Chapter 1
Aristotle's quartet: The elements in antiquity

In 1624 the French chemist Étienne de Clave was arrested for heresy. De Clave's inadmissible ideas did not concern the interpretation of holy scripture. Nor were they of a political nature. They did not even challenge the place of man in the universe, as Galileo was doing so boldly.

Étienne de Clave's heresy concerned the elements. He believed that all substances were composed of two elements – water and earth – and 'mixts' of these two with three other fundamental substances or 'principles': mercury, sulphur, and salt. It was not a new idea: the great French pharmacist Jean Béguin, who published *Tyrocinium chymicum* (*The Chemical Beginner*), one of the first chemistry textbooks, in 1610, maintained until his death a decade later that all matter had essentially those same five basic ingredients.

But want of originality did not help Étienne de Clave. His idea was heretical because it contradicted the system of elements propounded by the ancient Greeks and endorsed by Aristotle, their most influential philosopher. Aristotle took this scheme from his teacher Plato, who in turn owed it to Empedocles, a philosopher who lived during Athens's Golden Age of Periclean democracy in the fifth century BC. According to Empedocles there were four elements: earth, air, fire, and water.

Shocked into cultural insecurity by the fall of Rome, the medieval West emerged from the trauma of the Dark Ages with a reverence for the scholars of antiquity that conflated their beliefs with the doctrines of Christianity. The word of Aristotle became imbued with God's authority, and to question it was tantamount to blasphemy. Not until the late seventeenth century did the discoveries of Galileo, Newton, and Descartes restore the Western world's ability to think for itself about how the universe was arranged.

Which is why the plan of Étienne de Clave and a handful of other French intellectuals to debate a non-Aristotelian theory of the elements at the house of Parisian nobleman François de Soucy in August 1624 was squashed by a parliamentary order, leading to the arrest of its ringleader.

The controversy was not really about science. The use of law and coercion to defend a theory was not so much an indication that the authorities cared deeply about the nature of the elements as a reflection of their wish to preserve the status quo. Like Galileo's trial before the Inquisition, this was not an argument about 'truth' but a struggle for power, a sign of the religious dogmatism of the Counter-Reformation.

Free of such constraints, the ancient Greeks themselves discussed the elements with far more latitude. The Aristotelian quartet was preceded by, and in fact coexisted with, several other elemental schemes. Indeed, in the sixteenth century the Swiss scholar Conrad Gesner showed that no fewer than eight systems of elements had been proposed between the times of Thales (the beginning of the sixth century BC) and Empedocles. The Condemnation of 1624 notwithstanding, this eventually made it harder to award any privileged status to Aristotle's quartet, and helped to open up again the question of what things are made from.

What are things made from? This is a short book, but the answer can be given even more concisely. Chemistry's Periodic Table lists all the known elements and, apart from the slowly growing bottom row of human-made elements, it is comprehensive. Here is the answer. These are the elements: not one, not four, not five, but about ninety-two that appear in nature.

What are things made from? The Periodic Table is one of the pinnacles of scientific achievement, but it does not quite do justice to that question. Set aside the fact that the atomic building blocks are actually more subtly varied than the table implies (as we shall see later). Forget for a moment that these atoms are not after all fundamental and immutable, but are themselves composites of other entities. Let us not worry for now that most people have never even heard of many of these elements, let alone have the vaguest notion of what they look and behave like. And make it a matter for discussion elsewhere that the atoms of the elements are more often than not joined into the unions called molecules, whose properties cannot be easily intuited from the nature of the elements themselves.* Even then, it is not enough to present the Periodic Table as if to say that Aristotle was wildly wrong about what things are made from and so was everyone else until the late eighteenth century. In asking after the elements, we can become informed about the nature of matter not just by today's answer (which is the right one), but by the way in which the problem has been broached in other times too. In response, we are best served not by a list but by an exploration of the enquiry.

