ATOMISM OF LUCRETIUS SEEN THROUGH THE EYES OF A MODERN PHYSICAL CHEMIST

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Introduction

The classical Roman poet and philosopher Titus Lucretius Carus (*ca.* 98-*ca*. 54 BC) is today remembered for his atomistic philosophy laid out in his masterpiece *De rerum natura* (1). It is the largest and the most complete work of materialistic Epicurean philosophy which has survived to the present day, offering us a unique glimpse into the natural science of the Greco-Roman world. It also offers a stark contrast to the then-prevailing Aristotelean philosophy (2), which viewed matter as continuous and postulated four "elements" as fire, air, earth and water. It has been argued that the scientific revolution of the Renaissance roughly coincided with abandonment of the Aristotelean physics and re-discovery of *De rerum natura* with its atomism (3).

Little is known about life of Lucretius. *De rerum natura* is his only surviving work, and his name was mentioned a few times in letters written by his contemporaries, such as Cicero (Marcus Tullius Cicero, 106-43 BC) and Vergil (Publius Vergilius Maro, 70-19 BC). According to a letter from Cicero to his brother Quintus that dates to February, 54 BC, we know that *De rerum natura* had already been published, but since it lacks final polish (which however, may be due to errors by copiers over the centuries), we may conclude that Lucretius was dead at the time. According to St. Jerome (*ca*. 347-420) he died at the age of 44, so he was born probably around 98 BC.

Lucretius was probably of aristocratic descent (likely belonging to the ancient *gens* Lucretii), and it is obvious from his verses that he was well acquainted with the luxurious lifestyle of Roman high society. However, his verses also reveal that he had a broad knowledge of nature and country life, so we can assume that he spent a considerable part of his life on a countryside estate, which was also common for contemporary Roman elite. Since he held no public office and no records exist of him taking part in political life, he is likely to have lived a secluded life in the countryside.

The first century BC, the age when Lucretius lived, was full of turmoil, and was arguably the most tumultuous in Roman history. The Roman republic, having outgrown itself, became corrupt, dysfunctional and virtually ungovernable. Intrigues, conspiracies, political murders and all kinds of violence became common. Brutal civil wars were fought; bloody dictatorship followed after bloody dictatorship (4). Staying outside of Rome and taking no part in politics was a smart thing to do if one wanted to keep his head. In *De rerum natura* quite a few allusions to the contemporary power struggle and civil wars can be found.

Lucretius dedicated his masterpiece to his friend, and possibly a patron, an insignificant politician Gaius Memmius (5). It was intended to relieve the reader of fear and anxiety which plagued contemporary Romans (from rather obvious reasons!) and promote life of simple pleasures, free from lust for power. Contemporaries praised the high artistic values of his verses (these included Vergil himself!) but apparently cared little for his natural philosophy. With the decline of the Roman empire, Lucretius and his work were forgotten. A copy of *De rerum natura* was found about 1417 in a library of a German monastery by Italian humanist Gian Francesco Poggio Bracciolini (1380-1459), and its re-discovery coincided with the beginning of a new era (3). Lucretius's atomistic and deterministic view of the world which followed a few simple laws, influenced and inspired generations of philosophers and natural scientists from the beginnings of the Renaissance to the modern era. In his verses he laid out the basic outlines of most of natural sciences: physics (including atomism; he explains macroscopic properties of matter through their atomic composition, speculates on speed of sound and light, magnetism…), physiology (bodily functions explained through motion of atoms), cosmology (he states that the Universe is infinite), meteorology and geophysics and (physical) chemistry, which will be the topic of this paper.

Interest in *De rerum natura* appears to have waned in the 20th century, as did interest in classical Greek and Roman literature in general. One of the reasons might also be connected to fast advancement of all sciences and discovery of subatomic particles, which ran contrary to the ideas of classical philosophers. However, knowledge of aspects of modern physics and chemistry allow the reader to appreciate Lucretius in ways that were not available to earlier readers.

Many of the fundamental concepts and mechanisms upon which modern chemistry is built, can be found in the verses of *De rerum natura*, and they are the topic of this essay. While Lucretius was arguably a skilled poet and a great natural philosopher, his genius was not centuries, but *millennia* ahead of his time. Chemical science did not exist in the Classical age, and the Greek atomist philosophers were concerned more with theoretical principles than with physical reality. Alexandrian proto-chemistry, an early form of proto-science, thrived between 1st and 3rd centuries AD (more than a century after Lucretius's death) (6, 7); however, it was based on Aristotelean physics (2) rather than atomism, and eventually gave rise to alchemy (6, 8, 9).

