RANDOM HOUSE eBOOKS

The Magic Furnace

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About the Author

Marcus Chown is *New Scientist*'s cosmology consultant. He is the author of *Afterglow of Creation*, which was runner-up for the Rhône-Poulenc Science Book Prize, and was the winner of the 1994 Glaxo Wellcome ABSW Science Writers' Award.

ALSO BY MARCUS CHOWN

Afterglow of Creation

To my dad and mum, who never doubted I would be Albert Einstein, win the Nobel prize and punch out a bestseller.

Marcus Chown

THE MAGIC FURNACE

The Search for the Origins of Atoms

VINTAGE

Prologue

THE COSMIC CONNECTION

> I believe a leaf of grass is no less than the journeywork of the stars.
>
> Walt Whitman

EVERY BREATH YOU take contains atoms forged in the blistering furnaces deep inside stars. Every flower you pick contains atoms blasted into space by stellar explosions that blazed brighter than a billion suns. Every book you read contains atoms blown across unimaginable gulfs of space and time by the wind between the stars.

Astronomers often talk glibly of black holes and exploding stars, pulsars, quasars and the titanic eruption of the big bang. But if the truth be told it is extremely difficult to believe that any of these things are actually real – as real, for instance, as a mountain or an oak tree or a newborn baby. They are simply too remote, too far removed from the familiar world of our experience. It seems inconceivable that they could have the slightest connection with our everyday lives.

But this is an illusion.

Many of the most dramatic and awe-inspiring of cosmic events – from the violent death throes of stars to the titanic fireball that gave birth to the entire universe 15 billion years ago – are connected to us *directly* by way of the atoms that make up our bodies.

If the atoms that make up the world around us could tell their stories, each and every one of them would sing a tale to dwarf the greatest epics of literature. From carbon, baked in bloated red giants – stars so enormous they could swallow a million suns – to uranium, cooked in supernova explosions – just about the most violent cataclysms in all of creation. From boron, generated in atom-crunching collisions in the deep-freeze of interstellar space, to helium, forged in the hellish first few minutes of the big bang itself.

The iron in your blood, the calcium in your bones, the oxygen that fills your lungs each time you take a breath – all were baked in the fiery ovens deep within stars and blown into space when those stars grew old, and perished. Every one of us is a memorial to long-dead stars. Every one of us was quite literally made in heaven.

For thousands of years, astrologers have been telling us that our lives are controlled by the stars. Well, they were right in spirit if not in detail. For science in the twentieth century has revealed that we are far more intimately connected to events in the cosmos than anyone ever dared imagine. Each and every one of us is stardust made flesh.

The story of how we discovered the astonishing truth of our cosmic origins – how we found the magic furnace that forged the atoms – is one of the great untold stories of science. In fact, it is two stories intertwined: the story of atoms and the story of stars. Neither story can be told without the other. For the stars contain the key to unlocking the secret of atoms and the atoms the solution to the puzzle of stars.

The story of the quest for the origin of atoms is the story of two great theories, and the pendulum that has swung back and forth between them. One theory maintained that atoms were cooked inside stars then ejected into space to provide the raw material for new suns and new planets, while the other theory contended that atoms were assembled at the very birth of the universe, in the first blisteringly hot minutes of the big bang.

At first the pendulum swung to stars as the most likely site of the elusive magic furnace. Then, when it appeared that stars were simply not hot enough for the job of cooking atoms, the pendulum swung to the big bang. When the big bang turned out not to be up to the job either, the pendulum swung back to stars again – or at least most of the way to stars. For nature, as we are so often reminded, is under no obligation to make things simple just for our convenience.

But before we were in any position to discover the cosmic origin of atoms, we first needed to realise that atoms were actually made and not put in the universe on Day One by the Creator. And before we could realise this truth we needed to realise something even more basic and far from obvious: that everything is made of atoms …

Part One

Atoms

1
The Alphabet of Nature

HOW WE DISCOVERED THAT EVERYTHING ON EARTH IS MADE OF ATOMS.

