The Architecture of Matter

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While the history of the emergence of the science of the movements of celestial objects, i.e. the basis of astronomy, is in a sense rather straightforward and was essentially solved by Newton founded on some simple mathematical principles, that of the science of matter, the subject of the present volume, turned out to be far messier. The story begins, as it always does, with the classical Greek culture and their philosophical speculations. The Greeks have always been criticized for their lack of empirical observation and unbridled speculation. This is grossly unfair, the Greeks were keen observers of nature, but their technology was primitive. Technology is a collective enterprise and grows slowly, but thinking is an individual one, and in that regard the classical Greek philosophers exhibited a daring and a brilliance that easily rival contemporary thought, so there is no wonder that it is that aspect of their work that has survived. When it comes to the understanding of matter in a vague and abstract way their speculations often do not contradict the modern one, it is mainly in its intricacy they lie way behind, an intricacy which is the result of long winnowing by empirical observation and testing. Central to the authors thesis is that science progresses by an integration of the empirical method and the bold speculation. The naive assertion of Francis Bacon that Nature is an open book and it is only a matter of reading it with no preconceptions in order to achieve true knowledge, is by itself insufficient, although this view of science is the prevailing one shared by politicians and public alike. On the other hand the conceit of a Descartes, that one can work out everything from first principles, is in spite of its seductiveness, equally one-sided. Thinking is a manifestation of the imagination, and the imagination is only stimulated by obstacles, and empirical facts constitute the obstacles to overcome. No obstacles and in principle everything goes and the imagination dries out for want of nourishment. Yet in a sense, all attempts at fundamental science strive to obtain a picture congenial to human rational understanding, and thus in a sense reducing it to the cerebral manipulation of basic principles. The world as it appears to our senses is not only confusing but also bewildering and the foremost duty of the human mind is to structure it and make it understandable, which means to look for hidden principles. This is of course the essence of Platonism (its Platonic form so to speak, as opposed to its various concrete historical manifestations liable to ridicule), whose inspiration for all of serious science is somewhat underestimated[1].

[1] Science mainly refers to Natural Science, there is also humanistic and social sciences, which are very different. While many of them may emulate the forms of practices of Natural Science, they all seem to suffer from an inability to transcend the immediate sensual reality and really look for underlying causes, i.e. fully understanding the Platonic approach. Sometimes there are temporary successes, such as Freudianism, in which this actually seems to have been achieved, and hence generating a lot of intellectual excitement, but alas, empirical evidence turns out not to be accommodating in the long run, yet this should not detract from their laudable ambitions

The Greek assumed that matter could be reduced to some basic principles, that in fact they could be reduced to earth, fire, air and water, conveniently classified along the two principles of heat versus cold and humidity versus dryness, and then a fifth thrown in - ether- in order to make a correspondence with the five Platonic solids. This may seem quaint by our standards, but this as noted above an unfair assessment, it is in fact sophisticated and mirrors in many ways modern ways of formulating scientific theories, striving for simplicity as well as connecting disparate aspects of reality (cf. the hypothesized connection between matter and geometric entities). Where it differs from modern science is in its embryological state, it lacks the surrounding cloud of intricate details that comes from a deeper engagement with the empirical reality. In short, it is hard to find purchase. One way of doing so, which would later pave the triumph for the latter development of science, is quantification. Not that the Greeks were opposed to it, number mysticism played a pivotal role in the Pythagorean world view, but it is not always so easy to apply. The Pythagoreans are rightly ridiculed for their silliness with numbers, but where the level of technology allowed, they made definite non-silly applications of their philosophy, I am of course referring to the connections between vibrating strings, fractions, and musical harmony. A discovery that much excited them. The point of quantification is to stimulate the process of generating questions that can be addressed and even answered. Hence the importance of measurement in science, something which is often resented and ridiculed, most articulatedly by Goethe, not realizing that it is not an end, but a means to an end[2].