The concept of experiment developed only during the Renaissance, and the Classical philosophers were mostly deducing. Lucretius therefore is not a real (experimental) scientist, but a keen observer who based all his conclusions on simple observation (lacking even the simplest of instruments!) of things and phenomena in his environment.

It should be added that artisanal chemistry in the classical age was a well-established art, which had been developing since the dawn of civilisation. It involved metallurgy, ceramics, pharmacy and preparation of cosmetics. Egyptians were especially skilled in preparation of pigments, cosmetics and medications, so this was usually referred to as the "Egyptian art" (6, 9). However, these artisanal "chemists" had no coherent understanding of chemistry, and had no influence on Lucretius and his work.

Conservation of Matter

Eighteenth-century chemistry was still based on essentially Aristotelean ideas of a continuous matter, pretty much as was alchemy in the Middle Ages. It regarded matter as infinitely divisible, and mass was not considered a fundamental property. Therefore, there was no reason why mass *must* be positive. Why couldn't it be zero, or even negative? After all, it was rather obvious that in many reactions mass is reduced or increased. To realise that the total mass of reactants and products does not change required a great deal of experimental work using a sealed apparatus and a precision balance, and a great deal of imagination. This was developed gradually over two centuries.

It is often considered that modern chemistry began when Antoine Laurent Lavoisier (1743-1794) postulated the law of conservation of matter (as set forth in his seminal work *Traité élémentaire de chimie*, first published in 1789 (10)), which is regarded as the most basic law of chemistry. It was, however, only an empirical "law" discovered after numerous experiments, and its connection to atomism was realised only after John Dalton's (1766-1844) resuscitation of atomic theory in his 1808 book *New System of Chemical Philosophy* (11). Dalton imagined atoms as little spheres whose fundamental property was mass; actually atoms of different elements had different mass. He tabulated the first "atomic weights" (i.e., relative atomic mass), albeit rather inaccurate (12). Until advent of spectroscopy in 1860s mass was the only atomic property which could be determined.

Almost half a century before Lavoisier, the law of conservation of matter was discovered independently by a Russian, Mikhail Vasilievich Lomonosov (1711-1765), an ardent atomist and, pretty much like Lucretius, a man way ahead of his time. However, since he wrote mainly in Russian and since atomism was at the time not generally accepted, Lomonosov's work passed unnoticed and was largely forgotten. It was rediscovered only at the beginning of the 20th century by Boris Nikolayevich Menschutkin (1874-1938) (13).

However, nearly two millennia earlier, Lucretius postulated that (*i*) there are only atoms and empty space and (*ii*) atoms can be neither destroyed nor created. To put it simply, atoms are indestructible. (Note that the did not explicitly mention mass.)

> The next great principle is this: that nature
> Resolves all things back into their elements
> And never reduces anything to nothing.
> If anything were mortal in all its parts,
> Anything might suddenly perish, snatched from
> sight.
> For no force would be needed to effect
> Disruptions of its parts and loose its bonds.
> But as it is, since all things are composed
> Of everlasting seeds, until some force
> Has met it, able to shatter it with a blow,
> Or penetrate its voids and break it up,
> Nature forbids that anything should perish.
> (I, 215-224)

While Lucretius did not explicitly state that each atom has a mass, it may be inferred from his verses. Furthermore, Lucretius implicitly stated that many physical and chemical changes are recombinations of atoms, since no atoms are created or destroyed. This view is almost identical to Dalton's.

The Concept of the Chemical Element

The concept of the chemical element predates the law of conservation of matter by more than a century. The "elements" of classical philosophers and medieval alchemists were actually philosophical principles rather than tangible, physical substances (6, 9). Only in the 17th century did Robert Boyle (1627-1691) in his *The Sceptical Chymist: or Chymico-Physical Doubts & Paradoxes* (1661) give the first definition of a true chemical element as "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" (14). Therefore, a chemical element is a substance which cannot be resolved into different substances by chemical means. However, Boyle never gave a list of substances which he would consider as elemental. The first table of "simple substances" was proposed by Lavoisier in *Traité* élémentaire *de chimie* (10, 15). It comprised 33 substances which included several oxides (at the time their elements could not be isolated) as well as light and heat.