What are things made from? We have become a society obsessed with questions about composition, and for good reason. Lead in petrol shows up in the snow fields of Antarctica; mercury poisons fish in South America. Radon from the earth poses health hazards in regions built on granite, and natural arsenic contaminates wells in Bangladesh. Calcium supplements combat bone-wasting

* Molecules are the topic of the companion volume to this book, *Stories of the Invisible* (Oxford: Oxford University Press, 2001).

diseases; iron alleviates anaemia. There are elements that we crave, and those we do our best to avoid.

The living world is, at first glance, hardly a rich dish of elements. Just four of them are endlessly permuted in the molecules of the body: carbon, nitrogen, oxygen, and hydrogen. Phosphorus is indispensable, not only in bone but in the DNA molecules that orchestrate life in all its forms. Sulphur is an important component of proteins, helping to hold them in their complex shapes. But beyond these key players is a host of others that life cannot do without. Many are metals: iron reddens our blood and helps it to transport oxygen to our cells, magnesium enables chlorophyll to capture the energy of sunlight at the foot of the food pyramid, sodium and potassium carry the electrical impulses of our nerves. Of all the natural elements, eleven can be considered the basic constituents of life, and perhaps fifteen others are essential trace elements, needed by almost all living organisms in small quantities. ('Toxic' arsenic and 'sterilizing' bromine are among them, showing that there is no easy division of elements into 'good' and 'bad'.)

The uneven distribution of elements across the face of the earth has shaped history – stimulating trade and encouraging exploration and cultural exchange, but also promoting exploitation, war, and imperialism. Southern Africa has paid dearly for its gold and the elemental carbon of its diamonds. Many rare but technologically important elements, such as tantalum and uranium, continue to be mined from poor regions of the world under conditions (and for reasons) that some consider pernicious and hazardous.

All the naturally occurring stable elements were known by the mid-twentieth century, and experiments with nuclear energy at that time brought to light a whole pantheon of heavier, short-lived radioactive elements. But only with the development of new ultra-sensitive techniques of chemical analysis have we become alerted to the complexity with which they are blended in the world, seasoning the oceans and the air with exquisite delicacy.

And so today's bottles of mineral water list their proportions of sodium, potassium, chlorine, and much else, banishing the notion that all we are drinking is H_2O. We know that elements are labile things, which is why lead water pipes and lead-based paints are no longer manufactured, and why aluminium cooking utensils are (rightly or wrongly) accused on suspicion of causing dementia. The reputations of the elements continue to be shaped by folklore and received wisdom as much as by an understanding of their quantitative effects. Is aluminium, then, good in the mineral brighteners of washing powders but bad in pots and pans? Copper salts can be toxic, but copper bracelets are rumoured to cure arthritis. We take selenium supplements to boost fertility, while selenium contamination of natural waters devastates Californian ecosystems. Which of us can say whether 0.01 milligrams of potassium in our bottled water is too little or too much?

The terminology of the elements suffuses our language, sometimes divorced from the questions of composition to which it once referred. Plumbing today is more likely to be made from plastic pipes than from the Romans' *plumbum* (lead); the lead in pencils is no such thing. 'Cadmium Red' paints often contain no cadmium at all. Tin cans have no more than the thinnest veneer of metallic tin; it is too valuable for more. The American nickel contains relatively little of that metal. And when was the last time that a Frenchman's pocketful of jingling *argent* was made of real silver?

Such are reasons why the story of the elements is not simply a tale of a hundred or so different types of atom, each with its unique properties and idiosyncracies. It is a story about our cultural interactions with the nature and composition of matter. The Whiggish history of chemistry as a gradual elucidation and tabulation of matter's building blocks obscures a deeper and more profound enquiry into the constitution of the world, and the mutability of that constitution by human or natural agency.

