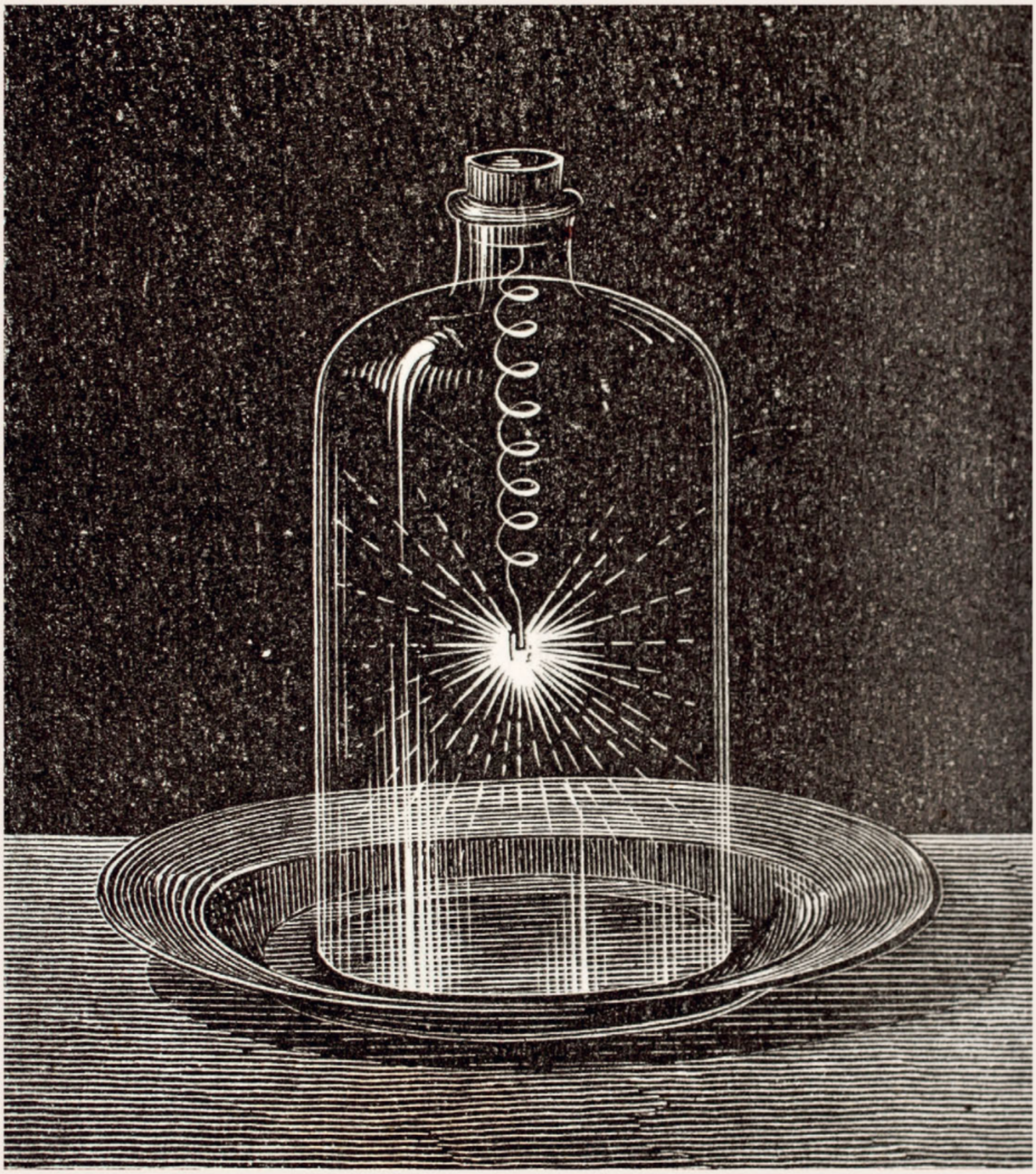
THE

ELEMENTS

A VISUAL HISTORY OF THEIR DISCOVERY



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FRONT COVER: Antique illustration of iron combustion in pure oxygen. Artist unknown, first published in *L'Eau* by Gaston Tissandier, Hachette, Paris, 1873.

PREVIOUS PAGE: The action of water on potassium and ammonia, and preparation of ammonia, from J. Pelouze et E. Fremy, *Notions générales de chimie*, Paris: Victor Masson, 1853, plate XIII. National Central Library of Florence.

INTRODUCTION

Among the many discoveries that humans have made about the world we live in, one of the most profound, as well as the most useful, is what it is made from. Every substance we can see and feel is composed of atoms—too small to see even with conventional light microscopes—of which there are just 90 or so varieties. What's more, many of those varieties are extremely rare; the familiar world encompasses perhaps just twenty to thirty of them. These varieties are called the *chemical elements*, and they help massively in the task of simplifying our understanding of the world around us. There was no guarantee, before we knew of these elements, that all matter could be dissected and categorized into such a relatively small number of fundamental constituents—compare this, for example, to the profusion of species we find in the living world, where there are more than 300,000 known varieties (and probably more than that still unknown) of beetles alone. So the manageably limited list of chemical elements is something to be grateful for.