However, Boyle's definition of the element is by no means a modern one. (His notion of the element is merely an irreducible substance, and did not involve atoms.) Dalton considered the chemical element consisting of a single type of atom: "By elementary principles, or simple bodies, we mean such as have not been decomposed, but are found to enter into combination with other bodies" (11). He distinguished atom types by their atomic weights, but today (i.e., since Bohr's model of the atom and Moseley's X-ray measurements) they are distinguished by the number of protons in their nuclei.

Lucretius imagined that atoms differ in shape, and that there exist only a limited number of shapes:

> Now I have explained this I will link a fact
> Associated with it and gaining credence from it:
> That atoms have a finite number of shapes.
> If this were not so, then inevitably
> Some atoms will have to be of infinite size.
> Within the small space of a single atom
> There can be no large variety of shapes.
> Suppose that atoms consist of three minimal
> parts,
> Or make them larger by adding a few more,
> When you have taken those parts of a single
> body
> And turned them top to bottom, changed them
> right and left,
> And have worked out in every possible way
> That shape each order gives to the whole body,
> Then, if you wish perhaps to vary the shapes,
> You must add other parts; thence it will follow
> That if you wish to change the shapes still further
> The arrangement in like manner will need others.
> Therefore novelty of shapes involves
> Increase in size. And so you cannot believe
> That atoms differ infinitely in shape
> Or you will make some have enormous magnitude,
> Which I have proved above to be impossible.
> (II, 478-499)

Each shape represents one type of an atom; and these types we would today understand as elements:

> Now let us consider the qualities of atoms,
> The extent to which they differ in their shapes
> And all the rich variety of their figures.
> Not that there are not many of the same shape,
> But all by no means are identical.
> Nor is this strange. For since their multitude
> As I have shown neither sum nor end,
> Not all, for sure, must be in the same build

All the rest, nor marked by the same shape.
(II, 334-341)

Therefore, Lucretius believed that the number of atoms of the same type, i.e., same element, is beyond count and that these atoms are very similar, but not exactly identical to each other. This view is similar to Dalton's (who considered that atoms of the same element are identical, but may be distinguished) (11) and 19th-century physicists; it was changed only in 1920s when quantum mechanics showed that atoms of the same element (and the same isotope!) can't be distinguished.

Lastly, consider corn of any kind.
Not every grain you'll find is quite the same,
But through their shapes there runs some difference.
So likewise all the various shells we see
Painting the lap of earth, the curving shore
Where waves beat softly on the thirsty sands.
Therefore again and yet again I say
That in the same way it must be that atoms,
Since they exist by nature and are not made by hand
To the fixed pattern of a single atom,
Must, some of them, be different in their shapes.
(II, 370-380)

Lucretius was aware that the multitude of different things (i.e., substances) was far greater than the number of atomic types. In fact, the number of different types of atoms is limited (see above, II, 478-484). Therefore, physical objects must be composed of various kinds of atoms. However, unlike Dalton, he apparently had no idea what the chemical element is like (in this he is similar to Boyle), and did not consider the existence of a chemically pure element (16):

Now here's another thing you should keep signed and sealed
And locked and treasured in your memory:
That there is nothing, among all things visible,
That consists of one kind of atom, only;
Nothing that is not a mixture of elements.
The more qualities and powers a thing possesses,
The more it tells that it has a great quantity
Of different atoms and of varied shapes.
(II, 581-588)

Bonding between Atoms

According to Lucretius atoms are hard and indestructible, so how can they form soft, destructible and transient bodies such as air or fire? We can argue that all macroscopic objects comprise myriads of different atoms and can be regarded as (temporary, perishable) unions of indestructible atoms. Lucretius believed that the atoms are "bound together" in some way; they can also be "unbound", thus the soft object perishes:

And here's another point. Though atoms of matter
Are completely solid, yet we can explain
Soft things—air, water, earth, and fire—
How they are made and what force works in them,
When once we see that void is mixed with things.
But on the other hand, if atoms are soft,
No explanation can be given how flints
And iron, hard things, can be produced; for nature
Will utterly lack a base on which to build.
Their pure solidity gives them mighty power,
And when they form a denser combination
Things can be knit together and show great strength.
(I, 565-575)