> If in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? Everything is made of atoms.
>
> Richard Feynman

> To see a world in a grain of sand
> And a heaven in a wild flower,
> Hold infinity in the palm of your hand
> And eternity in an hour.
>
> William Blake

IN THE MISTS of antiquity, it must have occurred to many people to ask the question: what happens if I take this stick, this piece of cloth, this clay tablet, and cut it in half, then in half again? Can I go on forever? Or will I eventually reach a point when I will be unable to cut it any smaller? The first person to record an answer to this question was the Greek philosopher Democritus.

Little is known about Democritus. His ideas have come down to us solely through the writings of others. He was born around 470 BC, but no one knows quite where. He travelled extensively throughout the Mediterranean and founded a school at Abdera in Thrace. Nowadays, the site is occupied by the Greek town of Avdhira near the border with Bulgaria, but in the fifth century BC it was a prosperous and bustling port on the shores of the Aegean.

Democritus was obsessed by a single question: what is the nature of matter? The question had first been posed more than a century earlier by Thales of Miletus, the founding father of Greek philosophy, but its imprecise wording had prevented a satisfactory answer. Democritus' genius was to refine Thales' question. In the course of relentless, exhausting discussions with his teacher, Leucippus, he transformed what was a vague enquiry into a question of exquisite precision for which there could be only two alternative answers: Could matter be subdivided forever?

Democritus' answer was an emphatic *no*. It was absolutely inconceivable to him that any material object could be cut into smaller and smaller parts without limit. Sooner or later, he reasoned, such a cleaving process must result in a grain of matter that could not be made any smaller. Since the Greek phrase for 'uncuttable' was *a-tomos*, Democritus christened the indestructible grains out of which everything was made 'atoms'. 'By convention there is sweet, by convention there is bitterness, by convention hot and cold, by convention colour,' he wrote. 'But in reality there are only atoms and the void.'

Atoms and the void.

The idea instantly made sense of several features of the world that were inexplicable if matter were continuous rather than grainy. Where, for instance, did salt go when it was stirred into a pot of warm water? If Democritus was right, it simply disintegrated into its constituent atoms which then lodged themselves in the empty spaces between the atoms of water. The atomic idea also explained how it was possible for fish to swim through the sea. If water was a continuous material, there would be no gaps for a fish to slip through. However, if the world was made of atoms separated by empty space, the tip of a fish's nose could slip between the atoms of the water, parting the liquid like a curtain as the fish swam forward.

There was no doubt that atoms could explain some puzzling phenomena. But in truth they were merely one man's daydreams. Atoms, if they really existed, were far too small to be perceived directly by the senses. How then would it ever be possible to establish their reality? Fortunately, there was a way.

The trick was to assume that atoms existed, then deduce a logical consequence of this assumption for the everyday world. If the consequence matched reality, then the idea of atoms was given a boost. If it did not, then it was time to look for a better idea.

In fact, this was precisely the same kind of argument that Democritus had used to support his revolutionary idea. By first assuming that atoms existed, he had deduced that salt should dissolve in water and that fish should have no difficulty swimming through the sea, two observations that both accorded with reality.

However, the ability of different substances to penetrate each other was merely a 'quality' of matter. If the idea of atoms were to be put on a firmer footing it would be necessary to deduce from the existence of atoms some measurable property of matter – a 'quantity' that could be gauged with a ruler or a set of scales or some other kind of measuring instrument. However, deducing a precise property of matter was impossible without a precise picture of atoms.

Democritus had envisaged free atoms as flying about ceaselessly through empty space. What was needed therefore was a precise picture of how atoms flew about through space. Such a picture required a knowledge of the laws that governed all motion. However, their formulation was well beyond the capabilities of Democritus. It would have to await the rise of science.