All the same, it's a dauntingly long list for new students of chemistry. They might have already heard of elements like carbon and oxygen, but scandium? Praseodymium? Even pronouncing the names of some of these elements can be a challenge, let alone remembering anything about them or finding the motivation to do so.

That's where history might help. The elements were discovered only very gradually over time—from about 1730, at a surprisingly steady rate of about one every two or three years, with occasional bursts or hiatuses. This happened through no concerted program of seeking (at least not until the past several decades, when any newly discovered elements have had to be deliberately *human-made*). It was a haphazard business: scientists and technologists might find a previously unknown element in an obscure mineral, say, or by splitting sunlight into a spectrum to seek a telltale gap where some new element has stripped a color from it, or by liquefying and distilling air to find tiny quantities of rare gases. These tales of discovery are like biographies, and they can make the elements seem less like a random collection of obscure nobodies and more like characters in the long and continuing saga of how we have tried to comprehend and manipulate our surroundings. To chemists, they genuinely come to acquire personalities: helpful or recalcitrant, intriguing or dull, friendly or hazardous. That chemists regularly conduct polls of their "favorite elements" can seem unutterably nerdy—until you get to know the elements yourself, in which case you will almost certainly find that you have developed preferences and aversions of your own.

Some elements have proved immensely useful: as crucial ingredients in drugs or other medical agents, for example, or for making new materials that are harder, stronger, shinier, better conductors of electricity, and so on. Some have brightly colored compounds (combinations with other elements) that are valuable as pigments and dyes. Some are sources of energy, or essential nutrients for health, or refrigerants that can keep things colder than deep space. Their properties and uses have even elevated a few elements to privileged inclusion in the cultural lexicon: opportunities are golden, clouds have silver linings, suggestions go down like lead balloons, opponents are crushed with an iron fist, provocateurs are denied the oxygen of publicity. We might speak of the sodium glare of streetlights, of hydrogen bombs, of nickel-and-dime stores, magnesium flares, with little if any understanding of why those particular elements are being invoked. The very notion of an "element" itself connotes a

OPPOSITE: A sage holding the tablet of ancient alchemical knowledge. From a later transcript of Muhammed ibn Umail al-Tamîmî's *Al-mâ' Al-waraqî* (The Silvery Water), Baghdad, ca. 1339, Topkapi Sarayi Ahmet III Library, Istanbul.

fundamental principle beyond chemistry, for we speak of the elements of law, of mathematics (the topic of the ancient Greek thinker Euclid's treatise *The Elements*), of language, of cookery.

All this implies that charting the history of the discovery of the chemical elements is more than an account of the development of chemistry as a science. It also offers us a view of how we have come to understand the natural world, including our own constitution. Furthermore, it shows how this knowledge has accompanied the evolution of our technologies and crafts—and "accompany" is the right word to use, because this narrative challenges the common but inaccurate view that science always moves from discovery to application. Often it is the reverse: practical concerns (such as mining or manufacturing) generate questions and challenges that lead to fresh discoveries. We can see too how scientific discovery is not some impersonal and inexorable process, but depends instead on the motivations, capabilities, and sometimes the idiosyncrasies of individual people: it requires determination, imagination, and ambition as well as insight and—never underestimate this—a substantial dash of good luck.

It's an unavoidable fact that histories of this kind must dwell, especially in the past several centuries, to a degree that we now rightly find uncomfortable, on the exploits and achievements of men of European heritage. Not only was it very difficult until recent times for women to gain entry into scientific institutions, but even those few who did often faced intense discrimination and prejudice. Marie Curie, for example, who did most of the work in finding the elements radium and polonium at the end of the nineteenth century, was nearly overlooked when

OPPOSITE: Wallchart of an early periodic table of the elements according to Mendeleev, 1893, Yoshida-South Library, Kyoto University.

ABOVE: *Chemical Magic and Practical Chemistry Cabinet* produced by F. Kingsley, London, ca. 1920, History of Science Museum, Oxford.

the work was rewarded by the 1903 Nobel Prize for Physics. Initially, the award was going to acknowledge only her husband and collaborator Pierre, before, forewarned, he objected. Similarly, Marie-Anne Paulze Lavoisier's contributions to the work of her husband, the eminent eighteenth-century French chemist Antoine Lavoisier, were long considered little more than wifely duties rather than those of a scientific collaborator. Even as late as the 1950s, the American nuclear chemist Darleane Hoffman, who made vital contributions to the discoveries of new, heavy radioactive elements, was told when she arrived at Los Alamos National Laboratory to lead a new team that there must be some mistake because "We don't hire women in that division."

