From *The Ascent of Man* by Jacob Bronowski

THE HIDDEN STRUCTURE

> *It is with fire that blacksmiths iron subdue*
> *Unto fair form, the image of their thought:*
> *Nor without fire hath any artist wrought*
> *Gold to its utmost purity of hue.*
> *Nay, nor the unmatched phoenix lives anew,*
> *Unless she burn.*
>
> Michelangelo, Sonnet 59

> *What is accomplished by fire is alchemy, whether in the furnace or kitchen stove.*
>
> Paracelsus

There is a special mystery and fascination about man's relation to fire, the only one of the four Greek elements that no animal inhabits (not even the salamander). Modern physical science is much concerned with the invisible fine structure of matter, and that is first opened by the sharp instrument of fire. Although that mode of analysis begins several thousand years ago in practical processes (the extraction of salt and of metals, for example) it was surely set going by the air of magic that boils out of the fire: the alchemical feeling that substances can be changed in unpredictable ways. This is the numinous quality that seems to make fire a source of life and a living thing to carry us into a hidden underworld within the material world. Many ancient recipes express it.

> *Now the substance of cinnabar is such that the more it is heated, the more exquisite are its sublimations. Cinnabar will become mercury, and passing through a series of other sublimations, it is again turned into cinnabar, and thus it enables man to enjoy eternal life.*

This is the classic experiment with which the alchemists in the Middle Ages inspired awe in those who watched them, all the way from China to Spain. They took the red pigment, cinnabar, which is a sulfide of mercury, and heated it. The heat drives off the sulfur and leaves behind an exquisite pearl of the mysterious silvery liquid metal mercury; to astonish and strike awe into the patron. When the mercury is heated in air it is oxidized and becomes, not (as the recipe thought) cinnabar again, but an oxide of mercury that is also red. Yet the recipe was not quite mistaken; the oxide can be turned into mercury again, red to silver, and the mercury to its oxide, silver to red, all by the action of heat.

It is not an experiment of any importance in itself, although it happens that sulfur and mercury are the two elements of which the alchemist before AD 1500 thought the universe was composed. But it does show one important thing, that fire has always been regarded not as the destroying element but as the transforming element. That has been the magic of fire.

I remember Aldous Huxley talking to me through a long evening, his white hands held into the fire, saying, ‘This is what transforms. These are the legends that show it. Above all, the legend of the Phoenix that is reborn in the fire, and lives over and over again in generation after generation.’ Fire is the image of youth and blood, the symbolic color in the ruby and cinnabar, and in ochre and hematite with which men painted themselves ceremonially. When Prometheus in Greek mythology brought fire to man, he gave him life and made him into a demigod - that is why the gods punished Prometheus.

In a more practical way, fire has been known to early man for about four hundred thousand years, we think. That implies that fire had already been discovered by Homo erectus; as I have stressed, it is certainly found in the caves of Peking man. Every culture since then has used fire, although it is not clear that they all knew how to make fire; in historical times one tribe has been found (the pygmies in the tropical rain forest on the Andaman Islands south of Burma) who carefully tended spontaneous fires because they had no technique for making fire in a more practical way.

In general, the different cultures have used fire for the same purposes: to keep warm, to drive off predators and clear woodland, and to make the simple transformations of everyday life -to cook, to dry and harden wood, to heat and split stones. But, of course, the great transformation that helped to make our civilization goes deeper: it is the use of fire to disclose a wholly new class of materials, the metals. This is one of the grand technical steps, a stride in the ascent of man, which ranks with the master invention of stone tools; for it was made by discovering in fire a subtler tool for taking matter apart. Physics is the knife that cuts into the grain of nature; fire, the flaming sword, is the knife that cuts below the visible structure into the stone.

Almost ten thousand years ago, not long after the beginning of the settled communities of agriculture, men in the Middle East began to use copper. But the use of metals could not become general until there was found a systematic process for getting them. That is the extraction of metals from their ores, which we now know was begun rather over seven thousand years ago, about the year 5000 BC in Persia and Afghanistan. At that time, men put the green stone malachite into the fire in earnest, and from it flowed the red metal, copper - happily copper is released at a modest temperature. They recognized copper because it is sometimes found in raw lumps on the surface, and in that form, it had been hammered and worked for over two thousand years already.