THE RISE OF SCIENCE

The Greeks, for all their dazzling brilliance, did not invent science. Although thinkers such as Democritus speculated endlessly about the great overarching principles that controlled the cosmos, they were fatally handicapped by a reluctance to test their speculations by prodding and probing the world around them. At the other end of the spectrum were the craftsmen, who fired and glazed pottery, who forged weapons out of bronze and iron. They prodded and probed the world but were handicapped by their reluctance to speculate about the principles that governed their craft.

For thousands of years the two traditions remained quite separate – the scholarly tradition, epitomised by those who theorised about the world but avoided getting their hands dirty, and the craft tradition, typified by those who obtained their knowledge of the world from solid hands-on experience but who developed no theory of what they were doing that might indicate better ways of doing it.

The two traditions were like two great rivers rolling down to the sea. Their eventual convergence might have been expected to create a bigger, more powerful river. What it in fact created was an overwhelming, unstoppable flood.

The third tradition, which emerged from the union of the scholarly and craft traditions, was of course science.

Science was an immensely powerful method of investigating the world. It involved carrying out careful experiments, with nature itself as the ultimate arbiter of which theories were right and which were wrong. In the sixteenth and seventeenth centuries, the revolutionary new method began to be practised by a small band of far-sighted men, few of whom at first recognised the power of the tool they were wielding. Of this small band, none used the tool to greater effect than Isaac Newton.

THE LAWS OF MOTION

Just as all roads once led to Rome, all paths in science invariably lead back to Newton, arguably the most powerful intellect the world has known. ‘Nature was to him an open book, whose letters he could read without effort,’ wrote Albert Einstein. Newton viewed the universe as a giant riddle set by the Creator which might be cracked by the relentless application of pure thought. In this task he was aided by almost superhuman powers of concentration, which enabled him to hold an abstract problem in the forefront of his mind for weeks until it finally yielded its secrets. Like the Greek philosophers before him, Newton attempted to discern the universal principles that governed the world. Unlike Democritus and his contemporaries, however, he carried out experiments both to test his theories and to discover new phenomena.

Newton’s investigations into the way bodies moved led him to his famous ‘laws of motion’, which govern how massive objects respond when subjected to forces. By applying the laws to the everyday world, Newton was able to explain the fall of weights dropped from tall towers, the flight of cannon balls shot through the air and the recoil of bowling balls involved in head-on collisions.

But Newton did not stop here. He took his laws of motion and carried them to an entirely different domain: the domain of the solar system, where very large bodies such as the moon and planets moved under the influence of the invisible but all-pervasive force of gravity. In doing so, Newton was able to explain why the moon raises tides twice a day in the world’s oceans, and why the planets trace out elliptical paths around the sun.

In fact, so successful were Newton’s laws of motion that they became a standard part of the tool-kit of science. One man who used them to brilliant effect was the eighteenth-century Swiss mathematician Daniel Bernoulli. If Newton’s genius was to take his laws of motion and apply them to the domain of the very large, Bernoulli's was to apply them to the domain of the very small: to the world of atoms.

ATOMS IN MOTION

Bernoulli is most famous for his discovery that the 'pressure' of a liquid or gas drops when it is forced to flow rapidly. The 'Bernoulli effect' is exploited every day by aircraft whose wings are shaped so that air flows faster over their top surfaces than their bottom surfaces. It is the excess of pressure pushing upwards on a wing that provides the 'lift' necessary for heavier-than-air flight.

But Bernoulli did a lot more than simply pioneer the field of 'fluid flow'. He also carried out a ground-breaking investigation of atoms and their consequences for the measurable properties of matter. Bernoulli had not the slightest idea what atoms looked like, or even how big they were. However, he had one big advantage over Democritus. He knew that free atoms were more than simply tiny grains flying about through space; they were tiny grains flying about through space and obeying Newton's laws of motions. To make the most of this insight, Bernoulli needed to find a situation in nature where a precise knowledge of the way in which atoms flew about might lead to a prediction of a measurable property of matter. He identified one in the case of a gas, which he visualised as a host of tiny grains in perpetual frenzied motion like a swarm of angry bees.