To go back to the Greek. Democritus (-460 - -370) taught that matter was composed of small irreducible particles, so called atoms, and the properties of matter could be reduced to that of combinations of particles. Can we say that already Democritus discovered atoms? Of course not, it was an entirely mental concept, for which he had no empirical evidence whatsoever. How could he ever have had it? Yet the idea of thinking of matter as composed of small indivisible and permanent entities, too small to be observed, played a crucial role ever since in thinking of matter, without there ever being any direct evidence for it. The worth of a hypothesis lies not so much in its literal truth as its fertility when it comes to asking questions. In fact atoms were for a long time thought of as a convenient fiction (such as the sun being in the center of the universe), and Ernst Mach famously held until the end of the 19th century that they had no real existence, a epistemological device, not an ontological entity. It was not until the beginning of the 20th century that the real existence of atoms was considered established, mainly by the work of Einstein and references to Brownian motion. To confirm an existence is not the same thing as discovery. Discovery means the encounter with the unexpected, confirmation is if anything a matter of expectation. Thus no one really discovered the atom, in glaring contradiction to the Baconian conception of science. Fruitful theoretical concepts eventually vindicate themselves. Whether the idea of atoms would have come about independently without the Greek tradition is a moot question. From a historical point of view, and history is about what actually happened, not what could have happened or ought to have happened. And the fact is that the atomist theory is a legacy of the Greek.

Another, a far deeper, wider and pervasive, influence was that of Aristotle. Surely

[2] For the average scientist this may be the end, as work may seem nothing else than it. This of course is a fair target of scorn.

the most distinguished scientist of the Classical era, and one of the most remarkable men of Antiquity, and hence of Western Civilization. His success and influence were so great in fact that they actually obscure his brilliance and make for the present disparagement. He differed from his master and mentor - Plato, by being far more down to earth and empirical. He presented a somewhat bowdlerized version of Plato's form, by emphasizing that the form arouse from the factual circumstances, not the other way around, a version which is far easier for most people (including modern philosophers) to swallow, and he had no real interest in mathematics, although he is rightly seen as the founder of logic[3]. He was a classifier and he turned his attention to the rich sensual world that Plato held in contempt. The wideness of his interests is staggering, and even more remarkable that for most of them he had very incisive things to say, which by virtue of the authority he had rightfully earned, would for better or for worse set the agenda for more than a thousand years. No modern scientist could come close to the mastery of so many things as he did, which is of course not only a testimony to his genius, but to the fact that it helps to be a pioneer. What did Aristotle think of matter? He adhered to the theory of the four elements, whether by conviction or merely piety is hard to say, as due to its primitive embryological status, it had no practical consequences. What is more significant is that although he made a distinction, as most people do, between inert matter, such as metals, stones, or whatever, and living, (although the distinction is not as obvious as most people would think, the status of fossils were for a long time ambiguous); he stressed the similarities. Just as organisms grow, develop and decay, something similar holds for inert matter, after all iron rusts. This development of organisms had a purpose, what is usually thought of as teleological, the ever classifier Aristotle having organized causes along four different lines. This would undercut the dogma that inert matter is immutable and thus that base metals such as lead and iron very well can be turned into gold provided that the right circumstances were provided. This paved the way for alchemy that unfortunate diversion of chemistry into barren ground. In retrospect this appears as naive and misguided. Misguided maybe, but naive? In many ways his ideas have been vindicated, nowadays we have the know-how, although not the motivation, to turn lead into gold.

Alchemy is a beautiful illustration of what happens if you have no theory but are entirely reliant on empirical observations. The world teaches you nothing you have to put the right questions, and the alchemists were never really able to, although they did admittedly come up with some poetic ideas of what was going on. But the period was not entirely wasted, the alchemists did acquire a lot of practical know-how, they became a kind of artisans and they developed much of the equipment with which chemists have dealt ever since. The difference between the laboratory of an alchemist and a more serious chemist in those days would hardly be noticeable to the un-aided eye. Newton too dabbled in alchemy but as always he had incisive things to say, although not even Newton was able to transmute elements. Newton took up the ideas of the Old Greeks and thought of matter as composed of small particles - corpuscles. There were some serious questions to be asked. How come matter sometimes formed gases while at other times it was solid. How to explain

[3] As the Swedish philosopher Wedberg remarks, he presented a logically systematic classification of syllogism, way before Euclid attempted the same for geometry.