The New World too worked copper, and smelted it by the time of Christ, but it paused there. Only the Old World went on to make metal the backbone of civilized life. Suddenly the range of man's control is increased immensely. He has at his command a material which can be molded, drawn, hammered, cast; which can be made into a tool, an ornament, a vessel; and which can be thrown back into the fire and reshaped. It has only one shortcoming: copper is a soft metal. As soon as it is put under strain, stretched in the form of a wire for instance, it visibly begins to yield. That is because, like every metal, pure copper is made up of layers of crystals. And it is the crystal layers, each like a wafer in which the atoms of the metal are laid out in a regular lattice, which slide over one another until they finally part. When the copper wire begins to neck (that is, develop a weakness), it is not so much that it fails in tension, as that it fails by internal slipping.

Of course, the coppersmith did not think like that six thousand years ago. He was faced with a robust problem, which is that copper will not take an edge. For a short time, the ascent of man stood poised at the next step: to make a hard metal with a cutting edge. If that seems a large claim for a technical advance, that is because, as a discovery, the next step is so paradoxical and beautiful.

If we picture the next step in modern terms, what needed to be done was plain enough. We have heard that copper as a pure metal is soft because its crystals have parallel planes which easily slip past one another. (It can be hardened somewhat by hammering to break up the large crystals and make them jagged.) We can deduce that if we could build something gritty into the crystals, that would stop the planes from sliding and would make the metal hard. Of course, on the scale of fine structure that I am describing, something gritty must be a different kind of atoms in place of some of the copper atoms in the crystals. We have to make an alloy whose crystals are more rigid because the atoms in them are not all of the same kind.

That is the modern picture; it is only in the last fifty years that we have come to understand that the special properties of alloys derive from their atomic structure. And yet, by luck or by experiment, the ancient smelters found just this answer: namely, that when to copper you add an even softer metal, tin, you make an alloy which is harder and more durable than either - bronze. Probably the piece of luck was that tin ores in the Old World are found together with copper ores. The point is that almost any pure material is weak, and many impurities will do to make it stronger. What tin does is not a unique but a general function: to add to the pure material a kind of atomic grit - points of a different roughness which stick in the crystal lattices and stop them from sliding.

I have been at pains to describe the nature of bronze in scientific terms because it is a marvelous discovery. And it is marvelous also as a revelation of the potential that a new process carries and evokes in those who handle it. The working of bronze reached its finest expression in China. It had come to China almost certainly from the Middle East, where bronze was discovered about 3800 BC. The high period of bronze in China is also the beginning of Chinese civilization as we think of it - the Shang dynasty, before 1500 BC.

The Shang dynasty governed a group of feudal domains in the valley of the Yellow River, and for the first time created some unitary state and culture in China. ln all ways it is a formative time, when ceramics are also developed and writing becomes fixed. (It is the calligraphy, both on the ceramics and the bronze, which is so startling.) The bronzes in the high period were made with an Oriental attention to detail which is fascinating in itself.

The Chinese made the mold for a bronze casting out of strips shaped round a ceramic core. And because the strips are still found, we know how the process worked. We can follow the preparation of the basic core, the incising of the pattern, and particularly the inscribed lettering on the strips formed on the core. The strips thus make up an outer ceramic mold which is baked hard to take the hot metal. We can even follow the traditional preparation of the bronze. The proportions of copper and tin that the Chinese used are fairly exact. Bronze can be made from almost any proportion between, say, five per cent and twenty per cent of tin added to the copper. But the best Shang bronzes are held at fifteen per cent tin, and there the sharpness of the casting is perfect. At that proportion, bronze is almost three times as hard as copper.

The Shang bronzes are ceremonial, divine objects. They express for China a monumental worship which, in Europe at that same moment, was building Stonehenge. Bronze becomes, from this time onwards, a material for all purposes, the plastic of its age. It has this universal quality wherever it is found, in Europe and in Asia.

But in the climax of the Chinese craftsmanship, the bronze expresses something more. The delight of these Chinese works, vessels for wine and food - in part playful and in part divine - is that they form an art that grows spontaneously out of its own technical skill. The maker is ruled and directed by the material; in shape and in surface, his design flows from the process. The beauty that he creates, the mastery that he communicates, comes from his own devotion to his craft.

The scientific content of these classical techniques is clear-cut. With the discovery that fire will smelt metals comes, in time, the subtler discovery that fire will fuse them together to make an alloy with new properties. That is as true of iron as of copper. Indeed, the parallel between the metals holds at every stage. Iron also was first used in its natural form; raw iron arrives on the surface of the earth in meteorites, and for that reason its Sumerian name is ‘metal from heaven’. When iron ores were smelted later, the metal was recognized because it had already been used. The Indians in North America used meteoric iron, but never could smelt the ores.