Bernoulli's brainwave was to realise that the atoms of such a gas would hammer relentlessly on the walls of any containing vessel. The effect of each individual impact would of course be vanishingly small. However, the effect of billions upon billions of atoms hammering away incessantly would be to push the walls back. A gas made of atoms would therefore exert a jittery force which our coarse senses would feel as an average push or ‘pressure’.

This was Bernoulli’s great insight: to connect the small-scale behaviour of the atoms of a gas to its large-scale pressure.

The pressure of a gas such as steam was easy to measure. It was necessary only to introduce the steam into a hollow cylinder containing a ‘piston’. In essence this was a movable wall which could travel up and down the cylinder in response to the pressure of the steam. The farther the piston moved along the cylinder, the higher was the steam pressure. The pressure of a gas provided a direct link between the world of human experience – where pistons could actually be seen to move – and the invisible world of atoms. But to make the link explicit, Bernoulli needed to use his picture of drumming atoms to deduce how the pressure of a gas should behave in different circumstances – for instance, if the gas was compressed or heated.

Bernoulli first made some simplifying assumptions. For instance, he assumed that atoms were very small compared with the gulf between them. This turns out to be a very good assumption. On average the atoms in the air around us are separated by several hundred times their diameters. If the atoms of a gas were blown up to the size of tennis balls, for instance, there would be barely 100 flying about in the volume of a large hall. The assumption that the atoms in a gas are a long way apart enabled Bernoulli to ignore any force that existed between them; any such a force – whether of attraction or repulsion – was unlikely to be long-range.[1] With the motion of each atom unaffected by its fellows, Newton’s laws ordained that it should fly at a constant speed in a straight line. The exception to this was of course when it slammed into a piston or the walls of a container. Bernoulli assumed that in such a collision a gas atom simply bounced off the surface without losing any speed whatsoever, in the process imparting a minuscule force to the wall.

Bernoulli now asked himself: what would happen to the pressure of a gas in a cylinder if someone squeezed the gas by pushing in the piston? To answer the question, he imagined pushing such a piston until the gas was compressed into half its original volume. Since the gas atoms would now have to fly only half as far as before between collisions, in any given interval of time they would collide with the piston twice as many times. Consequently, they would exert double the pressure. Similarly, if the gas were compressed to a third of its volume, its pressure would triple. This was exactly the way a real gas behaved. It had been observed by the English scientist Robert Boyle in 1660, and been named Boyle's law in his honour.

Bernoulli next asked: what would happen to the pressure of a gas in a cylinder if the gas was heated while its volume was left unchanged?

To answer this question, he exploited a remarkable insight which would not be generally accepted by the rest of the scientific community for more than a century. His insight was that the temperature of a gas was merely a measure of how fast on average its atoms were flying about. When a gas was heated, its atoms were simply speeded up.

Bernoulli imagined heating the steam in a cylinder with the piston in place. Since the atoms would now be moving faster, they would collide with the piston more often and with greater force. Consequently, the pressure of the gas would rise. This would be obvious to anyone trying to hold the piston in place because they would have to struggle harder to keep it from moving along the cylinder. Once again, this was precisely the way that a real gas behaved. It had been observed by the French scientist Jacques Alexandre César Charles in 1787, and christened Charles's law.

Bernoulli had triumphantly predicted two measurable properties of a gas – the way its pressure went up when its volume went down and the way its pressure went up when its temperature went up. And he had done it by simply assuming that a gas consisted of countless atoms which flew hither and thither and drummed on the walls of their containing vessel like hailstones on a tin roof. In the words of Piet Hein:

> Nature, it seems, is the popular name
> for millards and millards and millards
> of particles playing their infinite game
> of billards and billards and billards.

In the late nineteenth century, Bernoulli's method of deducing the properties of a gas from the collective behaviour of all of its atoms was taken to its logical conclusion by both James Clerk Maxwell in Britain, and Ludwig Boltzmann in Germany. But although Maxwell and Boltzmann's work provided the most convincing evidence yet that the world was composed of tiny grains of matter, the existence of atoms was far from generally accepted and remained the subject of intensely bitter debate well into the twentieth century.