Why, meanwhile, people of color feature rather little in this story is a question fraught with the entire history of Western global dominance and exploitation since early modern times, as well as the prejudices and systematic biases that still lead to their under-representation in the sciences today. It isn't clear for how much longer the story of element discovery will or, for that matter, can continue—but the rise of scientific excellence in Asia, at least, might lead us to expect as well as to hope that, if it does, then it will feature significantly more cultural richness and diversity.

Lanthanides

CHAPTER ONE

THE CLASSICAL ELEMENTS

LEFT: The legendary sage or deity known as Hermes Trismegistus teaching the Egyptian astronomer Ptolemy the World System. Silver plate with relief decoration, AD 500–600, The J. Paul Getty Museum, Villa Collection, Malibu, California.

THE CLASSICAL ELEMENTS

"The body of the world," Plato wrote around 360 BC in his wide-ranging philosophical treatise *Timaeus*, "is composed of four elementary constituents, earth, air, fire and water, the whole available amount of which is used up in its composition." In other words, what we can see around us is all there is of this elemental stuff.

This quartet of elements is often portrayed as the universal scheme in the ancient world. But it wasn't really. The four-element system was formulated in the fifth century BC by Empedocles, a philosopher who is surrounded by exotic stories. Some say he was a magician who could raise the dead, while legend has it that, deciding he was an immortal god, he died by leaping into the volcanic maw of Mount Etna. As with so many accounts of people who lived before reliable historical records, such tales should be taken with a pinch of salt.

BELOW: The four elements. Detail from *Various Verse Treatises On Moral Subjects and Natural History*, Italian, 1481, Harley 3577 manuscript, The British Library, London.

ca. 850 BC
The Greek alphabet is developed from the Phoenician alphabet.

776 BC
First recorded Olympic Games take place.

ca. 624–545 BC
Life of Thales of Miletus, sometimes regarded as the father of geometry and axiomatic reasoning in mathematics.

ca. 571–ca. 497 BC
Life of Pythagoras of Samos. Some of his followers proposed that the Earth is not the center of the cosmos but revolves around a "Central Fire."

ca. 460–ca. 370 BC
Life of Hippocrates of Cos, the founder of the Hippocratic school of medicine, who established the foundations of Western medicine, arguing that disease is a natural process rather than a result of divine punishment.

380 BC
Plato, student of Socrates, founds the Academy in Athens.

384–322 BC
Life of Aristotle. He was taught by Plato and founded the Peripatetic school of philosophy and the Aristotelian tradition.

ca. 287–212 BC
Life of Archimedes of Syracuse: inventor, engineer, mathematician, and astronomer.

Although Empedocles's elemental system persisted—partly thanks to its endorsement by the heavyweights Aristotle and Plato—in medieval Western tradition and beyond, there were several dissenting views, even among the Greek philosophers, about what the world is made of. That's hardly surprising because the answer is not obvious, nor is it easy to find out. But two principles seem to have guided these efforts. The first is that the fabrics of the world have rather diverse properties: some are solid, some fluid, some airy. Of course, we can make finer distinctions too: there are soft and sticky substances (like mud), say, as well as tough but pliable ones (like wood). They have different colors, tastes, smells. Yet many of the Greek philosophers drew only the most basic distinctions when trying to figure out what the fundamental elements were. Colors, for example, were superficial and could change—look at the way copper tarnishes to greenish verdigris. But solidity was shared by any substance that had a large degree of "earthiness."

The second guiding principle was that substances can be changed. Burn a log and much of it seems to vanish into the air, leaving an earthy residue of ash. Copper and iron can be melted into flowing form. So understanding the elements wasn't just a quest to describe a static, unchanging world; it also had to account for the transformations that we see around us.

It's tempting to imagine that ancient schemes of the elements arose from the same search for simplicity that made later chemists draw up a periodic table of elements and explain it with a unified view of what atoms are, or that led modern physicists to develop theories about the small family of fundamental particles that make up atoms. Maybe this impulse to find conceptual unity did indeed play a part—people have always found it helpful to try to break down complicated things and processes into simpler ones that are easier to grasp. That, after all, is a big part of the scientific enterprise. But the quest to understand the elements was also practically motivated. What was going on when bread was baked, when mortar set between the bricks, when a ceramic glaze developed a glossy hardness in a kiln? As we survey the history of the discovery of elements, never forget this: many of these discoveries have come about not because scientists, artisans, and technologists were looking for them, but because they were trying to make something useful. Chemistry is, and always has been, primarily an art of making—and if we want to know what the elements are, it's because it is always useful to appreciate your ingredients.

ABOVE: The four classical elements—*terra* (earth), *aqua* (water), *aer* (air), and *ignis* (fire)—depicted as arranged in concentric cosmic spheres. Robert Fludd's *Utriusque Cosmi Maioris Scilicet et Minoris Metaphysica, Physica Atque Technica Historia*, Oppenheim: J. T. de Bry, 1617, Getty Research Institute, Los Angeles.