solidity for e.g. without running into an infinite regress of postulating corpuscles to consist of corpuscles? Newton came up with the idea of corpuscles in a solid attracting each other while in a gas repelling each other. In the celestial world gravitational forces reigned supreme, how fitting and beautiful that the same thing would hold in the small world leading to a grand unification. Newton had a lot of authority and when he spoke people listened. He also proposed the corpuscular theory of light in contradistinction to the wave theory of Huygens, and at least in England, his theory as expounded in his *Optics* held sway. About the same time the ever busy Boyle studied gases out of whose outpourings posterity has singled out what is now called Boyle's Law, something that could readily be explained by the corpuscular theory[4]. But Boyle came to his law not by theoretical speculations but by a series of experiments. If interpreted in the Baconian spirit a lot of 'blind' (i.e. non-prejudiced by anticipation) experiments were done and out of the data a pattern was discerned. In a simple case like this the pattern might have been obvious from the reading, but the very idea of doing the experiments in the first place, i.e. of finding a relation between pressure and volumes bespeaks some tacit expectations. Another way of discovering the law was presented by the Frenchman Marriot inspired by the discovery of Torricelli, a student of Galileo, of how a tube filled with mercury when turned upside down only could raise to the height of some 28 inches, leaving a supposedly vacuum at the top. The explanation given being that the column of air in the atmosphere provided a pressure equal to that of the column of mercury. Thus the atmospheric pressure could be measured by the weight of the column, essentially its height times density. Pascal noted that the pressure would decrease when performed at a higher altitude, and hence a lower mercury pile. The difference could actually be used to measure the density of air close to sea level. An actual experiment was done, an apparatus was carried to the top of Puy de Dôme, and as expected, the pressure fell appreciably.This is incidentally a non-Baconian experiment. Why should an experiment be done on the top of a mountain? And if so why not everywhere? The expectation is that it is not the changed location per se which is interesting, but a change in altitude, which is based on expectation, having a theory, or if you prefer an explanation which would have other consequences than the immediate ones presented by the original experiment. But let us return to Marriot. He filled a 40 inch tube

[4] When small particles bounce against the wall, their sudden change of motion corresponds to a force whose reactionary one is exerted on the wall as pressure. If the container is scaled by a factor r its volume goes up as r^3 and its bounding surface as r^2. If the speed of the particles are constant, i.e. the temperature is constant, it means that distances particles have to move grows by r and hence the number of collisions per unit area is multiplied by a factor $\frac{1}{r} \times \frac{1}{r^2} = r^{-3}$. Hence under constant temperature $pV = k$ (pressure times volume is constant). If the volume is kept constant, but the speed of the particles scaled by a factor r the number of collisions per unit area is scaled by r as is the force exerted by the bouncing particle, thus pressure scales by r^2, but so does temperature, being proportional to the kinetic energy of the particles. Recall that increase in temperature is proportional to increase in energy to be supplied, everything else being unaffected. Hence the more general law of Boyle $pV = kT$ where k depends on the chemical characteristics of the gas, basically the molar weights. This sketch of a theoretical derivation, ultimately of the ideal gas law, was actually done by Daniel Bernoulli in the 1770's, but ignored until the mid 19th century when revived but ridiculed, and then established by Joule and Clasius and ultimately by Boltzmann.

with 27.5 inches of mercury leaving on top 12.5 inches of air at normal pressure. When quickly turned upside down into a mercury bath, submerging the top one inch into the bath. Then one would expect the mercury to reach only 14 inches instead of the normal 28 inches, leaving on top 25 inches of air instead of 12.5. Thus the pressure of the air was just one half atmospheric countering the full atmospheric outside, and in toto only a remaining half atmospheric pressure would be left to maintain the column, which hence would be one half as tall[5]. Thus indeed we have another kind of experiment, a so called crucial experiment (in the Baconian approach all experiments are of the same importance) in which we form very precise expectations and test them. They are quantitative which means that they can be formulated in a precise way and easily manipulated.

Boyle was a corpulist, but unlike modern atomists, he did not believe that the ways of combining matters is discrete, as in modern chemistry, with its list of fundamental elements (or just elements), but could be done more or less continuously. Boyle had an indefatigable curiosity, typical of a Baconminded scientist, all kinds of questions suggested experiments, i.e. *ad hoc* observation, not necessarily guided by foresight nor expectation. As a consequence his collected works amounts to an impressive bulk, not unusual for dedicated mediocrity.