Because it is much more difficult to extract from its ores than copper, smelted iron is, of course, a much later discovery. The first positive evidence for its practical use is probably a piece of a tool that has got stuck in one of the pyramids; that gives it a date before 2500 BC. But the wide use of iron was really initiated by the Hittites near the Black Sea around 1500 BC - just the time of the finest bronze in China, the time of Stonehenge.

And as copper comes of age in its alloy, bronze, so iron comes of age in its alloy, steel. Within five hundred years, by 1000 BC, steel is being made in India, and the exquisite properties of different kinds of steel come to be known. Nevertheless, steel remained a special and in some ways a rare material for limited use until quite recent times. As late as two hundred years ago, the steel industry of Sheffield was still small and backward, and the Quaker Benjamin Hunts man, wanting to make a precision watch-spring, had to turn metallurgist and discover how to make the steel for it himself.

Since I have turned to the Far East to look at the perfection of bronze, I will take an Oriental example also of the techniques that produce the special properties of steel. They reach their climax, for me, in the making of the Japanese sword, which has been going on in one way or another since AD 800. The making of the sword, like all ancient metallurgy, is surrounded with ritual, and that is for a clear reason. When you have no written language, when you have nothing that can be called a chemical formula, then you must have a precise ceremonial which fixes the sequence of operations so that they are exact and memorable.

So, there is a kind of laying on of hands, an apostolic succession, by which one generation blesses and gives to the next the materials, blesses the fire, and blesses the sword-maker. The man who was making this sword holds the title of a ‘Living Cultural Monument’, formally awarded to the leading masters of ancient arts by the Japanese government. His name is Getsu. And in a formal sense, he is a direct descendant in his craft of the sword-maker Masamune, who perfected the process in the thirteenth century - to repel the Mongols. Or so tradition has it; certainly, the Mongols at that time repeatedly tried to invade Japan from China, under the command of the grandson of Genghis Khan, the famous Kublai Khan.

Iron is a later discovery than copper because at every stage it needs more heat - in smelting, working and, naturally, in processing its alloy, steel. (The melting point of iron is about 1500^o C, almost 500^o C higher than that of copper.) Both in heat treatment and in its response to added elements, steel is a material in finitely more sensitive than bronze. In it, iron is alloyed with a tiny percentage of carbon, less than one per cent usually, and variations in that dictate the underlying properties of the steel.

The process of making the sword reflects the delicate control of carbon and of heat treatment by which a steel object is made to fit its function perfectly. Even the steel billet is not simple, because a sword must combine two different and incompatible properties of materials. It must be flexible, and yet it must be hard. Those are not properties which can be built into the same material unless it consists of layers. In order to achieve that, the steel billet is cut, and then doubled over again and again so as to make a multitude of inner surfaces. The sword that Getsu makes requires him to double the billet fifteen times. This means that the number of layers of steel will be 2^{15} which is well over thirty thousand layers. Each layer must be bound to the next, which has a different property. It is as if he were trying to combine the flexibility of rubber with the hardness of glass. And the sword, essentially, is an immense sandwich of these two properties.

At the last stage, the sword is prepared by being covered with clay to different thicknesses, so that when it is heated and plunged into water it will cool at different rates. The temperature of the steel for this final moment has to be judged precisely, and in a civilization in which that is not done by measurement, ‘it is the practice to watch the sword being heated until it glows to the color of the morning sun’. In fairness to the sword-maker, I ought to say that such color cues were also traditional in steelmaking in Europe: as late as the eighteenth century, the right stage at which to temper steel was when it glowed straw-yellow, or purple, or blue, according to the different use for which it was intended.

The climax, not so much of drama as of chemistry, is the quenching, which hardens the sword and fixes the different properties within it. Different crystal shapes and sizes are produced by the different rates of cooling: large, smooth crystals at the flexible core of the sword, and small jagged crystals at the cutting edge. The two properties of rubber and glass are finally fused in the finished sword. They reveal themselves in its surface appearance - a sheen of shot silk by which the Japanese set high store. But the test of the sword, the test of a technical practice, the test of a scientific theory, is 'Does it work?' Can it cut the human body in the formal ways that ritual lays down? The traditional cuts are mapped as carefully as the cuts of beef on a diagram in a cookery book: ‘Cut number two - the O-jo-dan.’ The body is simulated by packed straw, nowadays. But in the past a new sword was tested more literally, by using it to execute a prisoner.

The sword is the weapon of the Samurai. By it they survived endless civil wars that divided Japan from the twelfth century on. Everything about them is fine metalwork: the flexible armor made of steel strips, the horse trappings, the stirrups. And yet the Samurai did not know how to make any of these things themselves. Like the horsemen in other cultures they lived by force, and depended even for their weapons on the skill of villagers whom they alternately protected and robbed. In the long run, the Samurai became a set of paid mercenaries who sold their services for gold.