PROTE HYLE

"Most of the early philosophers believed that the essence of all things could be reduced to material principles." This sounds like a quotation from a history book about the ancient view of the world. Yet it was actually written in the fourth century BC by Aristotle, for whom what the philosophers had said two hundred years earlier was already history. "That from which all things come to be, the original state of their generation…that is what they hold to be the element and the principle of things," he went on. "While the state of the substance can change, the substance itself remains." What Aristotle is getting at here is the idea that ultimately there is only one primordial substance, from which everything else then arises.

BELOW: Anaximander of Miletus holding a sundial. Early third century AD mosaic, Rheinisches Landesmuseum, Trier.

If that were true, however, this would be a very short book indeed. Still, the picture that Aristotle paints is not so very different from the one most scientists believe in today. Our universe began with the Big Bang, when space and time and all it contains sprang from a seed so tiny and packed with energy that even our best physical theories can't describe it. What we do know is that there wasn't a lot of room for variety in that almost infinitesimally small bubble of space-time. All the distinctions we see today—between atoms of different elements, between the fundamental particles within atoms, and the forces through which they feel one another—must be erased if we rewind to those first instants of creation. That's about as much unity as we can imagine, and we don't have theories to tell us what it was like.

Yet Aristotle's primordial substance—which is often referred to in Greek as the *prote hyle* (first matter) or, later in Latin, the *prima materia*—wasn't anything quite as exotic and unimaginable as this. The idea was that the Creator—and the Greek philosophers did not doubt there must have been some cosmic creator, even if they didn't exactly imagine a God in the Judaeo-Christian sense—didn't work with four elements, but with just one, out of which others somehow arose. It's not easy today to grasp what this means. We tend to think of an element as *stuff*, as some substance we can see and hold. But the ancient Greeks often spoke of the prote hyle as a kind of "material cause": it brings into being all the substances we see around us. Not only can we not see this primal stuff, but it's not clear whether it is even *seeable*—any more than we can expect to look into the heart of the Big Bang and discern what is there.

The idea of prote hyle is often linked to one of the earliest traditions in Greek philosophy, known as the Milesian (or Ionian) school, which flourished in the seventh century BC. The earliest known member of this school was Thales of Miletus, that location being a city on the west coast of Anatolia in modern-day Turkey. Thales is, in fact, essentially the first Greek philosopher about whom we know anything at all, and even that comes from later, secondhand sources like Aristotle. Thales, as we'll see, had his own views about prote hyle, but his pupil and successor Anaximander summed up what it is about this concept that is so elusive. He called it *apeiron*, the "unlimited"—though he might as well have labeled it "don't ask," since he imagined it to be invisible, infinite, eternal, and unchangeable. Elements such as earth, air, fire, and water come from apeiron by an "eternal movement," which brings about a separation of opposite qualities: hot separates from cold, say, and dry from moist. It's perhaps a little fanciful, but also irresistible, to see here too a presentiment of the way modern physicists believe the profusion of particles and forces we see around us stemmed from processes of separation that they call "symmetry breaking" in the very early universe, through which a thing that was initially uniform transforms spontaneously into two different varieties.

In any case, the idea that the classical elements are both united and differentiated by their properties was popular with many thinkers after Anaximander. It was precisely because (unlike apeiron) elements such as water and earth have properties at all that we can experience them: we feel the wetness and coldness of water, for example. For Aristotle, one element can be transformed to another by a switch in their properties: if wet, cold water loses its wetness, it becomes dry, cold earth—which in turn becomes fire when the coldness is changed to hotness. An elemental system such as this might sound crude today and in some sense "wrong"—but it was a start toward making sense of how the physical world works.

If you think that Anaximander's prote hyle sounds rather vague and elusive, just consider what the philosopher Pythagoras made of it all. He lived on the Aegean island of Samos in the fifth century BC, and he and his followers took the view that what was truly fundamental in the world was not a substance—whether it was tangible and visible or not—but numbers. They regarded numbers as concrete and real, almost as if they are elemental "shapes"—one is a point, two a line, three a plane—from which all objects are built. And here, too, there are anticipations of the modern view in which all matter and forces are described by physicists in purely mathematical terms: here the stuff that chemists handle and transform seems to have vanished into abstraction.

ABOVE: The origin of matter: "In one body—cold fighting heat, wet, dry." From Michel de Marolles's *Tables of the Temple of the Muses*, Amsterdam: A. Wolfgank, 1676, Book 1, University of Illinois Urbana-Champaign.

WATER

Thales of Miletus decided that the primal substance from which all others come—the unique generative element—was water. Perhaps that sounds unlikely, but you can understand his reasoning. In the ancient world, water was the only known substance that could adopt all the states of matter: although most familiar as the liquid that fills the ocean basins and rushes through the channels of streams and rivers, it could also freeze solid as ice and evaporate into "air" (today we would say into vapor or gas). It also seems to be the essential source of all life: Thales had witnessed how vital the seasonal flooding of the Nile river was to the replenishment of the fertile alluvial deposits of its delta. Aristotle believed Thales was also influenced by the view that all foods are moist and that seeds germinate from moisture.