Pieces of the puzzle

The concept of elements is intimately entwined with the idea of atoms, but each does not demand the other. Plato believed in the four canonical elements of antiquity, but he did not exactly concur with the notion of atoms. Other Greek philosophers trusted in atoms but did not divide all matter into a handful of basic ingredients.

Thales of Miletus (*c*.620–*c*.555 BC), one of the first known enquirers into the constitution of the physical world, posited only one fundamental substance: water. There is ample justification for this view in myth; the Hebrew god was not the only deity to bring forth the world from a primal ocean. But the Milesian school of philosophers that Thales founded produced little consensus about the *prote hyle* or 'first matter' that constituted everything. Anaximander (*c*.611–547 BC), Thales' successor, avoided the issue with his contention that things are ultimately made of *apeiron*, the 'indefinite' and unknowable first substance. Anaximenes (d. *c*.500 BC) decided that air, not water, was primary. For Heraclitus (d. 460 BC), fire was the stuff of creation.

Why should anyone believe in a *prote hyle* at all – or, for that matter, in any scheme of elements that underlies the many substances we find in the world? Why not simply conclude that rock is rock, wood is wood? Metal, flesh, bone, grass . . . there were plenty of distinct substances in the ancient world. Why not accept them at face value, rather than as manifestations of something else?

Some science historians argue that these ancient savants were searching for unity: to reduce the multifarious world to a simpler and less puzzling scheme. A predilection for 'first principles' is certainly evident in Greek philosophy, but there is also a practical reason to invoke fundamental elements: things change. Water freezes or boils away. Wood burns, transforming a heavy log to insubstantial ashes. Metals melt; food is ingested and most of it is somehow spirited away inside the stomach.

If one substance can be transformed to another substance, might that be because they are, at root, merely different forms of the same substance? The idea of elements surely arose not because philosophers were engaged on some ancient version of the physicists' quest for a unified theory but because they wanted to understand the transformations that they observed daily in the world.

To this end, Anaximander believed that change came about through the agency of contending opposite qualities: hot and cold, and dry and moist. When Empedocles (*c.*490–*c.*430 BC) postulated the four elements that gained ascendancy in Western natural philosophy, he too argued that their transformations involved conflict.

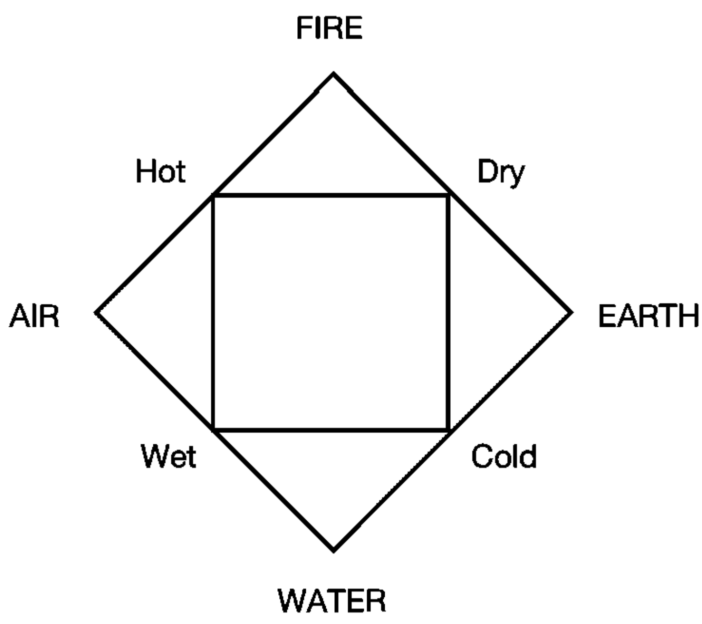
Empedocles does not exactly fit the mould of a sober and dignified Greek philosopher. Legend paints him as a magician and miracle worker who could bring the dead back to life. Reputedly he died by leaping into the volcanic maw of Mount Etna, convinced he was an immortal god. Small wonder, perhaps, that his earth, air, fire, and water were wrought into different blends – the materials of the natural world – through the agency of the colourful principles Love and Strife. Love causes mixing; Strife, separation. Their conflict is an eternal waxing and waning: at one time, Love dominates and things mix, but then Strife arises to pull them apart. This applies, said Empedocles, not just to the elements but to the lives of people and cultures.