Those who disputed the existence of atoms had strong convictions about what did and did not constitute science. The conviction, held most notably by the Austrian physicist Ernst Mach, was that science had no business to be concerning itself with any feature of the world which could not be observed directly with the senses.[2] Since nobody had actually *seen* an atom – nor were they ever likely to – Mach maintained that the whole atomic concept was unscientific and should be ruthlessly rooted out of science. When an army of scientific zealots, inspired by Mach's view, mounted a savage crusade against the proponents of atoms, it all proved too much for Boltzmann. Prone to bouts of depression and born with one skin too few, he succumbed to the pressure and committed suicide while on holiday in 1906.

Ironically, the final proof of the existence of atoms had come the year before Boltzmann took his life. It was provided by an obscure clerk in the Swiss patent office. His name was Albert Einstein.

THE CRAZY DANCE OF POLLEN GRAINS

The year 1905 was a miraculous year for the 25-year-old Einstein. In the space of twelve months, he published four trail-blazing papers. One was on the revolutionary new theory of 'special relativity' which redefined space and time; a second showed how to deduce the size of molecules from the behaviour of liquids; a third addressed the particle-like nature of light. The fourth paper has been a little overshadowed by the others but was nevertheless enormously significant. For it proved, once and for all, the reality of atoms. More specifically, it made sense of a baffling observation made almost a century earlier by a Scottish botanist called Robert Brown.

Brown, who had sailed to Australia on the Flinders expedition of 1801, had classified 4000 species of antipodean plants, in the process discovering the 'nucleus' of living cells. But his greatest discovery had come in 1827. While looking through a microscope at pollen grains floating in water, he was amazed to see that the grains were jiggling about as if something was repeatedly kicking them. The behaviour became known as 'Brownian motion'. He could think of no plausible explanation and nor could anyone else.

Einstein's genius was to realise that each pollen grain was indeed being kicked – by atoms or, more precisely, by molecules of water.[3] At a mere thousandth of a millimetre across, a pollen grain was small enough to be jostled by the very building blocks of matter. It was as if a giant inflatable rubber ball, taller than a person, was being pushed about a field by a large number of people. If each person was pushing in their own direction, without the slightest regard to their companions, at any instant there were likely to be slightly more people on one side than on the other. The imbalance would be enough to cause the ball to move erratically about the field. Similarly, the erratic motion of a pollen grain could be explained if at every moment there were slightly more water molecules bombarding it from one side than from another.

Einstein devised a mathematical theory to describe Brownian motion. Its predictions were triumphantly confirmed three years later by the French scientist Jean-Baptiste Perrin who, for convenience, replaced pollen grains with particles of gamboge, a yellow gum resin from a Cambodian tree.

Einstein's theory predicted how far and how fast the average pollen grain should travel in response to the relentless battering it was receiving from water molecules all around. Everything hinged on the size of the water molecules; the bigger they were, the bigger would be the imbalance of forces on a pollen grain, and the more exaggerated its consequent Brownian motion.

By comparing his observations of gamboge particles through a microscope with the predictions of Einstein's theory, Perrin was able to deduce the size of water molecules, and hence of the atoms out of which they were built. His conclusion was that atoms were only about a 10 billionth of a metre across – so small that it would take 10 million, arranged end to end, to span the width of a full stop on this page. Einstein and Perrin had found the most direct evidence yet for the existence of atoms. No one who peered into a microscope and saw the crazy dance of pollen grains under relentless machine-gun bombardment could now doubt that the world was really made from tiny, bullet-like particles.

But Brownian motion revealed only the combined effect of large numbers of particles on bodies which were far larger than atoms. The fundamental building blocks of all matter remained stubbornly out of sight.