In Thales's view, the other classical elements—air, fire, and earth—were all derived from water. The first two are airy "exhalations" of it, while earth appears out of water as a kind of sediment—not only are such tiny particles almost always present in river water, but a solid crust of salt remains when seawater evaporates. The Greek-Roman physician Galen claimed that one of Thales's original texts—now lost, if Galen was telling the truth—stated that the four elements "mix into one another by combination, solidification, and incorporation of things of the world."

Doesn't the evidence for leaping to such a far-reaching conclusion seem just a little…thin? Well, yes, by today's standards, when scientists propose ideas based on a careful observation of data and then test them experimentally to see if they stand up. But there was no such conception of science in the ancient world, and indeed it didn't really start to cohere until the seventeenth century. Yet by suggesting that water was the fundamental element, the basic component of all things, Thales was saying something important for the development of thought. First, this idea doesn't ascribe anything to the arbitrary whims of the gods or to causes that we might now regard as superstitious; it's a thoroughly rational idea. (Thales apparently thought that some divine agency provides the guiding intellect that fashions things out of water, but we can hardly hold that against him; many people today view God's role in a similar manner.) And it's also a simplifying idea, an attempt to explain many observed facts with a single underlying one. It's not yet science, but it is the kind of thinking science was going to need.

As we saw from the example of Anaximander, Thales's belief that water is the primordial element wasn't shared even by some of his followers. Others, however, embraced the idea. Hippon of Samos, who was not just a contemporary but virtually a neighbor of Pythagoras, thought that both water *and* fire were the most basic elements. And, in fact, the primacy of water was even being asserted as late as the

LEFT: A Greek *clepsydra* (water clock), made from clay, late fifth century BC. This one held two choes (6.4 quarts) and took six minutes to empty. Museum of the Ancient Agora, Athens.

seventeenth century, when the Flemish physician Jan Baptista van Helmont claimed to have *demonstrated* that everything was made of water.

Van Helmont was carrying out an experiment that had been proposed two hundred years earlier by the German cardinal and natural philosopher Nicholas of Cusa. Imagine, Nicholas had said, that you took a pot filled with earth, planted some herb seeds in it, and watered them daily. Before long you'd have some fine plants. But from where had they got their substance? Not from the earth, of which there would be as much as you started with. No, all you'd added was water—so surely *that* must be what the herbs were made from.

It's not a difficult experiment, and in a way many people did it over the ages to season their stews. But van Helmont conducted it as a scientist: by weighing the soil at the outset and at the end, along with the plant (a willow sapling) that he grew for five years. He even covered the pot with a metal lid, pierced with holes to let the air in but to keep dust out. And, in the end, he said, "one hundred and sixty-four pounds of Wood, Barks, and Roots arose out of water onely." It didn't, but that could hardly have been obvious to van Helmont. Plants build their fabric from carbon dioxide gas captured from the air in a process powered by the energy of sunlight. Moisture is essential, but not the only ingredient. The clever chemistry involved in *photosynthesis* (literally, "making with light") was only grasped in the twentieth century, and so we'd be well advised to be humble in giving due appreciation to the efforts of ancient philosophers to understand what are the elements of all things.

LEFT: The ancients watering with a "thumb pot." Title page from Charles Estienne's *Maison Rustique*, London: Adam Islip for John Bill, 1616, Wellcome Collection, London.

AIR

Just as Thales was succeeded by Anaximander as the leading light of the Milesian school of philosophy, so Anaximander had a protégé, named Anaximenes. He too had other ideas about the nature of prote hyle, the primordial element. It's not water, he said, and neither was he content to fall back on Anaximander's vague notion of apeiron. No—it is air. That might in itself seem a rather arbitrary substitution, but Anaximenes saw logic to it. The creation of the world was regarded back then as a process by which structure and substance emerged from a primordial Chaos—and what is less ordered and more chaotic than swirling, restless air? (The very word "gas," for which air is the familiar archetype just as water is the archetypal liquid, is derived from "chaos." The word is said to have been coined in the seventeenth century by Jan Baptista van Helmont.) Anaximenes imagined how that process of emergence happened: through what we today call condensation, in which gas (here, air) collapses to a dense substance. First, he said, air becomes water, and then as the density increases, earth and stone. This happens through a loss of heat—or as philosophers might have said then, by the action of cold. Conversely, air can undergo rarefaction (becoming even more tenuous) by raising its temperature, whereupon it becomes fire. In Anaximenes's "air-first" cosmology there's a rational, even mechanical, description of how all things came into being.

That's not to say there wasn't a mystical side to this belief, too: Anaximenes was said to have thought that ultimately air was the stuff of the supreme being. And given that air was at the time still thought to be without any mass or "body" itself, his idea wasn't so different to Anaximander's notion of elusive apeiron anyway.