Empedocles' four elements do not represent a multiplication of the *prote hyle*, but rather a gloss that conceals its complications. Aristotle agreed that ultimately there was only one primal substance, but it was too remote, too unknowable, to serve as the basis for a philosophy of matter. So he accepted Empedocles' elements as a kind of intermediary between this imponderable stuff and the tangible world. This instinct to reduce cosmic questions to manageable ones is one reason why Aristotle was so influential.

Aristotle shared Anaximander's view that the qualities heat, cold, wetness, and dryness are the keys to transformation, and also to our experience of the elements. It is *because* water is wet and cold that we can experience it. Each of the elements, in Aristotle's ontology, is awarded two of these qualities, so that one of them can be converted to another by inverting one of the qualities. Wet, cold water becomes dry, cold earth by turning wetness to dryness (Fig. 1).

It is tempting, and not wholly unrealistic, to regard these ancient philosophers as belonging to a kind of gentleman's club whose members are constantly borrowing one another's ideas, heaping lavish praise or harsh criticism on their colleagues, while all the while remaining 'armchair' scientists who decline, by and large, to dirty their hands through experiment. The same image serves for those who debated the fluctuating fortunes of atoms.

Leucippus of Miletus (fifth century BC) is generally credited with introducing the concept of atoms, but we know little more about



1. Aristotle believed that the four elements of Empedocles were each imbued with two qualities, by means of which they could be interconverted

him than that. He maintained that these tiny particles are all made of the same primal substance, but have different shapes in different materials. His disciple Democritus (*c.*460–370 BC) called these particles *atomos*, meaning uncuttable or indivisible. Democritus reconciled this fledgling atomic theory with the classical elements by positing that the atoms of each element have shapes that account for their properties. Fire atoms are immiscible with others, but the atoms of the other three elements get entangled to form dense, tangible matter.

What distinguished the atomists from their opponents was not the belief in tiny particles that make up matter, but the question of what separated them. Democritus supposed that atoms move about in a void. Other philosophers ridiculed this idea of 'nothingness', maintaining that the elements must fill all of space. Anaxagoras (*c.*500–428 BC), who taught both Pericles and Euripides in Athens, claimed that there was no limit to the smallness of particles, so that matter was infinitely divisible. This meant that tiny grains would fill up all the nooks between larger grains, like sand between stones. Aristotle asserted – and who can blame him? – that air would fill any void between atoms. (This becomes a problem only if you consider that air is itself *made* of atoms.)

Plato had it all figured out neatly. He was not an atomist in the mould of Democritus, but he did conceive of atom-like fundamental particles of the four Empedoclean elements. His geometrical inclinations led him to propose that these particles had regular, mathematical shapes: the polyhedra called regular Platonic solids. Earth was a cube, air an octahedron, fire a tetrahedron and water an icosahedron. The flat faces of each of these shapes can be made from two kinds of triangle. These triangles are, according to Plato, the true 'fundamental particles' of nature, and they pervade all space. The elements are converted by rearranging the triangles into new geometric forms.

There is a fifth Platonic regular solid too: the dodecahedron, which has pentagonal (five-sided) faces. This polyhedron cannot be made from the triangles of the other four, which is why Plato assigned it to the heavens. There is thus a fifth classical element, which Aristotle called the aether. But it is inaccessible to earthly beings, and so plays no part in the constitution of mundane matter.