(Note that Lucretius explicitly listed the four Aristotelean "elements" as combinations of atoms.) Therefore,

Material objects are of two kinds, partly atoms
And partly also compounds formed from atoms.
The atoms themselves no force can ever quench,
For by their solidity in the end they win.
(I, 483-486)

Why do the atoms stick together? What is the force which binds them? For a true materialist, there exists nothing but atoms and empty space. There should exist no metaphysical concepts, such as "force" (17). Atoms must be bound physically, but they are the smallest and simplest units of matter, so they can't be linked together by bodies even smaller. Lucretius found an ingenious way to bypass this apparent paradox: the atoms are "hooked":

… no rest, we may be sure,
Is given to atoms in the void abyss
But rather, as unceasing different
Movements impel them, some, colliding, leap
Only a short distance from the impact.
And those whose union being more closely packed
Leap back short distances after a collision,
Being fast entangled by their own complex shapes,
These constitute strong roots of stone and the brute bulk

> Of iron, and other objects of that kind.
> Of the rest, which wander further through the
> void,
> A few leap far apart, and far recoil
> Over great intervals; these make for us
> Thin air, and make the shining light of sun.
> And many wander through the mighty void
> Rejected from all union with others,
> Unable anywhere to gain admittance
> And bring their movements into harmony.
> (II, 95-111)

Through a simple observation (observing specks of dust in a ray of light, II, 114-141, see below), Lucretius deduces that the atoms are never at rest; even when held by "hooks" (as in iron), they nevertheless move and "recoil" all the time. It doesn't take much imagination to interpret this recoiling motion as vibration: atoms moving back and forth within their constraints. The surprisingly modern concept of ceaseless motion has its parallel in quantum mechanics, where atoms can only be in their vibrational ground states, but never at rest. Covalently bonded atoms ("strongly entangled") therefore vibrate with short amplitudes and high frequencies, while those held more loosely (e.g., in molecular crystals) vibrate with longer amplitudes and lower frequencies (as is the case with crystal lattice vibrations). Atoms and molecules in the gas phase ("wandering through the mighty void") may also rotate, with still lower frequencies. The idea of a constant motion did not exist in Aristotelean physics, and had been forgotten until development of kinetic theory of gases in the 19th century (18). A similar model, however, was laid out by Daniel Bernoulli in his *Hydrodynamica***,** published in 1738 (19).

The route from Aristotelean continuous matter (2) to the modern concept of chemical bonding was a long and winding one (8). In the last years of 18th century Germans Carl Friedrich Wenzel (1740-1793) and Jeremias Benjamin Richter (1762-1807) (6, 20) noted that the proportions of the compounds consumed in a chemical reaction is always the same. They opened the way to tables of "equivalent weights" (which conceptually differed from Dalton's atomic weights since they did not imply existence of atoms) and to one of the central concepts of chemistry, the valence. Later development of stoichiometry stemmed mainly from their works (6, 7, 15).

In 1852 Edward Frankland (1825-1899) stated what had already become obvious: "A tendency or law prevails (here), and that, no matter what the characters of the uniting atoms may be, the combining power of the attracting element, if I may be allowed the term, is always satisfied by the same number of these atoms" (21). A few years later Kekulé and Couper independently of each other invented structural formulae (22, 23).

Conceptually, the early valence theory was not far from Lucretius's hooks; however, it was more schematic and based on empirical evidence, rather than imagination. Lewis's theory of electron pairs (24, 25) eventually described the nature of covalent bonding: we can imagine every unpaired valence electron as a hook, so a chemical bond is a link formed by two hooks (four if the bond is double, etc.).

Since they hold the atoms together, these hooks must be responsible for (mechanical) properties of different stuff. This would imply that the very hard substances must comprise very hooked atoms, which are so entangled that it is extremely difficult to separate them.

> Again, things that seem hard and dense must be
> Composed much more of atoms hooked together
> Held tight deep down by branch-like particles.
> First in this class and in the leading rank
> Stand diamonds, well used to scorn all blows,
> Next come stout flints and the hard strength of
> iron
> And bronze that fights and shrieks when bolts
> are shot.
> But liquids in their fluid composition
> Must consist more of atoms smooth and round.
> You can pour poppy seeds as easily as water,
> The tiny spheres do not hold each other back,
> And if you knock a heap of them they run
> Downhill in the same way as water does.
> And all those things you see that in an instant
> Disperse, like smoke or clouds or flames, must
> be,
> If not composed entirely of smooth round atoms,
> At least not hampered by a close-knit texture,
> So they can sting the body and pass through
> stones
> Without adhering together.
> (II, 444-461)

Indeed, atoms in hard materials, as above mentioned diamond and flint (i.e., quartz) are linked together by a three-dimensional array of strong covalent bonds; the situation is similar in metals (such as iron), although they lack localised bonds.