Our understanding of how the material world is put together from its elements derives from two sources. One, that I have traced, is the development of techniques for making and alloying useful metals. The other is alchemy, and it has a different character. It is small in scale, is not directed to daily uses, and contains a substantial body of speculative theory. For reasons which are oblique but not accidental, alchemy was much occupied with another metal, gold, which is virtually useless. Yet gold has so fascinated human societies that I should be perverse if I did not try to isolate the properties that gave it its symbolic power.

Gold is the universal prize in all countries, in all cultures, in all ages. A representative collection of gold artefacts reads like a chronicle of civilizations. Enameled gold rosary, 16th century, English. Gold serpent brooch, 400 BC, Greek. Triple gold crown of Abuna, I7th century, Abyssinian. Gold snake bracelet, ancient Roman. Ritual vessels of Achaemenid gold, 6th century BC, Persian. Drinking bowl of Malik gold, 8th century BC, Persian. Bulls' heads in gold ... Ceremonial gold knife, Chimu, Pre-Inca, Peruvian, 9th century ...

Sculpted gold salt-cellar, Benvenuto Cellini, !6th-century figures, made for King Francis L Cellini recalled what his French patron said of it:

> *When I set this work before the king, he gasped in amazement and could not take his eyes off it He cried in astonishment, 'This is a hundred times more heavenly than I would ever have thought! What a marvel the man is.'*

The Spaniards plundered Peru for its gold, which the Inca aristocracy had collected as we might collect stamps, with the touch of Midas. Gold for greed, gold for splendor, gold for adornment, gold for reverence, gold for power, sacrificial gold, life-giving gold, gold for tenderness, barbaric gold, voluptuous gold...

The Chinese put their finger on what made it irresistible. Ko Hung said, ‘Yellow gold, if melted a hundred times, will not be spoiled.’ In that phrase, we become aware that gold has a physical quality that makes it singular; which can be tested or assayed in practice, and characterized in theory.

It is easy to see that the man who made a gold artefact was not just a technician, but an artist. But it is equally important, and not so easy to recognize, that the man who assayed gold was also more than a technician. To him gold was an element of science. Having a technique is useful but, like every skill, what brings it to life is its place in a general scheme of nature - a theory.

Men who tested and refined gold made visible a theory of nature: a theory in which gold was unique, and yet might be made from other elements. That is why so much of antiquity spent its time and ingenuity in devising tests for pure gold. Francis Bacon at the opening of the seventeenth century put the issue squarely.

> *Gold hath these natures – greatness of weight, closeness of parts, fixation, pliantness or softness, immunity from rust, color or tincture of yellow. If a man can make a metal that hath all these properties, let men dispute whether it be gold or no.*

Gold is the universal prize in all countries, in all cultures, in all ages.

Greek gold: Mask of an Achaean king, from a shaft grave in Mycenae, 16th century BC.

Persian gold: Gold dinar of Khusrau II minted in Iran.

Peruvian gold: Mochica puma, stamped with a design of two-headed serpents.

African gold: Cast gold badge. worn by the Asantehene's (king's) ‘soulwasher’· as a badge of office, a disk decorated with concentric incised bands, with a pyramidal boss. Ghana, before 1874.

Modern gold: Central input receiver, Concorde Multiplexing

Among the several classical tests for gold, one in particular makes the diagnostic property most visible. This is a precise test by cupellation. A bone ash vessel, or cupel, is heated in the furnace and brought up to a temperature much higher than pure gold requires. The gold, with its impurities or dross, is put in the vessel and melts. (Gold has quite a low melting point, just over 1000° C, almost the same as copper.) What happens now is that the dross leaves the gold and is absorbed into the walls of the vessel: so that all at once there is a visible separation between, as it were, the dross of this world and the hidden purity of the gold in the flame. The dream of the alchemists, to make synthetic gold, has in the end to be tested by the reality of the pearl of gold that survives the assay.

The ability of gold to resist what was called decay (what we would call chemical attack) was singular, and therefore both valuable and diagnostic. It also carried a powerful symbolism, which is explicit even in the earliest formulae. The first written reference we have to alchemy is just over two thousand years old, and comes from China. It tells how to make gold and to use it to prolong life. That is an extraordinary conjunction to us. To us gold is precious because it is scarce; but to the alchemists, all over the world, gold was precious because it was incorruptible. No acid or alkali known to those times would attack it That indeed is how the emperor's goldsmiths assayed or, as they would have said, parted it, by an acid treatment that was less laborious than cupellation.