The poetic elements

The four elements of antiquity perfuse the history of Western culture. Shakespeare's Lear runs amok in the stormy rain, the rushing air, and the 'oak-cleaving thunderbolts' of fire, nature's 'fretful elements'. Two of his sonnets are paired in celebration of the quartet: 'sea and land . . . so much of earth and water wrought', and 'slight air and purging fire'. Literary tradition has continued to uphold the four ancient elements, which supply the organizing principle of T. S. Eliot's *Quartets*.

The Greek philosophers coupled a four-element theory to the idea of four 'primary' colours: to Empedocles these were white, black, red, and the vaguely defined *ochron*, consistent with the preference of the classical Greek painters for a four-colour palette of white, black, red, and yellow. The Athenian astrologer Antiochos in the second century AD assigned these colours, respectively, to water, earth, air, and fire.

A determination to link the four elements to colours persisted long after the Greek primaries had been discarded. The Renaissance artist Leon Battista Alberti awarded red to fire, blue to air, green to water, and 'ash colour' (*cinereum*) to earth; Leonardo da Vinci made earth yellow instead. These associations would have surely informed the contemporaneous ideas of painters about how to mix and use colours.

This fourness of fundamental principles reaches further, embracing the four points of the compass (Chinese tradition acknowledges five elements, and five 'directions') and the four 'humours' of classical medicine. According to the Greek physician Galen (AD *c.*130–201), our health depends on the balance of these four essences: red blood, white phlegm, and black and yellow bile.

Even allowing for the ancient and medieval obsession with ‘correspondences’ among the characteristics and creations of nature, there is clearly something about the four Aristotelian elements that has deep roots in human experience. The Canadian writer Northrop Frye writes: ‘The four elements are not a conception of much use to modern chemistry – that is, they are not the elements of nature. But . . . earth, air, water and fire are still the four elements of imaginative experience, and always will be.’

This is why the French philosopher Gaston Bachelard felt it appropriate to explore the ‘psychoanalytic’ influence of these elements (in particular water and fire) in myth and poetry.

> I believe it is possible [he said] to establish in the realm of the imagination, a *law of the four elements* which classifies various kinds of material imagination by their connections with fire, air, water or earth . . . A material element must provide its own substance, its particular rules and poetics. It is not simply coincidental that primitive philosophies often made a decisive choice along these lines. They associated with their formal principles one of the four fundamental elements, which thus became signs of *philosophic disposition.*

Bachelard suggests that this disposition is, for every individual, conditioned by his or her material environment:

> the region we call home is less expanse than matter; it is granite or soil, wind or dryness, water or light. It is in it that we materialize our reveries, through it that our dream seizes upon its true substance. From it we solicit our fundamental colour. Dreaming by the river, I dedicated my imagination to water, to clear, green water, the water that makes the meadows green.

Despite a tendency to overestimate the primacy of the four-element scheme – there have been, as we have seen, many others – this idea goes some way towards explaining the longevity of Empedocles' elements. They *fit*, they accord with our experience. They distinguish different *kinds* of matter.

What this really means is that the classical elements are familiar representatives of the different *physical states* that matter can adopt. Earth represents not just soil or rock, but all solids. Water is the archetype of all liquids; air, of all gases and vapours. Fire is a strange one, for it is indeed a unique and striking phenomenon. Fire is actually a dancing plasma of molecules and molecular fragments, excited into a glowing state by heat. It is not a substance as such, but a variable combination of substances in a particular and unusual state caused by a chemical reaction. In experiential terms, fire is a perfect symbol of that other, intangible aspect of reality: light.

The ancients saw things this way too: that elements were *types*, not to be too closely identified with particular substances. When Plato speaks of water the element, he does not mean the same thing as the water that flows in rivers. River water is a manifestation of elementary water, but so is molten lead. Elementary water is 'that which flows'. Likewise, elementary earth is not just the stuff in the ground, but flesh, wood, metal.