However, since materials' properties vary wildly, atoms must have different kinds of hooks; therefore, some are more strongly entangled, while others are held together only weakly. It may then be assumed that viscosity of liquids is determined by size of the atoms' "hooks;" larger hooks are found in highly viscous liquids:

> And though we see wine pass quickly through a
> strainer,
> Yet olive oil by contrast lags and lingers;
> No doubt, either because its atoms are larger
> Or they are more hooked and more closely interwoven,
> And therefore cannot separate so quickly
> And trickle through the holes each one by one.
> (II, 391-396)

Lucretius'ss concept of "hooked" atoms goes beyond the valence theory, as it is able to distinguish between stronger and weaker bonds. In fact, it is closer to the modern model of localised bonding electron pairs than to the 19th-century valence. (In the 19th-century valence theory, existence of double and triple bonds was inferred from their ability to undergo reactions of addition, i.e., by a lack of saturation; the first data on bond strengths stem from calorimetric measurements during the final years of 19th century.) Between Lucretius and the discovery of the electron at the close of the 19th century, a Croatian Jesuit Ruđer Josip Bošković (1711-1787) (26) sketched the first potential between two elementary particles, which was eerily similar to the Morse curve, in his 1758 book *Theoria Philosophiae Naturalis* (27). This was, however, as far as pre-20th-century science could go.

The idea of weaker-than-single bonds developed gradually during the first three decades of 20th century. In early physical chemistry, the first assessment of attractive forces between unbound atoms and molecules was studied by van der Waals, and were for a long time termed "van der Waals forces" (28). Following Werner's theory of coordination bonds (which are, in fact, weak covalent bonds) came explanations of peculiar behaviours of certain compounds in aqueous solutions: Moore & Winmill's "weak union" (29, 30) and, eventually Huggins's "hydrogen bridges" (31, 32, 33), which are today known as hydrogen bonds (34). Weaker still forces kept being discovered throughout the following century: weak C-H···O hydrogen bonds (35, 36), interactions between π electron systems of conjugated rings (often erroneously called π···π interactions) (37, 38, 39), attractions of molecular dipoles, interactions involving halogen atoms ("halogen bonding") (40), etc. (41).

The most recent works show that hydrogen bonds and halogen bonds are qualitatively similar to covalent ones (42, 43, 44) and that in fact there is no clear-cut distinction between strong hydrogen bonds and weak covalent bonds (39), but rather some kind of a "grey scale" exists. Thus, we can imagine hydrogen bonds as smaller and longer "hooks." However, there is a type of interaction which can't be explained by the hooks: the ionic bond, which is as strong as the covalent one in the solid state, but dissipates in a solution (that is, if the solvent is polar). And, also, while covalent and hydrogen bonds are directional, ionic bonds (and other electrostatic interactions also) are not, so they can't be represented as "hooks."

Chemical Affinity

Affinity of one substance towards another is the very basis of chemical science; it defines what is commonly known as "chemical properties." While the notion of "substance" has considerably changed since the alchemists' days-from vaguely defined Aristotelean continuous matter, to chemical elements and compounds, to atoms, ions and molecules, the concept of affinity has persisted to this day. For example, a definition is given in the IUPAC Gold Book (45), although the term is seldom used. The first mentions of affinity of one substance towards another originated in the age of alchemy and are found in works of Albertus Magnus (13th century) and later alchemists (4, 7, 9). The most complete pre-atomistic work on chemical affinity was the 1775 masterpiece *De attractionibus electivis* (*Dissertation on Elective Attractions*) by Swedish chemist Torbern Olof Bergman (1735-1784) (46).