Returning to Newton, who never did an unplanned observation in pursuit of a problem, we are reminded of the forces between small particles, which might explain the solidity of substances, without begging the questions (such as if they were equipped with small hooks attaching themselves to each other). In particular he noted that if you have two polished glass plates (meaning that they are very plane) parallel to each other and dip them into water, the water will rise, the higher up the closer they are. In particular when the distance is one hundredth of an inch, the water will rise an inch. From considerations like those, which are not made explicit in the book, he is able to estimate the forces between particles and conclude not only that they are very strong compared to gravity but to give quantitative estimates. But in addition to attraction there was also repulsion, and the character of a gas Newton explained was due to a repulsive force between particles. In fact this force varying inversely to the separation was, according to Newton, mathematically equivalent to Boyle's law. He was proud of this and considered it on par with his derivation of Kepler's law through inverse square attraction. Posterity very much keeps the latter in memory, but the former is forgotten. The view is very different from a contemporary perspective. More importantly though was his claim that the fundamental particles were immutable and unchanging, they did not age nor change in any way, what was changing was the configurations of atoms and their temporary attachments. When bodies disintegrate it is exactly the attachments between the particles that breaks, not the particles themselves.

[5] This may seem *ad hoc*. Instead consider a tube containing a column of mercury of height M just enough to counterbalance normal air pressure. On top of the tube we have a column of air of height a. We can set the length of the tube as 1. Then the tube is turned upside down in a bath of mercury without submerging the top. We will now have readings a' and M' correspondingly with $a' + M' = 1$. We will get the equation $(1 - \frac{a}{a'})M = M'$ which results in the equation $a^2 - a(1 + a') + (a')^2 = 0$ this can be solved for a' in terms of a with only one positive root given by $a' = \frac{1}{2}(a + \sqrt{4a - 3a^2})$. In particular if we want to have $a' = 2a$ we need to solve the equation $3a^2 - a = 0$ which has the solution $a = \frac{1}{3}$ and hence $M = \frac{2}{3}$, thus the length of the tube should be $\frac{3}{2}$ of the given height of the Mercury column

It was to become the dogma for the next two hundred years. And a very useful dogma, even if from the modern point of view this can be shown no longer to be true (whatever is meant by that, it could just be that we have as yet not found the ultimate atoms prophecized by Democritus), had this dogma not provided the guiding idea, science of matter may very well have been permanently stymied. Idealization and concomitant simplification are inevitable in any piecemeal process of discovery. Or as Newton put it: God when creating the universe set down simple laws to enable man to discover them, one of which being the immutability of the atoms. In fact the mathematical intelligibility of the universe has always been seen as miraculously, maybe even more and more so, and one may be forgiven to indulge those who see this as a manifestation of God. Newton not content with philosophical speculation also tried to measure the size of those particles coming up with a value between $\frac{1}{500}$ and $\frac{1}{1000}$ of an inch, i.e. on the order of 10^{-3} cm to be compared with the Å of 10^{-8} cm used to measure atoms. Newton dabbled into alchemy and this has been taken as a sign of a darker side of his, but the authors remind the readers that reading *das Kapital* does not make you into a Marxist[6], and Newton had no choice as there was nothing else written on chemistry at the time, the ancients having very little to contribute just as his more respectable contemporary 'atomists'. With Newton atomist theories were once and for all moving out of the field of philosophical speculation and entering a more scientific quantitative phase. Yet what faced the people of the day in the 18th century was still confusion. It is not so easy just to sit and observe, as Bacon claimed, one need to have theories and conjectures to formulate what to expect and design observations accordingly. Philosophy and its concomitant speculations were inescapable components of any sustained and penetrating inquiry. One fundamental thing was to distinguish between the corporeal and the incorporeal, in other words to make a distinction between matter and what was not and hence to identify the field of materialism. One such distinction going back to the ancients was the distinction between primary and secondary qualities[7]. This means qualities which were intrinsic to objects as opposed to those which our sense organ endows them with. Weight, extension and its like as opposed to color and smell. Three criteria were prevalent among the people of the day. 1) The ability to produce physical effects (used by the Epicureans and pursued by Descartes). But this would include magnetic fields although they weighed nothing and you could walk straight through them. 2) Referred to things which were impenetrable[8], or as in the case of gases, could be made so by condensation. And finally 3) objects which were subject to gravity, thus having both mass and weight[9]. As the authors remark, the latter criterion was at the