When life was thought to be (and for most people was) solitary, poor, nasty, brutish, and short, to the alchemists, gold represented the one eternal spark in the human body. Their search to make gold and to find the elixir of life are one and the same endeavor. Gold is the symbol of immortality - but I ought not to say symbol, because in the thought of the alchemists' gold was the expression, the embodiment of incorruptibility, in the physical and in the living world together.

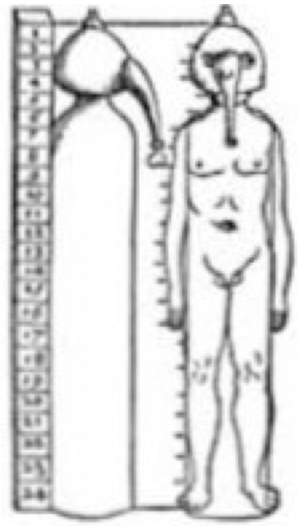
So, when the alchemists tried to transmute base metals into gold, the transformation that they sought in the fire was from the corruptible to the incorruptible; they were trying to extract the quality of permanence from the everyday. And this was the same as the search for eternal youth: every medicine to fight old age contained gold, metallic gold, as an essential ingredient, and the alchemists urged their patrons to drink from gold cups to prolong life.

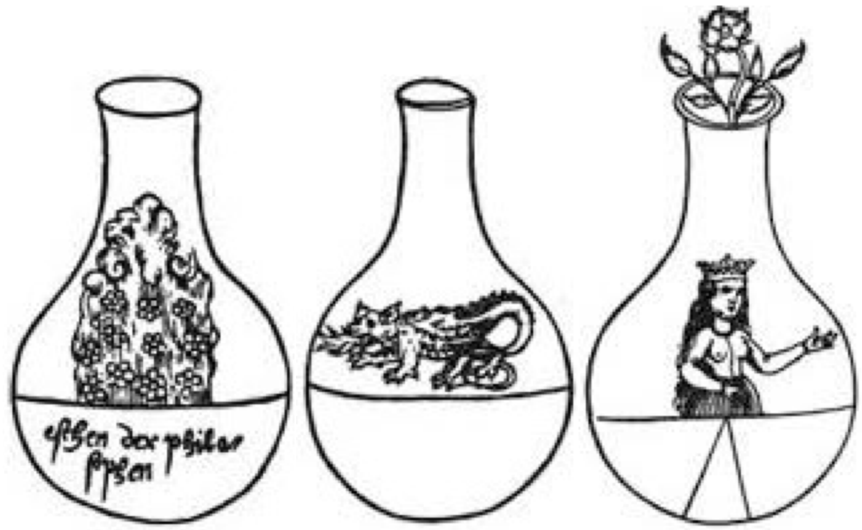
Alchemy is much more than a set of mechanical tricks or a vague belief in sympathetic magic. It is from the outset a theory of how the world is related to human life. In a time when there was no clear distinction between substance and process, element and action, the alchemical elements were also aspects of the human personality - just as the Greek elements were also the four humors which the human temperament combines. There lies therefore in their work a profound theory: one which derives in the first place of course from Greek ideas about earth, fire, air and water, but which by the Middle Ages had taken on a new and very important form.

To the alchemists then there was a sympathy between the microcosm of the human body and the macrocosm of nature. A volcano on a grand scale was like a boil; a tempest and rainstorm was like a fit of weeping. Under these superficial analogues lay the deeper concept. which is that the universe and the body are made of the same materials. or principles. or elements. To the alchemists there were two such principles. One was mercury, which stood for everything which is dense and permanent. The other was sulfur, which stood for everything that is inflammable and impermanent. All material bodies, including the human body, were made from these two principles and could be remade from them. For instance, the alchemists believed that all metals grow inside the earth from mercury and sulfur, the way the bones grow inside an embryo from the egg. And they really meant that analogy. It still remains in the symbolism of medicine now. We still use for the female the alchemical sign for copper, that is, what is soft: Venus. And we use tor the male the alchemical sign for iron, that is, what is hard: Mars.

That seems a terribly childish theory today, a hodge-podge of fables and false comparisons. But our chemistry will seem childish five hundred years from now. Every theory is based on some analogy, and sooner or later the theory fails because the analogy turns out to be false. A theory in its day helps to solve the problems of the day. And the medical problems had been hamstrung until about 1500, by the belief of the ancients that all cures must come either from plants or from animals - a kind of vitalism which would not entertain the thought that body chemicals are like other chemicals. and which therefore confined medicine largely to herbal cures.