Empedocles is usually attributed, in the fifth century BC, with realizing that air really does consist of "stuff"—you might even call it the discovery of air in the modern sense. It's said that he demonstrated this in an experiment using a water clock—what the Greeks called a *clepsydra*. There are several different types of water clock, but all work by measuring time according to how long it takes water to flow into or out of a vessel with holes or openings in it. One form is an inverted cone that drains through a small hole in its downward-pointing apex; in another, the passage of time is determined by how long it takes such a cone to fill and sink when placed in water. Empedocles's experiment seems to have involved blocking the outlet of a *clepsydra* with a finger so that water can't fill it completely when it is immersed, due to the air bubble trapped inside. When the finger is removed, the air bubbles out and the vessel sinks completely. So the air can't just be "nothing," since it has to get out of the vessel before water can enter.

BELOW: Bronze bust of Empedocles, second half of third century BC, Villa of the Papyri, Herculaneum, National Archeological Museum of Naples.

It's sometimes said that this was the first scientific experiment ever recorded. That's not a very meaningful claim, however. For one thing, a true experiment is a test to see if an idea is right or wrong (or perhaps just to gather information about an unexplained phenomenon). But it's doubtful that Empedocles would have changed his view if things hadn't turned out the way he expected; like most "experiments" in ancient times, this was more of a demonstration. And, in any case, it's very likely that it never happened at all; Empedocles simply described a girl carrying out the operation, and so he was probably just explaining what *would* happen—which, with its bubbles emerging from a submerged container, was probably pretty familiar to his audience. All the same, it was widely accepted from his time onward that air was indeed a physical substance, albeit one you couldn't feel, see, or taste.

Not, that is, unless the air moves. "The air round the earth is necessarily all of it in motion," wrote Aristotle, and this was the origin of the winds. As particles of air grow heavy, he said, they lose their warmth and sink—while fire may mix with air and cause it to rise. This interplay of air and fire, cooling and warming, produces the roiling of the atmosphere: an impressive presentiment of the modern view that convection currents and the differences in temperature, pressure, and humidity of the air may elicit everything from a gentle, flag-ruffling breeze to a raging hurricane.

RIGHT: Empedocles's four elements. Colored woodcu Lucretius's *De Rerum Naturc* century BC, printed in Bresc Thomas Ferrandus, 1473–14 John Rylands Library, Univ of Manchester.

FIRE

Three of the classical elements of Empedocles are representatives of the three states of matter: earth is solid, water liquid, and air gas. But where, then, does fire sit? It's the odd one out, for sure. Today, we know that fire is not a substance, but a process: it is what results when combustible substances burn. The bright, flickering flames of a gas or wood fire are composed of tiny soot particles so hot that they glow like the filament of a light bulb. They condense from a gaseous mixture of many different chemical substances, mostly carbon-based molecules broken up into small fragments or even into solitary atoms. The edge of a flame marks the place where the temperature falls too low for the soot particles to emit light. So the truth is that fire—which is to say, a flame—is extremely complicated, and even now the chemistry involved is not completely understood.

It's not hard to see why ancient philosophers thought there was something special and unique about fire. For there really is. It seems not just to hold but to generate heat—and it is also a source of light. Both of those things have been immensely valuable to humankind since long before recorded history. Some anthropologists argue that it was not so much the discovery of fire (at least 400,000 years ago) but of cooking that marked a turning point in human prehistory: the calorific boost of easily digested cooked meat fueled the development of bigger brains and freed up time that was otherwise devoted to chewing and digesting. With fire, our ancestors could also fend off the ice-age chill, keep predatory beasts at bay, and stay active and socializing after night fell.

One view is that, by making fire an element along with the other three, Empedocles's scheme embraced not just states of matter, but those other two vital aspects of the physical world: heat and light. Neither of these was close to being understood until the late nineteenth century, but elemental fire offered at least some reassurance that our intellect and worldview could contain them.

Given the importance of fire, it's perhaps not surprising that it too has been proposed as the primordial substance. That was the view of Heraclitus of Ephesus, a city in modern-day Turkey, around 500 BC. In one sense, he was simply choosing to focus on a different stage in the progression also identified by Thales and Anaximenes by which elements are transformed one into another in processes of condensation and rarefaction: fire may condense to water and then further to earth. For Heraclitus, however, those processes reflected his view that the *cosmos*—a term that first appears in his writings—was constantly changing, always in flux. It was Heraclitus who expressed the idea that one can never step in the same river twice. Without change, nothing could exist, and Heraclitus saw this as a consequence of the play of opposing forces: "all things happen according to strife and necessity," and only out of strife and conflict does harmony emerge. Something is always burning somewhere.

This was a fitting position given that fire was, at that time and long after, the ancient chemist's main and almost sole agent of transformation. It was the only means of inducing a change from one thing to another: smelting metals, baking bread, melting sand and soda into glass. The practical arts of chemistry were born of fire.