Atoms were a mere 10 millionth of a millimetre across. The possibility of seeing them directly might be entertained by science-fiction writers, but not by reputable scientists. Science fiction, however, has a peculiar habit of coming true. In 1980, two physicists in Switzerland invented and built one of the most remarkable instruments in the history of science. Using it, Gerd Binnig and Heinrich Rohrer became the first people in history to actually ‘see’ an atom.

SEEING ATOMS

The instrument that fulfilled Democritus’ 2000-year-old dream was called the ‘scanning tunnelling microscope’, or STM for short. It was born in the autumn of 1978 when Binnig, a 31-year-old German doctoral student, was putting the finishing touches to his thesis at Wolfgang Goethe University in Frankfurt.

Binnig was interested in the surfaces of ‘semiconductor’ materials such as silicon, which formed the foundations of computer chips. It was an interest which happened to be shared by Heinrich Rohrer, a middle-aged Swiss physicist who was visiting Binnig’s university from IBM’s research laboratory in Zurich. When the two men bumped into each other one day, their conversation turned to the prospects of ever being able to see the fine details of surfaces like silicon. Such a feat, if possible, would be a boon to computer manufacturers, who were constantly trying to shrink transistors and other electronic components and pack them closer together on the surface of chips. In this task, they were severely hampered by their ignorance of what such surfaces looked like on a very small scale. They were like gods who towered above the miniature landscape of their world but whose eyes were hopelessly blindfolded.

But even a blindfolded god has one means open to him to determine the lie of the land. He can use his sense of touch to feel the ups and downs of hills and valleys, and in this way build up a mental picture of the landscape. By running a giant finger over the ground, he might even be able to sense features as small as trees and buildings. Using a finger to explore the submicroscopic landscape of a material like silicon might seem a little fanciful. But, in essence, this was the idea that occurred to Binnig as he talked with Rohrer. Instead of a finger of flesh and blood, however, he envisioned a finger of metal – a very fine needle, like the stylus of an old-fashioned record player.

Of course, there was no way a needle could actually feel a surface like a human finger. However, if the needle were charged with electricity and placed extremely close to the surface of a metal or semiconductor, a minuscule, but measurable, electric current would leap the gap between the tip of the needle and the surface. It was known as a ‘tunnelling current’, and it had a crucial property which Binnig realised might be exploited: the current was extraordinarily sensitive to the width of the gap. If the needle were moved even a shade closer to the surface, the current would grow very rapidly; if it were pulled away a fraction, the current would plummet. The size of the tunnelling current therefore revealed the distance between the needle tip and the surface: it gave the needle an artificial sense of touch.

Rohrer was so impressed by Binnig’s idea that he invited him to Zurich to transform it into reality. It was the start of an immensely productive partnership which would ultimately lead Binnig and Rohrer to Stockholm to receive the 1986 Nobel prize for physics.

The first problem was to find a needle fine enough to feel the submicroscopic details of a surface. A needle is insensitive to features much smaller than itself, just as a finger is insensitive to the fine grooves on an old-fashioned vinyl record. Common sense therefore implied that a needle tip which could feel the undulations of individual atoms would itself have to be only a few atoms across. Unfortunately, this was hundreds of times finer than the finest needle in existence. However, in 1979, Binnig made a remarkable discovery. He found that the tunnelling current leapt to a metal surface from only a tiny patch of atoms at the very tip of the needle. It meant that a needle was actually tens of times sharper than it appeared. In fact, when Binnig and Rohrer made needles out of the metal tungsten, they discovered that the tips invariably consisted of a protruding clump of only a few atoms. With such needles it would be possible to sense features smaller than either man had ever dared hope.

But turning Binnig's idea into reality required more than an ultra-fine needle. It required an elaborate scaffolding of springs and shock absorbers to hold the needle just a whisker above the surface of a material and isolate it from stray vibrations. On the scale of atoms, even the footsteps of someone in the same building or the passage of a car down a nearby street would seem like a major earthquake. To control the height of the needle, Binnig and Rohrer exploited the tunnelling current itself. They arranged that if the current fell the needle would be automatically lowered and if the current grew the needle would be pulled up. In this way, Binnig and Rohrer were able to keep their needle at a constant height as it tracked back and forth across the surface of a material.