Now the alchemists freely introduced minerals into medicine: salt, for example, was a pivot in the turnabout, and a new theoretician of alchemy made it his third element. He also developed a very characteristic cure for a disease which raged round Europe in 1500 and had not been known before, the new scourge syphilis. To this day, we do not know where syphilis came from. It may have been brought back by the sailors in Columbus's ships; it may have spread from the east with the Mongol conquests; or it may simply not have been recognized before as a separate disease. The cure for it turned out to depend on the use of the most powerful alchemical metal, mercury. The man who made that cure work is a landmark in the change from the old alchemy to the new, on the way towards modern chemistry introchemistry, biochemistry, the chemistry of life. He worked in Europe in the sixteenth century. The place was Basel in Switzerland. The year was 1527.





The universe and the body are made of the same materials or principles or elements.

Paracelsus' figure of the furnace of the body with a scale for the study of urine in diagnosis of illness, from 'Aurora Thesaurusque philosophorum'. Basel 1577
Paracelsus' figure of the three elements, earth, air and fire.

There is an instant in the ascent of man when he steps out of the shadowland of secret and anonymous knowledge into a new system of open and personal discovery. The man that I have chosen to symbolize it was christened Aureolus Philippus Theophrastus Bombastus von Hohenheim. Happily, he gave himself the somewhat more compact name of Paracelsus, to publicize his contempt for Celsus and other authors who had been dead more than a thousand years, yet whose medical texts were still current in the Middle Ages. In 1500, the works of classical authors were still thought to contain the inspired wisdom of a golden age, in medicine and science as well as in the arts.

Paracelsus was born near Zurich in 1493, and died at Salzburg in 1541 at the early age of forty-eight. He was a perpetual challenge to everything that was academic: for example, he was the first man to recognize an industrial disease. There are both grotesque and endearing episodes in the undaunted, lifelong battle Paracelsus fought with the oldest tradition of his time, the practice of medicine. His head was a perpetual fountain of theories, many of them contradictory, and most of them outrageous. He was a Rabelaisian, picaresque, wild character, drank with students, ran after women, travelled much over the Old World and, until recently, figured in the histories of science as a quack. But that he was not. He was a man of divided but profound genius.

The point is that Paracelsus was a character. We catch in him, perhaps for the first time, the transparent sense that a scientific discovery flows from a personality, and that discovery comes alive as we watch it being made by a person. Paracelsus was a practical man, who understood that the treatment of a patient depends on diagnosis (he was a brilliant diagnostician) and on direct application by the doctor himself. He broke with the tradition by which the physician was a learned academic who read out of a very old book, and the poor patient was in the hands of some assistant who did what he was told. 'There can be no surgeon who is not also a physician,' Paracelsus wrote. 'Where the physician is not also a surgeon he is an idol that is nothing but a painted monkey.'

Such aphorisms did not endear Paracelsus to his rivals, but they did make him attractive to other independent minds in the age of the Reformation. That is how he came to be brought to Basel for the single year of triumph in his otherwise disastrous worldly career. In Basel in the year 1527 Johann Frobenius, the great Protestant and humanist printer, had a serious leg infection - the leg was about to be amputated - and in despair appealed to his friends in the new movement, who sent him Paracelsus. Paracelsus threw the academics out of the room, saved the leg. and effected a cure which echoed through Europe. Erasmus wrote to him saying: 'You have brought back Frobenius, who is half my life, from the underworld'.

It is not accidental that new, iconoclastic ideas in medicine and chemical treatment come cheek by jowl, in time and in place, with the Reformation that Luther started in 1517. A focus of that historic time was Basel. Humanism had flourished there even before the Reformation. There was a university with a democratic tradition, so that, although its medical men looked askance at Paracelsus, the City Council could insist that he be allowed to teach. The Frobenius family was printing books, among them some by Erasmus, which spread the new outlook everywhere and in all fields.

A great change was blowing up in Europe, greater perhaps even than the religious and political upheaval that Martin Luther had set going. The symbolic year of destiny was just ahead, 1543. In that year, three books were published that changed the mind of Europe: the anatomical drawings of Andreas Vesalius; the first translation of the Greek mathematics and physics of Archimedes; and the book by Nicolaus Copernicus, *The Revolution of the Heavenly Orbs*, which put the sun at the center of the heaven and created what is now called the Scientific Revolution.

All that battle between past and future was summarized prophetically in 1527 in a single action outside the Winster at Basel. Paracelsus publicly threw into the traditional student bonfire an ancient medical textbook by Avicenna, an Arab follower of Aristotle.

