearts and minds both. Madame Lavoisier had an incisive intellect and soon was working productively alongside her husband. Despite the demands of his job and busy social life, they managed to put in five hours of science on most days—two in the early morning and three in the evening—as well as the whole of Sunday, which they called their jour de bonheur (day of happiness). Somehow Lavoisier also found the time to be commissioner of gunpowder, supervise the building of a wall around Paris to deter smugglers, help found the metric system, and coauthor the handbook Méthode de Nomenclature Chimique , which became the bible for agreeing on the names of the elements.

As a leading member of the Académie Royale des Sciences, he was also required to take an informed and active interest in whatever was topical—hypnotism, prison reform, the respiration of insects, the water supply of Paris. It was in such a capacity in 1780 that Lavoisier made some dismissive remarks about a new theory of combustion that had been submitted to the academy by a hopeful young scientist. The theory was indeed wrong, but the scientist never forgave him. His name was Jean-Paul Marat.

The one thing Lavoisier never did was discover an element. At a time when it seemed as if almost anybody with a beaker, a flame, and some interesting powders could discover something new—and when, not incidentally, some two-thirds of the elements were yet to be found—Lavoisier failed to uncover a single one. It certainly wasn't for want of beakers. Lavoisier had thirteen thousand of them in what was, to an almost preposterous degree, the finest private laboratory in existence.

Instead he took the discoveries of others and made sense of them. He threw out phlogiston and mephitic airs. He identified oxygen and hydrogen for what they were and gave them both their modern names. In short, he helped to bring rigor, clarity, and method to chemistry.

And his fancy equipment did in fact come in very handy. For years, he and Madame Lavoisier occupied themselves with extremely exacting studies requiring the finest measurements. They determined, for instance, that a rusting object doesn't lose weight, as everyone had long assumed, but gains weight—an extraordinary discovery. Somehow as it rusted the object was attracting elemental particles from the air. It was the first realization that matter can be transformed but not eliminated. If you burned this book now, its matter would be changed to ash and smoke, but the net amount of stuff in the universe would be the same. This became known as the conservation of mass, and it was a revolutionary concept. Unfortunately, it coincided with another type of revolution—the French one—and for this one Lavoisier was entirely on the wrong side.

Not only was he a member of the hated Ferme Générale, but he had enthusiastically built the wall that enclosed Paris—an edifice so loathed that it was the first thing attacked by the rebellious citizens. Capitalizing on this, in 1791 Marat, now a leading voice in the National Assembly, denounced Lavoisier and suggested that it was well past time for his hanging. Soon afterward the Ferme Générale was shut down. Not long after this Marat was murdered in his bath by an aggrieved young woman named Charlotte Corday, but by this time it was too late for Lavoisier.

In 1793, the Reign of Terror, already intense, ratcheted up to a higher gear. In October Marie Antoinette was sent to the guillotine. The following month, as Lavoisier and his wife were making tardy plans to slip away to Scotland, Lavoisier was arrested. In May he and thirty-one fellow farmers-general were brought before the Revolutionary Tribunal (in a courtroom presided over by a bust of Marat). Eight were granted acquittals, but Lavoisier and the others were taken directly to the Place de la Revolution (now the Place de la Concorde), site of the busiest of French guillotines. Lavoisier watched his father-in-law beheaded, then stepped up and accepted his fate. Less than three months later, on July 27, Robespierre himself was dispatched in the same way and in the same place, and the Reign of Terror swiftly ended.

A hundred years after his death, a statue of Lavoisier was erected in Paris and much admired until someone pointed out that it looked nothing like him. Under questioning the sculptor admitted that he had used the head of the mathematician and philosopher the Marquis de Condorcet—apparently he had a spare—in the hope that no one would notice or, having noticed, would care. In the second regard he was correct. The statue of Lavoisier-cum-Condorcet was allowed to remain in place for another half century until the Second World War when, one morning, it was taken away and melted down for scrap.

In the early 1800s there arose in England a fashion for inhaling nitrous oxide, or laughing gas, after it was discovered that its use "was attended by a highly pleasurable thrilling." For the next half century it would be the drug of choice for young people. One learned body, the Askesian Society, was for a time devoted to little else. Theaters put on "laughing gas evenings" where volunteers could refresh themselves with a robust inhalation and then entertain the audience with their comical staggerings.

It wasn't until 1846 that anyone got around to finding a practical use for nitrous oxide, as an anesthetic. Goodness knows how many tens of thousands of people suffered unnecessary agonies under the surgeon's knife because no one thought of the gas's most obvious practical application.

I mention this to make the point that chemistry, having come so far in the eighteenth century, rather lost its bearings in the first decades of the nineteenth, in much the way that geology would in the early years of the twentieth. Partly it was to do with the limitations of equipment—there were, for instance, no centrifuges until the second half of the century, severely restricting many kinds of experiments—and partly it was social. Chemistry was, generally speaking, a science for businesspeople, for those who worked with coal and potash and dyes, and not gentlemen, who tended to be drawn to geology, natural history, and physics. (This was slightly less true in continental Europe than in Britain, but only slightly.) It is perhaps telling that one of the most important observations of the century, Brownian motion, which established the active nature of molecules, was made not by a chemist but by a Scottish botanist, Robert Brown. (What Brown noticed, in 1827, was that tiny grains of pollen suspended in water remained indefinitely in motion no matter how long he gave them to settle. The cause of this perpetual motion—namely the actions of invisible molecules—was long a mystery.)

Things might have been worse had it not been for a splendidly improbable character named Count von Rumford, who, despite the grandeur of his title, began life in Woburn, Massachusetts, in 1753 as plain Benjamin Thompson. Thompson was dashing and ambitious, "handsome in feature and figure," occasionally courageous and exceedingly bright, but untroubled by anything so inconveniencing as a scruple. At nineteen he married a rich widow fourteen years his senior, but at the outbreak of revolution in the colonies he unwisely sided with the loyalists, for a time spying on their behalf. In the fateful year of 1776, facing arrest "for lukewarmness in the cause of liberty," he abandoned his wife and child and fled just ahead of a mob of anti-Royalists armed with buckets of hot tar, bags of feathers, and an earnest desire to adorn him with both.

He decamped first to England and then to Germany, where he served as a military advisor to the government of Bavaria, so impressing the authorities that in 1791 he was named Count von Rumford of the Holy Roman Empire. While in Munich, he also designed and laid out the famous park known as the English Garden.