[6] maybe not even writing it. Popper notes with approval that Marx claimed that he was not a marxist, and considers this supposed distance between himself and his work a most laudable sentiment, maybe the most laudable of all his claims.

[7] According to Popper, Parmenides was the first one to formulate it

[8] In a given space there is only so many physical bodies you can press into it. But with any set of bodies (it may be even empty!) you can consider the set of subsets of that, as well as the set of subsets of the latter, and so on, and hence an infinite explosion of 'objects' all manifested so to speak in a limited space. We are here talking about combinations of bodies which are not impenetrable and hence do not occupy and reserve space as material bodies do.

[9] Does the soul have weight. Popular movies have been made on the question, the idea being at the

time rather sophisticated, as Newton's theory of gravitation was still new and not part of the 'common-sense'. Thus matters such as heat and magnetism seem to be devoid of mass yet very physical with definite effects, and that meant confusion during the 18th century. Even such a thing as air, its corporeal status was unsure. Sure, old classical experiments, as done by Heron, prefiguring Torricelli, indicating the material character of air, such as that of possessing weight. Boyle noted that smoke did not rise in air, also indicating the weight of the latter, a demonstration maybe more convincing to the laymen than those of Torricelli and Pascal. Similar problems affected the status of fire. Boyle did some careful experiments claiming that he had actually weighed the flames of fire. Lavoisier pondered the same question and was able to prove the opposite. Observations alone do not settle matters, observations need guiding theories to be interpreted. It may then be tempting to claim, along with the post-modernists, that truth is merely a matter of convention. This is a cheap way of interpreting the quandary, and only a more penetrating description of the historical record may reveal the folly of jumping to such conclusions.

Chemistry did not come to age until the end of the 18th century and blossomed during the 19th, and did in fact more than any other science at the time affect modern quotidian life. As noted before, what made it rise out of confusion, was major simplifications (dogmas) who later may turn out to be unwarranted idealizations. Imperfect theories, and all theories are of course imperfect, provide necessary prerequisites for criticism and improvement. The dogmas were basically two, one - that of the immutability of atoms due to Newton - we have already mentioned, the other was to focus on what could be weighed.

There are of course a lot of chemists of the 18th century still remembered today, such as the discoverers of oxygen - Scheele and Priestley, but foremost of them all is Lavoisier, who formulated the basic distinctions between elements, compounds and mixtures, with which chemists have worked ever since. One may briefly charter the story of progress. As to gases the experiments of the Anglican clergyman Hales in the first third of the 18th century, turned out to be crucial, and did away with the conceit that gases were somehow fundamentally different from solids and liquids. In particular he constructed the nowadays standard equipment to collect gases in containers and subject them to study. The study of gases were in fact revolutionized, and as noted new gases were being discovered during the second half of that century. Another subject of primary importance was heat, connected with that spurious matter - phlogiston -, which along with the ether belong to the 'cul de sacs' of modern science. Joseph Black (1728-99) made the distinction between temperature, which is felt, and quantities of heat, which could actually be measured and transported from one body to another (as when ice submerged in hot water, accepts the heat of the latter and melting as a consequence[10]). Was heat a matter of vibrating motion among the particles, a view held by Newton, or actually as claimed by Boerhaave (1668-38) a species of matter, but if so it had strange properties indeed. This leads us to the theory of phlogiston, developed by the German chemist Georg Ernst Stahl (1660-34) around 1700. The idea was that when a metal degraded to calx it lost its phlogiston, but when that

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moment of death, the body undergoes a small (but measurable) loss of weight, assumed to correspond to the soul departing from its corporeal prison.