There is something symbolic about that midsummer bonfire which I will try to conjure into the present. Fire is the alchemist's element by which man is able to cut deeply into the structure of matter. Then is fire itself a form of matter? If you believe that, you have to give it all sorts of impossible properties - such as, that it is lighter than nothing. Two hundred years after Paracelsus, as late as1730, that is what chemists tried to do in the theory of phlogiston as a last embodiment of material fire. But there is no such substance as phlogiston, just as there is no such principle as the vital principle - because fire is not a material, any more than life is material. Fire is a process of transformation and change, by which material elements are rejoined into new combinations. The nature of chemical processes was only understood when fire itself came to be understood as a process.

That gesture of Paracelsus had said, ‘Science cannot look back to the past. There never was a Golden Age.’ And from the time of Paracelsus it took another two hundred and fifty years to discover the new element, oxygen, which at last explained the nature of fire, and took chemistry forward out of the Middle Ages. The odd thing is that the man who made the discovery, Joseph Priestley, was not studying the nature of fire, but of another of the Greek elements, the invisible and omnipresent air.

Most of what remains of Joseph Priestley’s laboratory is in the Smithsonian Institution in Washington, D.C. And, of course, it has no business to be there. This apparatus ought to be in Birmingham in England, the center of the Industrial Revolution, where Priestley did his most splendid work. Why is it here? Because a mob drove Priestley out of Birmingham in 1791.

Priestley's story is characteristic of another conflict between originality and tradition. In I761 he had been invited, at the age of twenty-eight, to teach modern languages at one of the dissenting academies (he was a Unitarian) which took the place of universities for those who were not conformists of the Church of England. Within a year, Priestley was inspired by the lectures in science of one of his fellow teachers to begin a book about electricity; and from that he turned to chemical experiments. He also became excited about the American Revolution (he had been encouraged by Benjamin Franklin) and later the French Revolution. And so, on the second anniversary of the storming of the Bastille, the loyal citizens burned down what Priestley described as one of the most carefully assembled laboratories in the world. He went to America, but was not made welcome. Only his intellectual equals appreciated him; when Thomas Jefferson became President, he told Joseph Priestley, ‘Yours is one of the few lives precious to mankind’.

I would like to be able to tell you that the mob that destroyed Priestley's house in Birmingham shattered the dream of a beautiful, lovable, charming man. Alas, I doubt if that would really be true. I do not think Priestley was very lovable, any more than Paracelsus. I suspect that he was a rather difficult, cold, cantankerous, precise, prim, puritanical man. But the ascent of man is not made by lovable people. It is made by people who have two qualities: an immense integrity, and at least a little genius. Priestley had both.

The discovery that he made was that air is not an elementary substance: that it is composed of several gases and that, among those, oxygen - what he called ‘dephlogisticated air’ - is the one that is essential to the life of animals. Priestley was a good experimenter, and he went forward carefully in several steps. On 1 August 1774 he made some oxygen, and saw to his astonishment how brightly a candle burned in it. In October of that year he went to Paris, where he gave Lavoisier and others news of his finding. But it was not until he himself came back and, on 8 March 1775, put a mouse into oxygen, that he realized how well one breathed in that atmosphere. A day or two after, Priestley wrote a delightful letter in which he said to Franklin: 'Hitherto only two mice and myself have had the privilege of breathing it'.

Priestley also discovered that the green plants breathe out oxygen in sunlight, and so make a basis for the animals who breathe it in. The next hundred years were to show this is crucial; the animals would not have evolved at all if the plants had not made the oxygen first. But in the 1770s nobody had thought about that.

The discovery of oxygen was given meaning by the clear, revolutionary mind of Antoine Lavoisier (who perished in the French Revolution). Lavoisier repeated an experiment of Priestley's which is almost a caricature of one of the classical experiments of alchemy which I described at the beginning of this essay. Both men heated the red oxide of mercury, using a burning glass (the burning glass was fashionable just then), in a vessel in which they could see gas being produced, and could collect it. The gas was oxygen. That was the qualitative experiment; but to Lavoisier it was the instant clue to the idea that chemical decomposition can be quantified.

The idea was simple and radical; run the alchemical experiment in both directions, and measure the quantities that are exchanged exactly. First, in the forward direction: burn mercury (so that it absorbs oxygen) and measure the exact quantity of oxygen that is taken up from a closed vessel between the beginning of the burning and the end. Now turn the process into reverse: take the mercuric oxide that has been made, heat it vigorously and expel the oxygen from it again. Mercury is left behind, oxygen flows into the vessel, and the crucial question is: ‘How much?’ Exactly the amount that was taken up before. Suddenly the process is revealed for what it is, a material one of coupling and uncoupling fixed quantities of two substances. Essences, principles, phlogiston, have disappeared. Two concrete elements, mercury and oxygen, have really and demonstrably been put together and taken apart.