In between these undertakings, he somehow found time to conduct a good deal of solid science. He became the world's foremost authority on thermodynamics and the first to elucidate the principles of the convection of fluids and the circulation of ocean currents. He also invented several useful objects, including a drip coffeemaker, thermal underwear, and a type of range still known as the Rumford fireplace. In 1805, during a sojourn in France, he wooed and married Madame Lavoisier, widow of Antoine-Laurent. The marriage was not a success and they soon parted. Rumford stayed on in France, where he died, universally esteemed by all but his former wives, in 1814.

But our purpose in mentioning him here is that in 1799, during a comparatively brief interlude in London, he founded the Royal Institution, yet another of the many learned societies that popped into being all over Britain in the late eighteenth and early nineteenth centuries. For a time it was almost the only institution of standing to actively promote the young science of chemistry, and that was thanks almost entirely to a brilliant young man named Humphry Davy, who was appointed the institution's professor of chemistry shortly after its inception and rapidly gained fame as an outstanding lecturer and productive experimentalist.

Soon after taking up his position, Davy began to bang out new elements one after another—potassium, sodium, magnesium, calcium, strontium, and aluminum or aluminium, depending on which branch of English you favor.[1] He discovered so many elements not so much because he was serially astute as because he developed an ingenious technique of applying electricity to a molten substance—electrolysis, as it is known. Altogether he discovered a dozen elements, a fifth of the known total of his day. Davy might have done far more, but unfortunately as a young man he developed an abiding attachment to the buoyant pleasures of nitrous oxide. He grew so attached to the gas that he drew on it (literally) three or four times a day. Eventually, in 1829, it is thought to have killed him.

Fortunately more sober types were at work elsewhere. In 1808, a dour Quaker named John Dalton became the first person to intimate the nature of an atom (progress that will be discussed more completely a little further on), and in 1811 an Italian with the splendidly operatic name of Lorenzo Romano Amadeo Carlo Avogadro, Count of Quarequa and Cerreto, made a discovery that would prove highly significant in the long term—namely, that two equal volumes of gases of any type, if kept at the same pressure and temperature, will contain identical numbers of molecules.

Two things were notable about Avogadro's Principle, as it became known. First, it provided a basis for more accurately measuring the size and weight of atoms. Using Avogadro's mathematics, chemists were eventually able to work out, for instance, that a typical atom had a diameter of 0.00000008 centimeters, which is very little indeed. And second, almost no one knew about Avogadro's appealingly simple principle for almost fifty years.[2]

Partly this was because Avogadro himself was a retiring fellow—he worked alone, corresponded very little with fellow scientists, published few papers, and attended no meetings—but also it was because there were no meetings to attend and few chemical journals in which to publish. This is a fairly extraordinary fact. The Industrial Revolution was

[1] The confusion over the aluminum/aluminium spelling arose b cause of some uncharacteristic indecisiveness on Davy's part. When he first isolated the element in 1808, he called it alumium. For son reason he thought better of that and changed it to aluminum four years later. Americans dutifully adopted the new term, but mai British users disliked aluminum, pointing out that it disrupted the -ium pattern established by sodium, calcium, and strontium, so they added a vowel and syllable.

[2] The principle led to the much later adoption of Avogadro's number, a basic unit of measure in chemistry, which was named for Avogadro long after his death. It is the number of molecules found in 2.016 grams of hydrogen gas (or an equal volume of any other gas). Its value is placed at 6.0221367×10^{23}, which is an enormously large number. Chemistry students have long amused themselves by computing just how large a number it is, so I can report that it is equivalent to the number of popcorn kernels needed to cover the United States to a depth of nine miles, or cupfuls of water in the Pacific Ocean, or soft drink cans that would, evenly stacked, cover the Earth to a depth of 200 miles. An equivalent number of American pennies would be enough to make every person on Earth a dollar trillionaire. It is a big number.

driven in large part by developments in chemistry, and yet as an organized science chemistry barely existed for decades.

The Chemical Society of London was not founded until 1841 and didn't begin to produce a regular journal until 1848, by which time most learned societies in Britain—Geological, Geographical, Zoological, Horticultural, and Linnaean (for naturalists and botanists)—were at least twenty years old and often much more. The rival Institute of Chemistry didn't come into being until 1877, a year after the founding of the American Chemical Society. Because chemistry was so slow to get organized, news of Avogadro's important breakthrough of 1811 didn't begin to become general until the first international chemistry congress, in Karlsruhe, in 1860.

Because chemists for so long worked in isolation, conventions were slow to emerge. Until well into the second half of the century, the formula H_2O_2might mean water to one chemist but hydrogen peroxide to another. C_2H_4could signify ethylene or marsh gas. There was hardly a molecule that was uniformly represented everywhere.

Chemists also used a bewildering variety of symbols and abbreviations, often self-invented. Sweden's J. J. Berzelius brought a much-needed measure of order to matters by decreeing that the elements be abbreviated on the basis of their Greek or Latin names, which is why the abbreviation for iron is Fe (from the Latin ferrum) and that for silver is Ag (from the Latin argentum). That so many of the other abbreviations accord with their English names (N for nitrogen, O for Oxygen, H for hydrogen, and so on) reflects English's Latinate nature, not its exalted status. To indicate the number of atoms in a molecule, Berzelius employed a superscript notation, as in H^2O. Later, for no special reason, the fashion became to render the number as subscript: H_2O.

Despite the occasional tidyings-up, chemistry by the second half of the nineteenth century was in something of a mess, which is why everybody was so pleased by the rise to prominence in 1869 of an odd and crazed-looking professor at the University of St. Petersburg named Dmitri Ivanovich Mendeleyev.

Mendeleyev (also sometimes spelled Mendeleev or Mendeléef) was born in 1834 at Tobolsk, in the far west of Siberia, into a well-educated, reasonably prosperous, and very large family—so large, in fact, that history has lost track of exactly how many Mendeleyevs there were: some sources say there were fourteen children, some say seventeen. All agree, at any rate, that Dmitri was the youngest. Luck was not always with the Mendeleyevs. When Dmitri was small his father, the headmaster of a local school, went blind and his mother had to go out to work. Clearly an extraordinary woman, she eventually became the manager of a successful glass factory. All went well until 1848, when the factory burned down and the family was reduced to penury. Determined to get her youngest child an education, the indomitable Mrs. Mendeleyev hitchhiked with young Dmitri four thousand miles to St. Petersburg—that's equivalent to traveling from London to Equatorial Guinea—and deposited him at the Institute of Pedagogy. Worn out by her efforts, she died soon after.