[10] One could of course also reason symmetrically, ice contained a quantity of cold which water absorbed and hence cooled.

was taken up the metal could be restored. Careful observations revealed that calx was actually heavier than the metal, and thus if phlogiston had mass, it had negative such, a possibility not to be rejected out of hand (after all we have no problems with positive *and* negative charge), and indeed instead of gravity it had levity, to use a term popular among the Cartesians. It is here that Antoine-Laurent Lavoisier (1743-94) steps in. A man of some modest fortune playing a minor role in politics and administration before the revolution, being swept up in its enthusiasm and devoured (and beheaded) during its subsequent fury. Lavoisier was temperamentally a Newtonian, and hence he brought to the problems of physics the mindset of a physicist. At the same time, the authors stress, he was of a very practical mind. Chemistry had up to this point come up with an embarrassment of riches as to observational facts, as a result of a sustained industrialized application of the vision of Bacon. But there seemed to be no rhyme nor reason to what had been unearthed. The task of Lavoisier was to bring some order to the chaos, in short to supply some kind of theory, to this matter of details, whose confusion was reflected in the welter-skelter of strange and ad hoc terminology. In particular to bring some order to the bewildering terminology was his first mission, and that he also had a certain familiarity with the law did aid. He formulated some basic principles, the first being that in any process, be it natural or artificial, nothing is lost, nothing is created. In short a theory of invariance with roots in old Ionian philosophy[11]. The second, definitely vaguer, can be seen as a taxonomic principle, that chemical substances conform to some natural order, just as organic ones. It is tempting to interpret those to the Periodic table of Mendeleev and the Tree of Life due to Darwin, and which was to some extent prefigured by Linnaeus, who was engaged in exactly the kind of taxonomic venture Lavoisier envisioned. But to return to the first principle, what was it that was conserved? To us the answer seem obvious, mass of course, but at the time there were so many other things that entered into the equation, and whose status was unclear, among other things the proposed phlogiston, that any inquiry ran the risk of going in fruitless circles. But Lavoisier choose mass as a fruitful candidate for invariance, along what he called caloric, i.e. the quantity of heat. He embarked also on the taxonomic project in typical 18th century spirit, in order to clarify by introducing a new vocabulary and syntax to chemistry. Historically the most momentous discovery and clarification was his showing that when mercury is reduced to calx, it does not lose phlogiston but gains oxygen, and conversely in the reverse process. Priestley was impressed by his experiment at first but then returned to the phlogiston theory and presented vivid and admirable arguments for it. Thus once again the interpretation of an observation depends on what theory you believe in. Pace Bacon it is impossible to interpret an observation without prejudice, or as Popper would put it, without any expectation. Lavoisier eventually won the day, not so much because observations proved him right, but because his theoretical approach was more elegant and had more explaining power and could dispense with additional *ad hoc* arguments, with which the phlogiston theory became more and more burdened. Thomas Kuhn in his celebrated book of scientific paradigms, take this as an exemplary (paradigmatic?) tale. The Life of Lavoisier was cut short and it

[11] Popper in his *The world of Parmenides* relates this to Parmenides and his theory of the immutability, which in modern science is manifested in the principle of invariance. Popper makes that the foundations of equations, when what is on both sides of the equality signs are really the same but expressed differently.

was not to him the exploitation of his method was granted[12]. Instead that was taken by John Dalton (1766-44) with whom the old classical atomist theory became truly scientific.

One crucial question was whether in a compound the participating elements were to be found in a fixed ratio or did vary, the case of the former we nowadays take for granted, but which was far from clear at the time. Different ideas were proposed. Berthollet (1748-22) claimed that they could vary indefinitely while Proust (1755-26) thought that the ratios would fixed. (Lavoisier had been uncommitted on this point.) The verdict was on Proust's side, but Berthollet can be forgiven, as the issue, as it was fought out, was to a great extent a verbal one, the authors point out, as one has to make a clear distinction between a pure compound and a mixture, in any complicated process, a compound may in its partially dissolved state to a large extent be seen as a mixture. But once again clear demarcations and clear ideas win the day, even if they are hard to discern in the messy world of observation[13].