It was as if lightning flickered from the finger of a god to the ground. If he lifted his finger too high, the lightning died away until he had no sense of the surface; if he moved it too close, the lightning grew to a painful intensity. By keeping the lightning crackling at a tolerable level, he was able to follow the ups and downs of the terrain with his finger.

A god had the option of building up a picture of the miniature landscape in his imagination. However, no such possibility was open to Binnig and Rohrer. Instead, the two physicists had to resort to a computer to convert the up-and-down motion of their needle into a visual image. When they did so, what they saw on their computer screen in Zurich took their breath away.

It was one of the most remarkable images in the history of science. It was an image to rank with the image of the earth rising above the grey desolation of the moon, or with the sweeping spiral staircase of DNA. For it was the first ever picture of the invisible realm that underpinned the everyday world. Here, at long last, were atoms in all their microscopic glory.[4] They looked like tiny footballs. They looked like oranges, stacked in boxes row on row. But, most of all, they looked like the tiny hard grains of matter which one man had seen so clearly in his mind's eye two and a half thousand years earlier.

The scanning tunnelling microscope revealed Democritus' tiny motes of matter, whose graininess explained where salt went when it dissolved in water and how fish swam through the sea. It revealed Bernoulli's hard little balls, whose relentless hammering on a piston made sense of the behaviour of a gas. It revealed Einstein's tiny bullet-like particles, whose machine-gun bombardment of pollen grains explained the frenetic dance of Brownian motion. But, for all its spectacular success, the scanning tunnelling microscope revealed only one side of atoms. As Democritus himself had realised, atoms were a lot more than simply grains in motion.

THE ALPHABET OF NATURE

Democritus had imagined atoms coming in a number of different kinds – which differed in their size and shape and perhaps their weight. By arranging these various types in different patterns, it was possible to make a rose, a bar of gold or a human being. Atoms, in short, were the alphabet of nature. If Democritus was right, the bewildering complexity of the world was nothing more than an elaborate illusion. It was merely a consequence of the myriad ways in which a handful of fundamental building blocks of matter could be put together.

It was one of the most breathtaking leaps of the imagination in history. With the power of thought alone, Democritus had lifted a corner of the veil that shrouded the world from our senses. He had found that, underneath it, reality was remarkably simple.

The key step in proving such a revolutionary idea would of course be identifying the different kinds of atom. However, the fact that atoms were far too small to be perceived directly by the senses made the task every bit as formidable as proving that atoms were tiny grains of matter in ceaseless motion. In the circumstances, the only possibility was to find substances that were made exclusively of atoms of a single kind.

Identifying such 'elemental' substances was unlikely to be easy. After all, the whole basis of Democritus' atomic thesis was that the complexity of the world reflected the endless combinations of its basic building blocks. The likelihood was therefore that most elemental substances were bound together with other elemental substances and that very few were actually in their pure state.

The Greeks had considered the primary constituents of the world to be water, air, earth and fire. However, in reality, none of these, apart from water, was even close to being elemental. It would be left to others, equally wrong in their beliefs, to inadvertently identify the real primary constituents of matter. These were the alchemists who, during the Middle Ages, struggled heroically to ‘transmute’ base substances like lead into precious substances like gold. In the process, the alchemists accumulated a wealth of information about how substances combined with each other. In attaining their stated goal, however, they failed utterly. It was impossible to turn lead into gold. But this in itself was an important discovery, had the alchemists only recognised it. It was a strong indication that some substances were truly permanent and indestructible. All that was needed was for someone to draw the right conclusion. The man who did so was Antoine Lavoisier, a French aristocrat whose life was ended by the guillotine in the spring of 1794.