Mendeleyev dutifully completed his studies and eventually landed a position at the local university. There he was a competent but not terribly outstanding chemist, known more for his wild hair and beard, which he had trimmed just once a year, than for his gifts in the laboratory.

However, in 1869, at the age of thirty-five, he began to toy with a way to arrange the elements. At the time, elements were normally grouped in two ways—either by atomic weight (using Avogadro's Principle) or by common properties (whether they were metals or gases, for instance). Mendeleyev's breakthrough was to see that the two could be combined in a single table.

As is often the way in science, the principle had actually been anticipated three years previously by an amateur chemist in England named John Newlands. He suggested that when elements were arranged by weight they appeared to repeat certain properties—in a sense to harmonize—at every eighth place along the scale. Slightly unwisely, for this was an idea whose time had not quite yet come, Newlands called it the Law of Octaves and likened the arrangement to the octaves on a piano keyboard. Perhaps there was something in Newlands's manner of presentation, but the idea was considered fundamentally preposterous and widely mocked. At gatherings, droller members of the audience would sometimes ask him if he could get his elements to play them a little tune. Discouraged, Newlands gave up pushing the idea and soon dropped from view altogether.

Mendeleyev used a slightly different approach, placing his elements into groups of seven, but employed fundamentally the same principle. Suddenly the idea seemed brilliant and wondrously perceptive. Because the properties repeated themselves periodically, the invention became known as the periodic table.

Mendeleyev was said to have been inspired by the card game known as solitaire in North America and patience elsewhere, wherein cards are arranged by suit horizontally and by number vertically. Using a broadly similar concept, he arranged the elements in horizontal rows called periods and vertical columns called groups. This instantly showed one set of relationships when read up and down and another when read from side to side. Specifically, the vertical columns put together chemicals that have similar properties. Thus copper sits on top of silver and silver sits on top of gold because of their chemical affinities as metals, while helium, neon, and argon are in a column made up of gases. (The actual, formal determinant in the ordering is something called their electron valences, for which you will have to enroll in night classes if you wish an understanding.) The horizontal rows, meanwhile, arrange the chemicals in ascending order by the number of protons in their nuclei—what is known as their atomic number.

The structure of atoms and the significance of protons will come in a following chapter, so for the moment all that is necessary is to appreciate the organizing principle: hydrogen has just one proton, and so it has an atomic number of one and comes first on the chart; uranium has ninety-two protons, and so it comes near the end and has an atomic number of ninety-two. In this sense, as Philip Ball has pointed out, chemistry really is just a matter of counting. (Atomic number, incidentally, is not to be confused with atomic weight, which is the number of protons plus the number of neutrons in a given element.) There was still a great deal that wasn't known or understood. Hydrogen is the most common element in the universe, and yet no one would guess as much for another thirty years. Helium, the second most abundant element, had only been found the year before—its existence hadn't even been suspected before that—and then not on Earth but in the Sun, where it was found with a spectroscope during a solar eclipse, which is why it honors the Greek sun god Helios. It wouldn't be isolated until 1895. Even so, thanks to Mendeleyev's invention, chemistry was now on a firm footing.

For most of us, the periodic table is a thing of beauty in the abstract, but for chemists it established an immediate orderliness and clarity that can hardly be overstated. "Without a doubt, the Periodic Table of the Chemical Elements is the most elegant organizational chart ever devised," wrote Robert E. Krebs in The History and Use of Our Earth's Chemical Elements, and you can find similar sentiments in virtually every history of chemistry in print.

Today we have "120 or so" known elements—ninety-two naturally occurring ones plus a couple of dozen that have been created in labs. The actual number is slightly contentious because the heavy, synthesized elements exist for only millionths of seconds and chemists sometimes argue over whether they have really been detected or not. In Mendeleyev's day just sixty-three elements were known, but part of his cleverness was to realize that the elements as then known didn't make a complete picture, that many pieces were missing. His table predicted, with pleasing accuracy, where new elements would slot in when they were found.

No one knows, incidentally, how high the number of elements might go, though anything beyond 168 as an atomic weight is considered "purely speculative," but what is certain is that anything that is found will fit neatly into Mendeleyev's great scheme.

The nineteenth century held one last great surprise for chemists. It began in 1896 when Henri Becquerel in Paris carelessly left a packet of uranium salts on a wrapped photographic plate in a drawer. When he took the plate out some time later, he was surprised to discover that the salts had burned an impression in it, just as if the plate had been exposed to light. The salts were emitting rays of some sort.

Considering the importance of what he had found, Becquerel did a very strange thing: he turned the matter over to a graduate student for investigation. Fortunately the student was a recent émigré from Poland named Marie Curie. Working with her new husband, Pierre, Curie found that certain kinds of rocks poured out constant and extraordinary amounts of energy, yet without diminishing in size or changing in any detectable way. What she and her husband couldn't know—what no one could know until Einstein explained things the following decade—was that the rocks were converting mass into energy in an exceedingly efficient way. Marie Curie dubbed the effect "radioactivity." In the process of their work, the Curies also found two new elements—polonium, which they named after her native country, and radium. In 1903 the Curies and Becquerel were jointly awarded the Nobel Prize in physics. (Marie Curie would win a second prize, in chemistry, in 1911, the only person to win in both chemistry and physics.)

At McGill University in Montreal the young New Zealand–born Ernest Rutherford became interested in the new radioactive materials. With a colleague named Frederick Soddy he discovered that immense reserves of energy were bound up in these small amounts of matter, and that the radioactive decay of these reserves could account for most of the Earth's warmth. They also discovered that radioactive elements decayed into other elements—that one day you had an atom of uranium, say, and the next you had an atom of lead. This was truly extraordinary. It was alchemy, pure and simple; no one had ever imagined that such a thing could happen naturally and spontaneously.

Ever the pragmatist, Rutherford was the first to see that there could be a valuable practical application in this. He noticed that in any sample of radioactive material, it always took the same amount of time for half the sample to decay—the celebrated half-life—and that this steady, reliable rate of decay could be used as a kind of clock. By calculating backwards from how much radiation a material had now and how swiftly it was decaying, you could work out its age. He tested a piece of pitchblende, the principal ore of uranium, and found it to be 700 million years old—very much older than the age most people were prepared to grant the Earth.