Plato's elements can be interconverted because of the geometric commonalities of their 'atoms'. For Anaxagoras, all material substances are mixtures of all four elements, so one substance changes to another by virtue of the growth in proportion of one or more elements and the corresponding diminution of the others. This view of matter as intimate blends of elements is central to the antiquated elementary theories, and is one of the stark contrasts with the modern notion of an element as a fundamental substance that can be isolated and purified.

Age of metals

With Aristotle's endorsement, the Empedoclean elements thrived until the seventeenth century. With that blessing withheld, atomism withered. The Greek philosopher Epicurus (341–270 BC) established an atomistic tradition that was celebrated in 56 BC by the Roman poet Lucretius in his tract *De rerum natura* (*On the Nature of Things*). This atomistic poem was condemned by religious zealots in the Middle Ages, and barely escaped complete destruction. But it surfaced in the seventeenth century as a major influence on the French scientist Pierre Gassendi (1592–1655), whose vision of a mechanical world of atoms in motion represented one of the many emerging challenges to the Aristotelian orthodoxy.

Not everyone was ready for such radical changes. Gassendi's fellow 'mechanist' Marin Mersenne (1588–1648), in many ways a progressive thinker, nevertheless endorsed the Condemnation of 1624 in which Étienne de Clave was arrested, claiming that such gatherings encouraged the propagation of 'alchemical' ideas. Alchemy, however, had plenty more to say about the elements.

It may seem strange from today's perspective that several of the substances recognized today as elements – the metals gold, silver, iron, copper, lead, tin, and mercury – were not classed as such in antiquity, even though they could be prepared in an impressively pure state. Metallurgy is one of the most ancient of technical arts, and yet it impinged relatively little on the theories of the elements until after the Renaissance. Metals, with the exception of fluid mercury, were considered simply forms of Aristotelian 'earth'.

Alchemy, which provided the theoretical basis for metallurgy, gradually changed this. It added a deeper sophistication to ideas about the nature and transformation of matter, providing a bridge between the old and new conceptions of the elements.

If the notion of a single *prote hyle* was initially something of a dead end for a theory of matter, the Aristotelian elements were not a great deal better. The differences between lead and gold mattered very much to society, but the four-element theory could say little about them. A more refined scheme was needed to account for the metals.

Gold and copper are the oldest known metals, since they occur in their pure, elemental forms in nature. There is evidence of the mining and use of gold in the region of Armenia and Anatolia from before 5000 BC; copper use is similarly ancient in Asia. Copper mostly occurs not as the metal, however, but as a mineral ore: a chemical compound of copper and other elements, such as copper carbonate (the minerals malachite and azurite). These copper ores were used as pigments and colouring agents for glazes, and it is likely that copper smelting, which dates from around 4300 BC, arose from a happy accident during the glazing of stone ornaments called faience in the Middle East. The synthesis of bronze, an alloy of copper and tin, dates from about the same time.

Lead was smelted from one of its ores (galena) since around 3500 BC, but was not common until 1,000 years later. Tin seems to originate in Persia around 1800–1600 BC, and iron in Anatolia around 1400 BC. This sequence of discovery of the metals reflects the degree of difficulty in separating the pure metal from its ore: iron clings tightly to oxygen in the common mineral ore haematite (ochre), and intense heat and charcoal are needed to prise them apart.

With this profusion of metals, some scheme was needed to classify them. Convention dictated that this be at first a system of correspondences, so that the seven known metals became linked with the seven known celestial bodies and the seven days of the week (Table 1). Since all metals shared attributes in common (shininess, denseness, malleability), it seemed natural to suppose that they were different only in degree and not in kind. Thus arose

Table 1 *The seven 'classical' metals and their correspondences*

Metal	Celestial body	Day
Gold	Sun	Sunday
Silver	Moon	Monday
Mercury (Quicksilver)	Mercury	Wednesday (Fr. *Mercredi*)
Copper	Venus	Friday (Fr. *Vendredi*)
Iron	Mars	Tuesday (Fr. *Mardi*)
Tin	Jupiter	Thursday (Fr. *Jeudi*)
Lead	Saturn	Saturday

the precept that metals 'mature' in the earth, beginning with dull, dirty lead and culminating in glorious gold.