Now Dalton went beyond Proust. Initially a meteorologist intrigued by the fact that the air, though a mixture of gases, did not separate into layers of each, did discover on the study of them that they could be dissolved into more elemental ones, with simple numerical relations, such as 3:2[14]. This lead to the daring and fundamental idea that the basic elements of chemical substances were identical to the immutable particles of Newton and modern chemistry was born. From now on the standard chemical formulas for reactions were born, as well as the terminology for compounds. Dalton believed that the chemical formula for water was HO and that oxygen was seven times as heavy as hydrogen. He had found that when he split water into its components, the oxygen weighed seven times as much as the oxygen, and if they combined 1:1, the same ratios should also hold for the basic atoms (the concept of a mole). He had no way of weighing individual atoms but he could infer their relative weights from large scale phenomena. Thus between 1775 and 1825 chemistry was transformed from a bewildering confusion into a clearly delineated theory of an almost Pythagorean character. Yet the astounding success of chemistry invited its detractors. Among those can be mentioned Diderot, Goethe and Lamarck as well as Blake. That was a motley crew, including the painter Blake and the poet Goethe, who had definite scientific pretensions, and as an anatomist gained permanent acknowledgment by his discovery of a hitherto unknown bone in the mammalian skeleton. They resented the materialistic theory of chemistry reducing it to inanimate matter and would have much preferred an older more physiological approach. The very mathematical nature of the new conceptions were anathema to their temperaments. In particular it became a quantitative science reducing the study to what could be measured, and in doing so, according to Lamarck they left out the problems which really mattered, the very nature of the chemical substances, their properties (beyond the merely quantitative one gathers) and their mutual affinities. Of course the mathematical approach does exactly that, at least ultimately, but

[12] The great contemporary mathematician Lagrange noted that separating his head from his body only took a moment, but it deprived mankind of a life of future discoveries.

[13] In fact the distinction between compound and mixture is not so clear cut, in the interstices of pure crystals foreign atoms may be inserted in various proportions, and hence we can think of intermediate compounds whose chemical formulas would involve fractional figures.

[14] This may make you think of Pythagoras and vibrating strings and harmonious notes

that is to anticipate far too far. But of course they had a point, by simply giving out the fact that oxygen weighed sixteen times as much as hydrogen (which careful chemists eventually found out) it explained very little about the substances themselves, just as the weight of a man is not much of a clue to his general character and intelligence. But once again science cannot take everything on at once, it has to concentrate on what it can fruitfully accomplish. If that entails quantitative description, be it so. All one can do is to pursue it as far as it goes and in the process come up with new ideas, as new ideas never come up in a vacuum, but results from an extended conversation with the empirical world. And besides the skeptics had no alternatives to offer, at least no workable ones. And Goethe rejected the analytic methods of scientists altogether, the method of taking apart into smaller constituencies and putting together, but saw the experiments of the scientists as invasive, destroying exactly what they professed to study. It was barbaric, he pointed out, to study white light by subjecting it to a prism and turning it into colored light instead. What was left was sympathetic understanding. As strictures against say Social Science, there is much to Goethe's view that commends itself, but Natural Science is an altogether different ball park as Collingwood never tired of pointing out.

Now through the foundations laid bare results followed in a systematic ways. Avogadro (1776-56) managed to weigh individual atoms, i.e. computing how many atoms there were in a mole[15], Mendeleev (1834-07) discovered, as already noted, the periodicity of the elements and were able thereby not only to predict unknowns ones, but also to predict some if their physical and chemical properties. More significantly wave theory, especially light as waves, was resurrected and developed, which lead to Maxwell's theory of electromagnetic fields which pointed to the future. A great synthesis was performed, so successful that at the end of the 19th century there was a feeling that the basics of science had been solved, what was left were mainly in the nature of mopping up operations. And so radioactivity was discovered, which would lead to a rupture between classical physics (and chemistry) and Quantum theory, the status of which is not entirely resolved in spite of its striking successes. But that requires a book by itself, as does the chapters on the connections between chemistry and biology, which took their first tentative steps in the 19th century, doing away with the conceit that there was a different kind of matter involved in the living organic world and that of inanimate objects. The death-knell to the idea of vitalism. Goethe would have shivered.

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[15] Avogadro's number 6×10^{23} is worth committing to memory