In the spring of 1904, Rutherford traveled to London to give a lecture at the Royal Institution—the august organization founded by Count von Rumford only 105 years before, though that powdery and periwigged age now seemed a distant eon compared with the roll-your-sleeves-up robustness of the late Victorians. Rutherford was there to talk about his new disintegration theory of radioactivity, as part of which he brought out his piece of pitchblende. Tactfully—for the aging Kelvin was present, if not always fully awake—Rutherford noted that Kelvin himself had suggested that the discovery of some other source of heat would throw his calculations out. Rutherford had found that other source. Thanks to radioactivity the Earth could be—and self-evidently was—much older than the twenty-four million years Kelvin's calculations allowed.

Kelvin beamed at Rutherford's respectful presentation, but was in fact unmoved. He never accepted the revised figures and to his dying day believed his work on the age of the Earth his most astute and important contribution to science—far greater than his work on thermodynamics.

As with most scientific revolutions, Rutherford's new findings were not universally accepted. John Joly of Dublin strenuously insisted well into the 1930s that the Earth was no more than eighty-nine million years old, and was stopped only then by his own death. Others began to worry that Rutherford had now given them too much time. But even with radiometric dating, as decay measurements became known, it would be decades before we got within a billion years or so of Earth's actual age. Science was on the right track, but still way out.

Kelvin died in 1907. That year also saw the death of Dmitri Mendeleyev. Like Kelvin, his productive work was far behind him, but his declining years were notably less serene. As he aged, Mendeleyev became increasingly eccentric—he refused to acknowledge the existence of radiation or the electron or anything else much that was new—and difficult. His final decades were spent mostly storming out of labs and lecture halls all across Europe. In 1955, element 101 was named mendelevium in his honor. "Appropriately," notes Paul Strathern, "it is an unstable element."

Radiation, of course, went on and on, literally and in ways nobody expected. In the early 1900s Pierre Curie began to experience clear signs of radiation sickness—notably dull aches in his bones and chronic feelings of malaise—which doubtless would have progressed unpleasantly. We shall never know for certain because in 1906 he was fatally run over by a carriage while crossing a Paris street.

Marie Curie spent the rest of her life working with distinction in the field, helping to found the celebrated Radium Institute of the University of Paris in 1914. Despite her two Nobel Prizes, she was never elected to the Academy of Sciences, in large part because after the death of Pierre she conducted an affair with a married physicist that was sufficiently indiscreet to scandalize even the French—or at least the old men who ran the academy, which is perhaps another matter.

For a long time it was assumed that anything so miraculously energetic as radioactivity must be beneficial. For years, manufacturers of toothpaste and laxatives put radioactive thorium in their products, and at least until the late 1920s the Glen Springs Hotel in the Finger Lakes region of New York (and doubtless others as well) featured with pride the therapeutic effects of its "Radioactive mineral springs." Radioactivity wasn't banned in consumer products until 1938. By this time it was much too late for Madame Curie, who died of leukemia in 1934. Radiation, in fact, is so pernicious and long lasting that even now her papers from the 1890s—even her cookbooks—are too dangerous to handle. Her lab books are kept in lead-lined boxes, and those who wish to see them must don protective clothing.

Thanks to the devoted and unwittingly high-risk work of the first atomic scientists, by the early years of the twentieth century it was becoming clear that Earth was unquestionably venerable, though another half century of science would have to be done before anyone could confidently say quite how venerable. Science, meanwhile, was about to get a new age of its own—the atomic one.

Chapter 7: Elemental Matters

Discussion Questions

1. What is alchemy? How does it differ from chemistry? How is it the same as chemistry?

2. Summarize the discoveries of Karl Scheele. Why didn't he get any credit for these discoveries?

3. Antione-Laurent Lavoisier is considered the "Father of Chemistry." Describe two of his more important works that could have led to this title.

4. Why did chemistry discoveries stall in the early 1800's?

5. Humphry Davy is a famous for discovering elements. What elements did he discover and what technique did he use to do so?

6. Who wrote the Law of Octaves and how is it applied to the periodic table?

7. Describe two pros and two cons from the discovery of radioactive materials mentioned in this chapter.

9 THE MIGHTY ATOM

WHILE EINSTEIN AND Hubble were productively unraveling the large-scale structure of the cosmos, others were struggling to understand something closer to hand but in its way just as remote: the tiny and ever- mysterious atom.

The great Caltech physicist Richard Feynman once observed that if you had to reduce scientific history to one important statement it would be "All things are made of atoms." They are everywhere and they constitute every thing. Look around you. It is all atoms. Not just the solid things like walls and tables and sofas, but the air in between. And they are there in numbers that you really cannot conceive.

The basic working arrangement of atoms is the molecule (from the Latin for "little mass"). A molecule is simply two or more atoms working together in a more or less stable arrangement: add two atoms of hydrogen to one of oxygen and you have a molecule of water. Chemists tend to think in terms of molecules rather than elements in much the way that writers tend to think in terms of words and not letters, so it is molecules they count, and these are numerous to say thc least. At sea level, at a temperature of 32 degrees Fahrenheit, one cubic centimeter of air (that is, a space about the size of a sugar cube) will contain 45 billion billion molecules. And they are in every single cubic centimeter you see around you. Think how many cubic centimeters there are in the world outside your window—how many sugar cubes it would take to fill that view. Then think how many it would take to build a universe. Atoms, in short, are very abundant.

They are also fantastically durable. Because they are so long lived, atoms really get around. Every atom you possess has almost certainly passed through several stars and been part of millions of organisms on its way to becoming you. We are each so atomically numerous and so vigorously recycled at death that a significant number of our atoms—up to a billion for each of us, it has been suggested—probably once belonged to Shakespcare. A billion more each came from Buddha and Genghis Khan and Beethoven, and any other historical figure you care to name. (The personages have to be historical, apparently, as it takes the atoms some decades to become thoroughly redistributed; however much you may wish it, you are not yet one with Elvis Presley.)

So we are all reincarnations—though short-lived ones. When we die our atoms will disassemble and move off to find new uses elsewhere—as part of a leaf or other human being or drop of dew. Atoms, however, go on practically forever. Nobody actually knows how long an atom can survive, but according to Martin Rees it is probably about 10^{35} years—a number so big that even I am happy to express it in notation.

Above all, atoms are tiny—very tiny indeed. Half a million of them lined up shoulder to shoulder could hide behind a human hair. On such a scale an individual atom is essentially impossible to imagine, but we can of course try.