This was the central belief of alchemy. If metals may indeed be interconverted one to another in the deep earth, perhaps the alchemist could find a way to accelerate the process artificially and make gold from baser metals. But how was this done?

Attempts to transmute other metals to gold may have been made as long ago as the Bronze Age. But after the eighth century AD they were no longer haphazard; they had a theoretical underpinning in the sulphur-mercury theory of the Arabic alchemist Jabir ibn Hayyan. Jabir is more the name of a school of thought than of a person. Many more writings are attributed to him than he could possibly have written, and there is some doubt about whether he existed at all. The Jabirian tradition works curious things with the Aristotelian elements. It accepts them implicitly but then, so far as metals are concerned, adds another layer between these fundamental substances and reality.

According to Jabir, the ‘fundamental qualities’ of metals are the Aristotelian hot, cold, dry, and moist. But the ‘immediate qualities’ are two ‘principles’: sulphur and mercury. All metals are deemed to be mixtures of sulphur and mercury. In base metals they are impure; in silver and gold they attain a higher state of purity. The purest mixtures of this sulphur and mercury yield not gold but the Holy Grail of alchemy, the Philosopher’s Stone, the smallest quantity of which can transform base metals to gold.

Some scholars have identified Jabir’s sulphur and mercury with the Aristotelian opposites fire and water. One thing is sure: they are not the yellow sulphur and the glistening, fluid mercury of the chemistry laboratory, which were known in more or less pure form even to the alchemists. Instead, these two principles were rather like the four classical elements: ‘ideal’ substances embodied only imperfectly in earthly materials.

So the Jabirian system embraced the four classical elements and then buried them, just as the Aristotelian elements allowed but ignored the universal *prote hyle*. It marks the beginning of a tendency to pay lip service to Aristotle while getting on with more practical concerns about what things are made of.

The next step away from the traditions of antiquity involved the addition of a third ‘principle’ to Jabir’s sulphur and mercury: salt. Whereas the first two were components of metals, salt was considered an essential ingredient of living bodies. In this way alchemical theory became more than a theory of metallurgy and embraced all the material world. The three-principle theory is generally attributed to the Swiss alchemist Paracelsus (1493–1541), although it is probably older. Paracelsus asserted that sulphur, salt, and mercury ‘form everything that lies in the four elements’.

So these Paracelsian principles were not meant to be elements in themselves, but rather a material manifestation of the ancient elements. By the end of the seventeenth century, things had moved on again. There was no longer any perceived obligation to square one's views with Aristotle, and the 'principles' were widely regarded as elements in their own right. Jean Béguin listed a popular scheme of five elements: mercury, sulphur, salt, phlegm, and earth. He claimed that none of them was pure – each contained a little of the others.

Johann Becher (1635–*c.*1682), an influential German alchemist of the most flamboyant kind, accepted that air, water, and earth were elements, but did not accord them equal status. Air, he believed, was inert and did not take part in processes of transformation. He felt that the differences between the many dense substances of the world stemmed from three different types of earth. *Terra fluida* was a fluid element that gave metals their shininess and heaviness. *Terra pinguis* was a 'fatty earth', abundant in organic (animal and vegetable) matter, which made things combustible. *Terra lapidea* was 'vitreous earth', which made things solid. These three earths are in fact nothing but mercury, sulphur, and salt in disguise, but we will see later how modern chemistry arose out of them.

The sceptical chymist

The impetus for this sudden profusion and elaboration of elemental schemes came mostly from experiment. No longer content to apportion matter into the abstract, remote elements of the Greeks, the early chemists of the seventeenth century began trying to understand matter by practical means.