Five years before his death, Lavoisier compiled the first list of substances which he believed could not, by any means, be broken down into simpler substances. Lavoisier’s list consisted of 23 ‘elements’. Some later turned out not to be elements at all but many were indeed elemental. They included sulphur and mercury, iron and zinc, silver and gold. Lavoisier’s scheme was a turning point in the history of science. It signalled the death of alchemy and the birth of chemistry. The practitioners of the new science took as their starting point the existence of nature’s elements and sought to combine these into new patterns. In doing so, they created ‘compound’ substances which had never before existed in the world. For chemists everything was in the combinations. And, because of the endless number of ways of combining nature’s elements, in twos and threes and fours and so on, chemistry was a science with infinite possibilities.

In all likelihood each of Lavoisier’s elements was a great mass of one kind of atom. However, the French chemist did not explicitly connect the concept of elements with the concept of atoms. This was left to an English schoolmaster and amateur scientist called John Dalton. In 1803, Dalton noticed that when elements combined to make a compound, they always did so in fixed proportions. For instance, when oxygen and hydrogen united to make water, precisely 8 grams of oxygen was used up for every 1 gram of hydrogen.[5] It was Dalton's genius to see in this simple observation the unmistakable fingerprint of invisible atoms combining with each other.

The observation was exactly what you would expect, Dalton reasoned, if oxygen consisted of large numbers of oxygen atoms, all identical, and hydrogen large numbers of hydrogen atoms, again all identical, and that the formation of water from oxygen and hydrogen involved the two kinds of atoms colliding and sticking to make large numbers of particles of water. Today, we call such particles 'molecules'. Since water has an identity as distinctive as either oxygen or hydrogen, it followed that water molecules were all identical. In other words, they each contained a fixed number of oxygen atoms and a fixed number of hydrogen atoms. Now if oxygen atoms all had a certain weight which was unique to oxygen and hydrogen atoms had a certain weight which was unique to hydrogen, then a fixed number of oxygen atoms translated into a fixed weight of oxygen atoms and a fixed number of hydrogen atoms translated into a fixed weight of hydrogen atoms. Each water molecule must therefore contain the same weight of oxygen atoms relative to hydrogen atoms.

Here then was the reason why the 'law of fixed proportions' applied to water. It was merely a reflection of the fact that each molecule of water contained a fixed number of oxygen atoms and a fixed number of hydrogen atoms.

If, say, the oxygen atoms in a single water molecule weighed 8 times as much as its hydrogen atoms, then the oxygen atoms in a million water molecules would still weigh 8 times as much as the hydrogen atoms in a million water molecules. It was irrelevant how much water was involved – the same factor would always hold. The observation that water used up 8 grams of oxygen for every gram of hydrogen therefore indicated that the oxygen atoms in a single water molecule weighed 8 times as much as the hydrogen atoms.

Dalton hazarded a guess that each water molecule contained just one oxygen atom bound to one hydrogen atom. It enabled him to conclude that an oxygen atom must weigh 8 times as much as a hydrogen atom. He was wrong. Today, everyone knows that the formula for water is H_2O and that each water molecule in fact contains two atoms of hydrogen and one atom of oxygen. Rather than being 8 times as heavy as a hydrogen atom, an oxygen atom is actually 16 times as heavy. However, this minor error affected none of Dalton's reasoning.

The law of fixed proportions holds because a compound consists of a large number of identical molecules, each made of a fixed number of atoms of each component element. Just as Bernoulli had seen the unmistakable fingerprint of the atom in motion in the behaviour of a gas, Dalton had seen the fingerprint of the interacting atom in the way elements combined with each other.

Now two entirely different lines of reasoning had yielded independent evidence of atoms. Everything in the garden seemed rosy. However, there was the small matter of the number of different elements and, by implication, the number of different kinds of atom.

Democritus had never specified how many distinct types of atom there should be. However, his entire thesis had been that the complexity of the world was a consequence of the combinations of a limited number of fundamental building blocks. Lavoisier's list of elements indicated that there were about 20 different kinds of atom. However, the number of elements proliferated and another 32 were added to the list in the forty years after the French chemist's death.