Start with a millimeter, which is a line this long: -. Now imagine that line divided into a thousand equal widths. Each of those widths is a micron. This is the scale of microorganisms. A typical paramecium, for instance, is about two microns wide, 0.002 millimeters, which is really very small. If you wanted to see with your naked eye a paramecium swimming in a drop of water, you would have to enlarge the drop until it was some forty feet across. However, if you wanted to see the atoms in the same drop, you would have to make the drop fifteen miles across.

Atoms, in other words, exist on a scale of minuteness of another order altogether. To get down to the scale of atoms, you would need to take each one of those micron slices and shave it into ten thousand finer widths. That's the scale of an atom: one ten-millionth of a millimeter. It is a degree of slenderness way beyond the capacity of our imaginations, but you can get some idea of the proportions if you bear in mind that one atom is to the width of a millimeter line as the thickness of a sheet of paper is to the height of the Empire State Building.

It is of course the abundance and extreme durability of atoms that makes them so useful, and the tininess that makes them so hard to detect and understand. The realization that atoms are these three things—small, numerous, practically indestructible—and that all things are made from them first occurred not to Antoine-Laurent Lavoisier, as you might expect, or even to Henry Cavendish or Humphry Davy, but rather to a spare and lightly educated English Quaker named John Dalton, whom we first encountered in the chapter on chemistry.

Dalton was born in 1766 on the edge of the Lake District near Cockermouth to a family of poor but devout Quaker weavers. (Four years later the poet William Wordsworth would also join the world at Cockermouth.) He was an exceptionally bright student—so very bright indeed that at the improbably youthful age of twelve he was put in charge of the local Quaker school. This perhaps says as much about the school as about Dalton's precocity, but perhaps not: we know from his diaries that at about this time he was reading Newton's Principia in the original Latin and other works of a similarly challenging nature. At fifteen, still schoolmastering, he took a job in the nearby town of Kendal, and a decade after that he moved to Manchester, scarcely stirring from there for the remaining fifty years of his life. In Manchester he became something of an intellectual whirlwind, producing books and papers on subjects ranging from meteorology to grammar. Color blindness, a condition from which he suffered, was for a long time called Daltonism because of his studies. But it was a plump book called A New System of Chemical Philosophy, published in 1808, that established his reputation.

There, in a short chapter of just five pages (out of the book's more than nine hundred), people of learning first encountered atoms in something approaching their modern conception. Dalton's simple insight was that at the root of all matter are exceedingly tiny, irreducible particles. "We might as well attempt to introduce a new planet into the solar system or annihilate one already in existence, as to create or destroy a particle of hydrogen," he wrote.

Neither the idea of atoms nor the term itself was exactly new. Both had been developed by the ancient Greeks. Dalton's contribution was to consider the relative sizes and characters of these atoms and how they fit together. He knew, for instance, that hydrogen was the lightest element, so he gave it an atomic weight of one. He believed also that water consisted of seven parts of oxygen to one of hydrogen, and so he gave oxygen an atomic weight of seven. By such means was he able to arrive at the relative weights of the known elements. He wasn't always terribly accurate—oxygen's atomic weight is actually sixteen, not seven—but the principle was sound and formed the basis for all of modern chemistry and much of the rest of modern science.

The work made Dalton famous—albeit in a low-key, English Quaker sort of way. In 1826, the French chemist P .J. Pelletier traveled to Manchester to meet the atomic hero. Pelletier expected to find him attached to some grand institution, so he was astounded to discover him teaching elementary arithmetic to boys in a small school on a back street. According to the scientific historian E. J. Holmyard, a confused Pelletier, upon beholding the great man, stammered:

"Est-ce que j'ai l'honneur de m'addresser à Monsieur Dalton?" for he could hardly believe his eyes that this was the chemist of European fame, teaching a boy his first four rules. "Yes," said the matter-of-fact Quaker. "Wilt thou sit down whilst I put this lad right about his arithmetic?"

Although Dalton tried to avoid all honors, he was elected to the Royal Society against his wishes, showered with medals, and given a handsome government pension. When he died in 1844, forty thousand people viewed the coffin, and the funeral cortege stretched for two miles. His entry in the Dictionary of National Biography is one of the longest, rivaled in length only by those of Darwin and Lyell among nineteenth-century men of science.

For a century after Dalton made his proposal, it remained entirely hypothetical, and a few eminent scientists—notably the Viennese physicist Ernst Mach, for whom is named the speed of sound—doubted the existence of atoms at all. "Atoms cannot be perceived by the senses . . . they are things of thought," he wrote. The existence of atoms was so doubtfully held in the German-speaking world in particular that it was said to have played a part in the suicide of the great theoretical physicist, and atomic enthusiast, Ludwig Boltzmann in 1906.

It was Einstein who provided the first incontrovertible evidence of atoms' existence with his paper on Brownian motion in 1905, but this attracted little attention and in any case Einstein was soon to become consumed with his work on general relativity. So the first real hero of the atomic age, if not the first personage on the scene, was Ernest Rutherford.

Rutherford was born in 1871 in the "back blocks" of New Zealand to parents who had emigrated from Scotland to raise a little flax and a lot of children (to paraphrase Steven Weinberg). Growing up in a remote part of a remote country, he was about as far from the mainstream of science as it was possible to be, but in 1895 he won a scholarship that took him to the Cavendish Laboratory at Cambridge University, which was about to become the hottest place in the world to do physics.

Physicists are notoriously scornful of scientists from other fields. When the wife of the great Austrian physicist Wolfgang Pauli left him for a chemist, he was staggered with disbelief. "Had she taken a bullfighter I would have understood," he remarked in wonder to a friend. "But a chemist . . ."

It was a feeling Rutherford would have understood. "All science is either physics or stamp collecting," he once said, in a line that has been used many times since. There is a certain engaging irony therefore that when he won the Nobel Prize in 1908, it was in chemistry, not physics.

Rutherford was a lucky man—lucky to be a genius, but even luckier to live at a time when physics and chemistry were so exciting and so compatible (his own sentiments notwithstanding). Never again would they quite so comfortably overlap.