Alchemy always had a strong experimental side. In their endless quest for the Philosopher's Stone, alchemists burnt, distilled, melted, and condensed all manner of substances and stumbled across many technologically important new compounds, such as phosphorus and nitric acid. But in the 1600s there appeared a transitional group of natural philosophers whose primary objective was no longer to conduct the Great Work of alchemical transformation but to study and understand matter at a more mundane level. These ‘chymists’ were neither alchemists nor chemists; or, rather, they were a bit of both. One of them was Robert Boyle (1627–91).

The Eton-educated son of an Irish aristocrat, Boyle became part of the innermost circle of British science in the mid-seventeenth century. He was on good if not intimate terms with Isaac Newton (hardly anyone was intimate with Newton), and was involved in the founding of the Royal Society in 1661. Like many of his contemporaries, he was passionately interested in alchemy; but, crucially, he was also an independent and penetrating thinker.

Traditionally portrayed as a broadside against alchemy in general, Boyle’s classic book *The Sceptical Chymist* (1661) in fact aims to distinguish the learned and respectable alchemical ‘adepts’ (such as Boyle himself) from the ‘vulgar laborants’ who sought after gold by means of blind recipe following. The book’s lasting value to chemistry comes from Boyle’s assault on all the main schools of thought about the elements. These, he said, are simply incompatible with the experimental facts.

The conventional four-element theory claimed that all four of Aristotle’s elements are present in all substances. But Boyle observes that some materials cannot be reduced to the classical elementary components, however they are manipulated by ‘Vulcan’, the heat of a furnace:

> Out of some bodies, four elements cannot be extracted, as Gold, out of which not so much as any *one* of them hath been hitherto. The like may be said of Silver, calcined Talke [roasted talc], and divers other fixed bodies, which to reduce into four heterogeneal substances, is a taske that has hitherto proved too hard for Vulcan.

In other words, elements are to be found not by theorizing but by experiment: ‘I must proceed to tell you that though the assertors of the four elements value reason so highly . . . no man had ever yet made any sensible trial to discover their number.'

Boyle's definition of an element is nothing very controversial by the standards of the times:

> certain primitive and simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the ingredients of which all those called perfectly mixt bodies are immediately compounded, and into which they are ultimately resolved.

But he then proceeds to question whether anything of this sort truly exists – that is, whether there are elements at all. Certainly, Boyle holds back from offering any replacement for the elemental schemes he demolishes, although he shows some sympathy for the idea, advocated by the Flemish scientist Johann Baptista van Helmont, that everything is made of water.

By the end of the seventeenth century, then, scientists were not really any closer to enumerating the elements than were the Greek philosophers. Yet a hundred years later the British chemist John Dalton (1766–1844) wrote a textbook that outlined a recognizably modern atomic theory and gave a list of elements that, while still very incomplete and sometimes plain wrong, is in content and in spirit a clear precursor to today's tabulation of the hundred and more elements. Why had our understanding of the elements changed so fast?

Boyle's demand for experimental analysis as the arbiter of elemental status is a central component of this change. Another reason for the revolution was the relinquishment of old preconceptions about what elements should be like. For the classical scholars, an element had to correspond to (or at least be recognizable in) stuff that you found around you. Many of the substances today designated as elements are ones almost all of us will never see or hold; in antiquity, that would seem an absurd complication. (True, no one could hold the aether, but everyone could see that the heavens sat over the earth.) Some confusion was also dispelled as scientists began to appreciate that substances could change their physical state – from solid to liquid to gas – without changing their elemental composition. Ice is not water turned to 'earth' – it is frozen water.

In short, there is nothing *obvious* about the elements. Until the twentieth century, scientists had no idea why there should be so many, nor indeed why there should not be thousands more. The elements cannot be deduced by casual inspection of the world, but only by the most exacting scrutiny using all the complicated tools of modern science.

This is why, perhaps, some people would like to stick with earth, air, fire, and water. They are not the elements of chemistry, but they say something resonant about how we interact with the world and about the effect that matter has on us.