OPPOSITE: Claudio de Domenico Celentano di Valle Nove's *Book of Alchemical Formulas*, Naples, 1606, Getty Research Institute, Los Angeles.

SOLIDS: EARTH, WOOD, METAL

If you are now thinking that surely one of these ancient philosophers must have made the fourth element of the classical pantheon—earth—their prote hyle, you'd be right. Xenophanes of Colophon, who lived during the late sixth and early fifth centuries BC and founded the so-called Eleatic school of philosophers, has been attributed with saying "Everything is born of earth and everything returns to earth"—in which we can hear a premonition of the Christian ritual phrase: "Ashes to ashes, dust to dust." And, after all, doesn't earth seem the most likely candidate for a primordial matter, given that, like most of the objects around us, it is solid, visible, and tangible? We have even named our own world after this substance.

Yet even ancient sources are divided as to whether Xenophanes really took the view that earth was the basis of all matter. Some, such as Galen, say

LEFT: Second day of Creation (Genesis 1:1-8), God divides the water from the earth. From *Bible Pictures* by William de Brailes, Oxford, French manuscript on parchment, ca. 1250. The Walters Art Museum, Baltimore.

OPPOSITE: The Universal Chart of the Eight Trigrams showing the *Wu Xing* (Five Elements) at the center. From Wu Weizhen's *Wanshou Xianshu* (The Immortals' Book of Longevity), Ming Dynasty, Wellcome Collection, London.

he asserted that there were *two* basic elements: earth and water. He was certainly interested in both of these; he discussed the water cycle and the formation of clouds from moisture drawn up from the sea by the heat of the Sun, long before Aristotle wrote about such natural processes in his great text on weather and the Earth, *Meteorologica*. Furthermore, Xenophanes's notion that the world emerged from the interplay of earth and water mirrors the Christian story of Genesis: "And God called the dry land Earth; and the gathering together of the waters called he Seas."

All the same, the world view of Xenophanes and the Eleatic school contrasted with Heraclitus's cosmos of flux, stressing instead concepts of permanence and unity. That's what you might expect from someone inclined to set solidity at the heart of the elements.

Yet earth wasn't the only common solid substance in the ancient world. In China, philosophers believed there were five fundamental substances: water, fire, earth, wood, and metal (the *Wu Xing*). These corresponded to the *five* cardinal directions in Chinese thought: not just north, east, south, and west, but also the center. In this scheme, earth occupies the central position and represents the coming together of all the elements. A Chinese Han-Dynasty treatise of around 135 BC says that "Earth has its place in the center and is the rich soil of Heaven…Earth is what brings these Five Elements and Four Seasons all together…if they did not rely on Earth in the center, they would all collapse."

The Chinese five-element system was first laid out clearly in the third century BC by the philosopher Zou Yan—who, Confucius and Lao Tzu notwithstanding, has been described as the real founder of all Chinese scientific thought. Just as the seasons change one to another, so the five elements can be transformed in a cyclic view of the universe that reflects a faith in the process of death and rebirth. This succession of substances is a central concept in alchemy, underpinning the idea that metals can be transmuted so that lead might be turned to gold. For Chinese alchemists in particular, this link between transmutation and the cycle of life connected their chemical manipulations to the possibility of sustaining human life by preparing elixirs. All this transformation operates according to the balance of the opposed cosmic forces of *yin* and *yang*, which play a similar role to the Love and Strife, the mixing and separation, invoked by Empedocles and other Greeks. Again, without making too much of the parallel, it's impossible not to be struck by the echoes here of modern ideas of how the physical world gets its forms from basic substances and particles interacting via forces—and, in particular, by how the atoms from which all chemical elements are made are constituted from subatomic particles united in a delicate balance of electrical attraction and repulsion.

IN SEARCH OF THE ATOM

The word atom comes from the Greek *atomos*, which means "unsplittable." We know now that atoms *can* be split (as well as merged), and later we'll see how that process has given us many new elements. But even if atoms aren't the most fundamental units of matter, the concept of a chemical element only makes sense up to this degree of subdivision: pull matter apart beyond the level of the atom, and there can be no elements left.

It's both extraordinary and odd that the ancient Greeks—at least, some of them—decided that all substances must be made of atoms: that ultimately they have a graininess beyond which they can't be divided any more. This, after all, isn't our everyday experience. You can cut a piece of cheese smaller and smaller, and if there comes a limit to that process, it's only because your knife or your vision is too blunt. With a razor blade and magnifying glass you can do better, and with a microscope, better still. Why would anyone think there was a limit?

Yet Leucippus of Miletus, in the fifth century BC, did come to that conclusion. At least, so we're told—what little we do know about him comes from the accounts of others, and it's not even completely agreed where he was born. We know more about the philosopher said to be his pupil, Democritus, who is believed to have come up with the word *atomos* to describe these indivisible grains.