For all his success, Rutherford was not an especially brilliant man and was actually pretty terrible at mathematics. Often during lectures he would get so lost in his own equations that he would give up halfway through and tell the students to work it out for themselves. According to his longtime colleague James Chadwick, discoverer of the neutron, he wasn't even particularly clever at experimentation. He was simply tenacious and open-minded. For brilliance he substituted shrewdness and a kind of daring. His mind, in the words of one biographer, was "always operating out towards the frontiers, as far as he could see, and that was a great deal further than most other men." Confronted with an intractable problem, he was prepared to work at it harder and longer than most people and to be more receptive to unorthodox explanations. His greatest breakthrough came because he was prepared to spend immensely tedious hours sitting at a screen counting alpha particle scintillations, as they were known—the sort of work that would normally have been farmed out. He was one of the first to see—possibly the very first—that the power inherent in the atom could, if harnessed, make bombs powerful enough to "make this old world vanish in smoke."

Physically he was big and booming, with a voice that made the timid shrink. Once when told that Rutherford was about to make a radio broadcast across the Atlantic, a colleague drily asked: "Why use radio?" He also had a huge amount of good-natured confidence. When someone remarked to him that he seemed always to be at the crest of a wave, he responded, "Well, after all, I made the wave, didn't I?" C. P. Snow recalled how once in a Cambridge tailor's he overheard Rutherford remark: "Every day I grow in girth. And in mentality."

But both girth and fame were far ahead of him in 1895 when he fetched up at the Cavendish.[1] It was a singularly eventful period in science. In the year of his arrival in Cambridge, Wilhelm Roentgen discovered X rays at the University of Würzburg in Germany, and the next year Henri Becquerel discovered radioactivity. And the Cavendish itself was about to embark on a long period of greatness. In 1897, J. J. Thomson and colleagues would discover the electron there, in 1911 C. T. R. Wilson would produce the first particle detector there (as we shall see), and in 1932 James Chadwick would discover the neutron there. Further still in the future, James Watson and Francis Crick would discover the structure of DNA at the Cavendish in 1953.

In the beginning Rutherford worked on radio waves, and with some distinction—he managed to transmit a crisp signal more than a mile, a very reasonable achievement for the time—but gave it up when he was persuaded by a senior colleague that radio had little future. On the whole, however, Rutherford didn't thrive at the Cavendish. After three years there, feeling he was going nowhere, he took a post at McGill University in Montreal, and there he began his long and steady rise to greatness. By the time he received his Nobel Prize (for "investigations into the disintegration of the elements, and the chemistry of radioactive substances," according to the official citation) he had moved on to Manchester University, and it was there, in fact, that he would do his most important work in determining the structure and nature of the atom.

[1] The name comes from the same Cavendishes who producec Henry. This one was William Cavendish, seventh Duke of Devonshire, who was a gifted mathematician and steel baron in Victoriar England. In 1870, he gave the university £6,300 to build an experimental lab.

By the early twentieth century it was known that atoms were made of parts—Thomson's discovery of the electron had established that—but it wasn't known how many parts there were or how they fit together or what shape they took. Some physicists thought that atoms might be cube shaped, because cubes can be packed together so neatly without any wasted space. The more general view, however, was that an atom was more like a currant bun or a plum pudding: a dense, solid object that carried a positive charge but that was studded with negatively charged electrons, like the currants in a currant bun.

In 1910, Rutherford (assisted by his student Hans Geiger, who would later invent the radiation detector that bears his name) fired ionized helium atoms, or alpha particles, at a sheet of gold foil.[2] To Rutherford's astonishment, some of the particles bounced back. It was as if, he said, he had fired a fifteen-inch shell at a sheet of paper and it rebounded into his lap. This was just not supposed to happen. After considerable reflection he realized there could be only one possible explanation: the particles that bounced back were striking something small and dense at the heart of the atom, while the other particles sailed through unimpeded. An atom, Rutherford realized, was mostly empty space, with a very dense nucleus at the center. This was a most gratifying discovery, but it presented one immediate problem. By all the laws of conventional physics, atoms shouldn't therefore exist.

Let us pause for a moment and consider the structure of the atom as we know it now. Every atom is made from three kinds of elementary particles: protons, which have a positive electrical charge; electrons, which have a negative electrical charge; and neutrons, which have no charge. Protons and neutrons are packed into the nucleus, while electrons spin around outside. The number of protons is what gives an atom its chemical identity. An atom with one proton is an atom of hydrogen, one with two protons is helium, with three protons is lithium, and so on up the scale. Each time you add a proton you get a new element. (Because the number of protons in an atom is always balanced by an equal number of electrons, you will sometimes see it written that it is the number of electrons that defines an element; it comes to the same thing. The way it was explained to me is that protons give an atom its identity, electrons its personality.)

Neutrons don't influence an atom's identity, but they do add to its mass. The number of neutrons is generally about the same as the number of protons, but they can vary up and down slightly. Add a neutron or two and you get an isotope. The terms you hear in reference to dating techniques in archeology refer to isotopes—carbon-14, for instance, which is an atom of carbon with six protons and eight neutrons (the fourteen being the sum of the two).

Neutrons and protons occupy the atom's nucleus. The nucleus of an atom is tiny—only one millionth of a billionth of the full volume of the atom—but fantastically dense, since it contains virtually all the atom's mass. As Cropper has put it, if an atom were expanded to the size of a cathedral, the nucleus would be only about the size of a fly—but a fly many thousands of times heavier than the cathedral. It was this spaciousness—this resounding, unexpected roominess—that had Rutherford scratching his head in 1910.

It is still a fairly astounding notion to consider that atoms are mostly empty space, and that the solidity we experience all around us is an illusion. When two objects come together in the

[2] Geiger would also later become a loyal Nazi, unhesitatingly betraying Jewish colleagues, including many who had helped him.

real world—billiard balls are most often used for illustration—they don't actually strike each other. "Rather," as Timothy Ferris explains, "the negatively charged fields of the two balls repel each other . . . were it not for their electrical charges they could, like galaxies, pass right through each other unscathed." When you sit in a chair, you are not actually sitting there, but levitating above it at a height of one angstrom (a hundred millionth of a centimeter), your electrons and its electrons implacably opposed to any closer intimacy.

The picture that nearly everybody has in mind of an atom is of an electron or two flying around a nucleus, like planets orbiting a sun. This image was created in 1904, based on little more than clever guesswork, by a Japanese physicist named Hantaro Nagaoka. It is completely wrong, but durable just the same. As Isaac Asimov liked to note, it inspired generations of science fiction writers to create stories of worlds within worlds, in which atoms become tiny inhabited solar systems or our solar system turns out to be merely a mote in some much larger scheme. Even now CERN, the European Organization for Nuclear Research, uses Nagaoka's image as a logo on its website. In fact, as physicists were soon to realize, electrons are not like orbiting planets at all, but more like the blades of a spinning fan, managing to fill every bit of space in their orbits simultaneously (but with the crucial difference that the blades of a fan only seem to be everywhere at once; electrons are).