It might seem a dizzy hope that we can march from the primitive processes of the first coppersmiths and the magical speculations of the alchemists to the most powerful idea in modem science: the idea of the atoms. Yet the route, the firewalker's route, is direct. One step remains beyond the notion of chemical elements that Lavoisier quantified, to its expression in atomic terms by the son of a Curnberland handloom weaver, John Dalton.

After the fire, the sulfur, the burning mercury, it was inevitable that the climax of the story should take place in the chill damp of Manchester. Here, between 1803 and 1808, a Quaker schoolmaster called John Dalton turned the vague knowledge of chemical combination, brilliantly illuminated as it had been by Lavoisier, suddenly into the precise modern conception of atomic theory. It was a time of marvelous discovery in chemistry - in those five years ten new elements were found; and yet Dalton was not interested in any of that. He was, to tell the truth, a somewhat colorless man. (He was certainly color-blind, and the genetic defect of confusing red with green that he described in himself was long called ‘Daltonism’.)

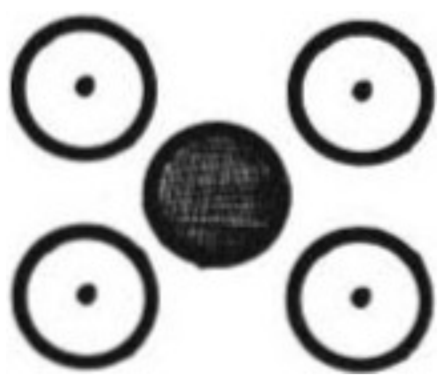
Dalton was a man of regular habits, who walked out every Thursday afternoon to play bowls in the countryside. And the things he was interested in were the things of the countryside, the things that still characterize the landscape in Manchester: water, marsh gas, carbon dioxide. Dalton asked himself concrete questions about the way they combine by weight. Why, when water is made of oxygen and hydrogen, do exactly the same amounts always come together to make a given amount of water? Why when carbon dioxide is made, why when methane is made, are there these constancies of weight?

Throughout the summer of 1803 Dalton worked at the question. He wrote: ‘An enquiry into the relative weights of the ultimate particles is, as far as I know, entirely new. I have lately been prosecuting this enquiry with remarkable success.’ And he thereby realized that the answer must be. Yes, the old-fashioned Greek atomic theory is true. But the atom is not just an abstraction; in a physical sense, it has a weight which characterizes this element or that element. The atoms of one element (Dalton called them ‘ultimate or elementary particles’) are all alike, and are different from the atoms of another element; and one way in which they exhibit the difference between them is physically, as a difference in weight. ‘I should apprehend there are a considerable number of what may properly be called elementary particles, which can never be metamorphosed one into another.'

In 1805 Dalton published for the first time his conception of atomic theory, and it went like this. If a minimum quantity of carbon, an atom, combines to make carbon dioxide, it does so invariably with a prescribed quantity of oxygen - two atoms of oxygen.

If water is then constructed from the two atoms of oxygen, each combined with the necessary quantity of hydrogen, it will be one molecule of water from one oxygen atom and one molecule of water from the other.

The weights are right: the weight of oxygen that produces one unit of carbon dioxide will produce two units of water. Now are the weights right for a compound that has no oxygen in it - for marsh gas or methane, in which carbon combines directly with hydrogen? Yes, exactly. If you remove the two oxygen atoms from the single carbon dioxide molecule, and from the two water molecules, then the material balance is precise: you have the right quantities of hydrogen and carbon to make methane.



The weighed quantities of different elements that combine with one another express, by their constancy, an underlying scheme of combination between their atoms.

lt is the exact arithmetic of the atoms which makes of chemical theory the foundation of modern atomic theory. That is the first profound lesson that comes out of all this multitude of speculation about gold and copper and alchemy, until it reaches its climax in Dalton.

The other lesson makes a point about scientific method. Dalton was a man of regular habits. For fifty-seven years, he walked out of Manchester every day: he measured the rainfall, the temperature - a singularly monotonous enterprise in this climate. Of all that mass of data, nothing whatever came. But of the one searching, almost childlike question about the weights that enter the construction of these simple molecules - out of that came modern atomic theory. That is the essence of science: ask an impertinent question, and you are on the way to the pertinent answer.