LEFT: The *Systema Antiquorum* or Democritean Universe. From John Seller's *Atlas Cælestis*, London: J. Seller, ca. 1675, Chart 23, Robert Gordon Map Collection, Stanford University Libraries, California.

OPPOSITE: The Platonic solids with their respective elements. Detail from Johannes Kepler's *Harmonices Mundi*, Linz: Johann Planck, Book V, 1619, Smithsonian Libraries, Washington DC.

This early atomistic theory may have been an attempt to reconcile the view of the Eleatic school that permanence sits at the heart of matter with the evident fact that—as anyone could see—change occurs. Perhaps change is nothing more than the rearrangement of imperishable, eternal atoms? Maybe too these various arrangements of just a few types of atom could explain how it is that the world contains a mere handful of elements yet innumerable varieties of substance? Aristotle compared this with the way in which just a small number of letters is needed to make an almost limitless number of words—an analogy that is spookily close to the metaphor chemists deploy today for how atoms combine to make a panoply of molecules and materials.

If, however, all stuff is composed of atoms, what sits between them? For Leucippus and Democritus, this was simply empty space: a void. Other philosophers thought it ridiculous to suppose that nothingness could exist; some felt that atoms must fill up all of space completely, while others argued that matter must be infinitely divisible after all, so that tiny grains could fill up any nooks between larger grains *ad infinitum*. Aristotle argued that if there were spaces between atoms, they'd be filled with air—which was all very well unless you accepted that air was an element like the others and therefore made of atoms, too.

What were atoms like? Democritus didn't say, but Plato in the third century BC had his own ideas. Because he was convinced that the cosmos had been built by the Creator using principles of mathematical harmony and perfection, he decided that these atoms would have the shapes of the symmetrical, three-dimensional objects (polyhedra) that can be made from regular polygons: flat shapes in which all the sides and angles are equal. There are an infinite number of regular polygons, but only three of them can be the building blocks of polyhedra containing just one type of face: equilateral triangles, squares, and pentagons. And there are just five of the resulting polyhedra, now called the Platonic solids.

Plato said that four of these objects represent the shapes of the atoms of the four elements—and that those shapes help to explain the element's properties. Solid, stable earth is made by packing together cube-shaped particles, while the polyhedra with the fewest faces—the tetrahedron—is the most mobile and therefore the unit of fire. What's more, the tetrahedron has the sharpest points, which is why fire is so "penetrating." Air and water—respectively, an octahedron and icosahedron, both also made up from equilateral triangles—are intermediate states between this solidity and mobility.

"We must, of course," Plato wrote, "think of the individual units of all four bodies as being far too small to be visible, and only becoming visible when massed together in large numbers." Again, what's most impressive about these early ideas of the elements—wrong though they are—is that they attempt to explain why the stuff of the world behaves the way it does based on a theory of what they are made of at scales we can't see or (these philosophers believed) ever hope to see.

This makes it sound as though Plato shared Democritus's views about the atomic nature of matter, but that he made them geometric atoms. Yet that's not quite right. It's not easy to figure out how "real" Plato thought these atoms are, and he never even deigned to mention Democritus. But for Plato, all of reality as we know it had an ambiguous quality: it was, he suspected, just the shadow of something eternal, harmonious, and geometrical.

AETHER

What about that fifth Platonic solid? It is the dodecahedron, and its twelve faces are pentagons. Was there any place for it in the Platonic cosmos? There was, but not on Earth. "The gods used [it]," Plato wrote, "for embroidering the constellations on the whole heaven." It comes closest out of all the Platonic solids to resembling a sphere, the most perfect and symmetrical of shapes, and so it is the most suited to being the stuff of the eternal, perfect heavens. Aristotle adopted this idea and gave it a name: it was the "fifth element" or *quintessence*, which he also called the aether.

For Aristotle, the four classical elements have innate predispositions to move in certain directions: fire and air go up, water and earth go down (think of rain and the falling of a thrown stone). Aether did neither. Being perfect and outside the earthly realm, it reflected the behavior of the heavenly bodies (which were made from it) by moving in circles. At a stroke, then, he explained why those objects—the Sun, Moon, planets, and stars—appear to rotate around the Earth. They do so because that's in the nature of their substance. This wasn't, to tell the truth, much of an explanation at all: the argument, like the motion, is circular.

This "fifth element" then was a rather makeshift idea. No one had ever seen it, and no one ever could: it wasn't possible to transmute any of the four earthly elements into aether. And the aether was intangible and invisible—in the figure of speech that stemmed from it, it was ethereal.

All the same, the idea was remarkably tenacious. It seemed to imply a fundamental divide between the Earth and the heavens—aether was governed by quite different rules from earthly matter. That idea persisted, more or less, right up until the early

LEFT: Ptolemaic model of the universe, with the Earth at center, surrounded by the other three elements. From Andreas Cellarius's *Harmonia Macrocosmica*, Amsterdam: Johannes Janssonius, 1660, Barry Lawrence Ruderman Map Collection, Stanford University Libraries, California.