Needless to say, very little of this was understood in 1910 or for many years afterward. Rutherford's finding presented some large and immediate problems, not least that no electron should be able to orbit a nucleus without crashing. Conventional electrodynamic theory demanded that a flying electron should very quickly run out of energy—in only an instant or so—and spiral into the nucleus, with disastrous consequences for both. There was also the problem of how protons with their positive charges could bundle together inside the nucleus without blowing themselves and the rest of the atom apart. Clearly whatever was going on down there in the world of the very small was not governed by the laws that applied in the macro world where our expectations reside.

As physicists began to delve into this subatomic realm, they realized that it wasn't merely different from anything we knew, but different from anything ever imagined. "Because atomic behavior is so unlike ordinary experience," Richard Feynman once observed, "it is very difficult to get used to and it appears peculiar and mysterious to everyone, both to the novice and to the experienced physicist." When Feynman made that comment, physicists had had half a century to adjust to the strangeness of atomic behavior. So think how it must have felt to Rutherford and his colleagues in the early 1910s when it was all brand new.

One of the people working with Rutherford was a mild and affable young Dane named Niels Bohr. In 1913, while puzzling over the structure of the atom, Bohr had an idea so exciting that he postponed his honeymoon to write what became a landmark paper. Because physicists couldn't see anything so small as an atom, they had to try to work out its structure from how it behaved when they did things to it, as Rutherford had done by firing alpha particles at foil. Sometimes, not surprisingly, the results of these experiments were puzzling. One puzzle that had been around for a long time had to do with spectrum readings of the wavelengths of hydrogen. These produced patterns showing that hydrogen atoms emitted energy at certain wavelengths but not others. It was rather as if someone under surveillance kept turning up at particular locations but was never observed traveling between them. No one could understand why this should be.

It was while puzzling over this problem that Bohr was struck by a solution and dashed off his famous paper. Called "On the Constitutions of Atoms and Molecules," the paper explained how electrons could keep from falling into the nucleus by suggesting that they could occupy only certain well-defined orbits. According to the new theory, an electron moving between orbits would disappear from one and reappear instantaneously in another without visiting the space between. This idea—the famous "quantum leap"—is of course utterly strange, but it was too good not to be true. It not only kept electrons from spiraling catastrophically into the nucleus; it also explained hydrogen's bewildering wavelengths. The electrons only appeared in certain orbits because they only existed in certain orbits. It was a dazzling insight, and it won Bohr the 1922 Nobel Prize in physics, the year after Einstein received his.

Meanwhile the tireless Rutherford, now back at Cambridge as J. J. Thomson's successor as head of the Cavendish Laboratory, came up with a model that explained why the nuclei didn't blow up. He saw that they must be offset by some type of neutralizing particles, which he called neutrons. The idea was simple and appealing, but not easy to prove. Rutherford's associate, James Chadwick, devoted eleven intensive years to hunting for neutrons before finally succeeding in 1932. He, too, was awarded with a Nobel Prize in physics, in 1935. As Boorse and his colleagues point out in their history of the subject, the delay in discovery was probably a very good thing as mastery of the neutron was essential to the development of the atomic bomb. (Because neutrons have no charge, they aren't repelled by the electrical fields at the heart of an atom and thus could be fired like tiny torpedoes into an atomic nucleus, setting off the destructive process known as fission.) Had the neutron been isolated in the 1920s, they note, it is "very likely the atomic bomb would have been developed first in Europe, undoubtedly by the Germans."

As it was, the Europeans had their hands full trying to understand the strange behavior of the electron. The principal problem they faced was that the electron sometimes behaved like a particle and sometimes like a wave. This impossible duality drove physicists nearly mad. For the next decade all across Europe they furiously thought and scribbled and offered competing hypotheses. In France, Prince Louis-Victor de Broglie, the scion of a ducal family, found that certain anomalies in the behavior of electrons disappeared when one regarded them as waves. The observation excited the attention of the Austrian Erwin Schrödinger, who made some deft refinements and devised a handy system called wave mechanics. At almost the same time the German physicist Werner Heisenberg came up with a competing theory called matrix mechanics. This was so mathematically complex that hardly anyone really understood it, including Heisenberg himself ("I do not even know what a matrix is ," Heisenberg despaired to a friend at one point), but it did seem to solve certain problems that Schrödinger's waves failed to explain. The upshot is that physics had two theories, based on conflicting premises, that produced the same results. It was an impossible situation.

Finally, in 1926, Heisenberg came up with a celebrated compromise, producing a new discipline that came to be known as quantum mechanics. At the heart of it was Heisenberg's Uncertainty Principle, which states that the electron is a particle but a particle that can be described in terms of waves. The uncertainty around which the theory is built is that we can know the path an electron takes as it moves through a space or we can know where it is at a given instant, but we cannot know both.[3] Any attempt to measure one will unavoidably

[3] There is a little uncertainty about the use of the word uncertainty in regard to Heisenberg's principle. Michael Frayn, in an afterword to his play Copenhagen, notes that several words in German-Unsicherheit, Unscharfe, Unbestimmtheit-have been used by various translators, but that none quite equates to the English uncertainty. Frayn suggests that indeterminacy would be a better word for the principle and indeterminability would be better still.

disturb the other. This isn't a matter of simply needing more precise instruments; it is an immutable property of the universe.

What this means in practice is that you can never predict where an electron will be at any given moment. You can only list its probability of being there. In a sense, as Dennis Overbye has put it, an electron doesn't exist until it is observed. Or, put slightly differently, until it is observed an electron must be regarded as being "at once everywhere and nowhere."

If this seems confusing, you may take some comfort in knowing that it was confusing to physicists, too. Overbye notes: "Bohr once commented that a person who wasn't outraged on first hearing about quantum theory didn't understand what had been said." Heisenberg, when asked how one could envision an atom, replied: "Don't try."

So the atom turned out to be quite unlike the image that most people had created. The electron doesn't fly around the nucleus like a planet around its sun, but instead takes on the more amorphous aspect of a cloud. The "shell" of an atom isn't some hard shiny casing, as illustrations sometimes encourage us to suppose, but simply the outermost of these fuzzy electron clouds. The cloud itself is essentially just a zone of statistical probability marking the area beyond which the electron only very seldom strays. Thus an atom, if you could see it, would look more like a very fuzzy tennis ball than a hard-edged metallic sphere (but not much like either or, indeed, like anything you've ever seen; we are, after all, dealing here with a world very different from the one we see around us).

It seemed as if there was no end of strangeness. For the first time, as James Trefil has put it, scientists had encountered "an area of the universe that our brains just aren't wired to understand." Or as Feynman expressed it, "things on a small scale behave nothing like things on a large scale." As physicists delved deeper, they realized they had found a world where not only could electrons jump from one orbit to another without traveling across any intervening space, but matter could pop into existence from nothing at all—"provided," in the words of Alan Lightman of MIT, "it disappears again with sufficient haste."

Perhaps the most arresting of quantum improbabilities is the idea, arising from Wolfgang Pauli's Exclusion Principle of 1925, that the subatomic particles in certain pairs, even when separated by the most considerable distances, can each instantly "know" what the other is doing. Particles have a quality known as spin and, according to quantum theory, the moment you determine the spin of one particle, its sister particle, no matter how distant away, will immediately begin spinning in the opposite direction and at the same rate.

It is as if, in the words of the science writer Lawrence Joseph, you had two identical pool balls, one in Ohio and the other in Fiji, and the instant you sent one spinning the other would immediately spin in a contrary direction at precisely the same speed. Remarkably, the phenomenon was proved in 1997 when physicists at the University of Geneva sent photons seven miles in opposite directions and demonstrated that interfering with one provoked an instantaneous response in the other.

Things reached such a pitch that at one conference Bohr remarked of a new theory that the question was not whether it was crazy, but whether it was crazy enough. To illustrate the nonintuitive nature of the quantum world, Schrödinger offered a famous thought experiment in which a hypothetical cat was placed in a box with one atom of a radioactive substance attached to a vial of hydrocyanic acid. If the particle degraded within an hour, it would trigger a mechanism that would break the vial and poison the cat. If not, the cat would live. But we could not know which was the case, so there was no choice, scientifically, but to regard the cat as 100 percent alive and 100 percent dead at the same time. This means, as Stephen Hawking has observed with a touch of understandable excitement, that one cannot "predict future events exactly if one cannot even measure the present state of the universe precisely!"

Because of its oddities, many physicists disliked quantum theory, or at least certain aspects of it, and none more so than Einstein. This was more than a little ironic since it was he, in his annus mirabilis of 1905, who had so persuasively explained how photons of light could sometimes behave like particles and sometimes like waves—the notion at the very heart of the new physics. "Quantum theory is very worthy of regard," he observed politely, but he really didn't like it. "God doesn't play dice," he said.[4]

Einstein couldn't bear the notion that God could create a universe in which some things were forever unknowable. Moreover, the idea of action at a distance—that one particle could instantaneously influence another trillions of miles away—was a stark violation of the special theory of relativity. This expressly decreed that nothing could outrace the speed of light and yet here were physicists insisting that, somehow, at the subatomic level, information could. (No one, incidentally, has ever explained how the particles achieve this feat. Scientists have dealt with this problem, according to the physicist Yakir Aharanov, "by not thinking about it.")

Above all, there was the problem that quantum physics introduced a level of untidiness that hadn't previously existed. Suddenly you needed two sets of laws to explain the behavior of the universe—quantum theory for the world of the very small and relativity for the larger universe beyond. The gravity of relativity theory was brilliant at explaining why planets orbited suns or why galaxies tended to cluster, but turned out to have no influence at all at the particle level. To explain what kept atoms together, other forces were needed, and in the 1930s two were discovered: the strong nuclear force and weak nuclear force. The strong force binds atoms together; it's what allows protons to bed down together in the nucleus. The weak force engages in more miscellaneous tasks, mostly to do with controlling the rates of certain sorts of radioactive decay.

The weak nuclear force, despite its name, is ten billion billion billion times stronger than gravity, and the strong nuclear force is more powerful still—vastly so, in fact—but their influence extends to only the tiniest distances. The grip of the strong force reaches out only to about 1/100,000 of the diameter of an atom. That's why the nuclei of atoms are so compacted and dense and why elements with big, crowded nuclei tend to be so unstable: the strong force just can't hold on to all the protons.

The upshot of all this is that physics ended up with two bodies of laws—one for the world of the very small, one for the universe at large—leading quite separate lives. Einstein disliked that, too. He devoted the rest of his life to searching for a way to tie up these loose ends by finding a grand unified theory, and always failed. From time to time he thought he had it, but it always unraveled on him in the end. As time passed he became increasingly marginalized and even a little pitied. Almost without exception, wrote Snow, "his colleagues thought, and still think, that he wasted the second half of his life."

[4] Or at least that is how it is nearly always rendered. The actual quote was: "It seems hard to sneak a look at God's cards. But that He plays dice and uses 'telepathic' methods. . . is something that I cannot believe for a single moment."

Elsewhere, however, real progress was being made. By the mid-1940s scientists had reached a point where they understood the atom at an extremely profound level—as they all too effectively demonstrated in August 1945 by exploding a pair of atomic bombs over Japan.

By this point physicists could be excused for thinking that they had just about conquered the atom. In fact, everything in particle physics was about to get a whole lot more complicated. But before we take up that slightly exhausting story, we must bring another straw of our history up to date by considering an important and salutary tale of avarice, deceit, bad science, several needless deaths, and the final determination of the age of the Earth.

Chapter 9: The Mighty Atom

Discussion Questions

1. Atoms and molecules are very small. How many molecules of sugar are in one sugar cube and explain what this means for the studying of chemistry?
2. Describe how atoms are "recycled" and how can chemical reactions happen if atoms are not created or destroyed?
3. What are the contributions John Dalton made to the study of chemistry?
4. Describe the experiment that Ernest Rutherford and Hans Geiger did with ionized helium atoms. What did it teach them about the structure of the atom?
5. In what way is it correct to say that objects never really touch each other?
6. What is the role of neutrons in an atom and what function do they serve for the nucleus of the atom?
7. Describe Shrodinger's cat experiment and how did this hypothetical experiment affect Stephen Hawking's stance on the universe?
8. In what two ways did Feynman state things on a small scale do not behave like things on a large scale?