Reflecting on the possibility of different "kinds of atoms" (in today's language, different elements) combining with each other, Lucretius reaches the same conclusion: not all atoms can be combined in every possible way. However, his knowledge of chemical compounds could not be compared to those of 18th-century chemists (such as Bergman), and his reasoning can be hardly regarded as scientific:

> Do not imagine that atoms of every kind
> Can be linked in every sort of combination.
> If that were so, then monsters everywhere
> You'ld see, things springing up half-man, half-
> beast,
> Tall branches sprouting from the living body,
> Limbs of land animals joined with those of sea.
> Chimeras breathing flame from hideous mouths
> Nature would feed throughout the fertile earth,
> Too fertile, generating everything.
> That those things do not happen is manifest.
> (II, 699-708)
> …
> Not that there are not many atoms endowed
> With the same shape, but as a general rule

Things do not consist wholly of the same atoms.
Further, since the seeds are different, different also
Must be their intervals, paths, weights, and impacts,
Connections, meetings, motions. These separate
Not only animals, but land from sea,
And hold the expanse of heaven apart from earth.
(II, 722-729)

Density

The classic definition of density, which predates the resurgence of atomism, is a ratio of mass to volume. Such an empirical measure says nothing of atoms and voids contained within an object. A more fundamental designation of density arrived with the advent of X-ray crystallography: a ratio of mass of unit cell contents (i.e., sum of atomic masses of all atoms within the unit cell) and its volume. For high-quality single crystals, this value is close to the experimentally determined one. A corollary is that the arrays of closely packed atoms have high density, while the "porous" frameworks containing voids (pores or channels) have low density. Lucretius's thinking is in line with modern crystallographers:

Lastly, why do we see some things heavier
Than others, though their volume is the same?
For if there is as much matter in a ball of wool
As there is in lead, the weight must be the same,
Since it is the function of matter to press downwards.
But void, by contrast, stays forever weightless.
Therefore a thing of equal size but lighter
Declares itself to have more void inside it,
But the heavier by contrast makes proclaim
That it has more matter in it and much less of void.
(I, 358-367)

Note that this reasoning also predates the concept of relative atomic masses, and therefore doesn't apply to materials with the same packing of atoms, but different densities (such as some metals).

Microscopic and Macroscopic Properties

One of the modern attributes of chemical science is that it provides a link between the microscopic (on the level of atoms and molecules) and macroscopic world. That is, modern physical chemistry is able to deduce properties and behaviour of bulk matter by studying structure and properties of molecules. However, the first meaningful correlations between micro- and macroscopic properties were Biot's work on optical activity (47) and Pasteur's work on molecular chirality (47, 48, 49). More insights into the atomic world had been gained in the close of 19th century through the developments of spectroscopy and statistical mechanics. These discoveries already relied on quite sophisticated instrumentation. Lacking any instruments other than their own eyes, classical atomists had to rely on their own deductive ability and imagination (and perhaps an occasional polished gemstone which could act as a crude magnifying glass).

Since most macroscopic properties of matter are perishable, Lucretius correctly concluded that they are not atomic properties-atoms are permanent and may possess only those properties which are permanent. For example, colour is prone to changes-most pigments fade over time and coloured stones are ground into whitish powder. Therefore, colour is not an atomic property: atoms are colourless, and the colour is a result of a certain spatial arrangement of atoms.

Now here's a matter which with labour sweet
I have researched. When you see before your eyes
A white thing shining bright, do not suppose
That it is made of white atoms; nor when you see something black
That it is made of black atoms; or that anything
Imbued with colour has it for the reason
That its atoms are dyed with corresponding colour.
The atoms of matter are wholly without colour,
Not of the same colour as things, nor of different colour.
And it you think the mind cannot comprehend
Bodies of this kind, you wander astray.
(II, 730-740)
…
Again, the more a thing is divided up
Into minute parts, the more you see the colour
Fades gradually away and is extinguished.
When purple cloth for instance is pulled to pieces
Thread by thread, the purple and the scarlet,
Brightest of colours, are totally destroyed.
So that you may see that, before its particles
Are reduced to atoms, they breathe out all their colour.
(II, 825-832)
...
Any colour can change completely into another,
Which primal atoms never ought to do.
For something must survive unchangeable

Lest all things utterly return to nothing.
For all things have their own fixed boundaries;
Transgress them, and death follows instantly.
Therefore beware of staining atoms with colour
Lest you find all things utterly return to nothing.
(II, 749-756)
...
If atoms are by nature colourless
But possess different shapes from which they make
Colours of every kind in varied hues—
A process in which it is of great importance
How they combine, what positions they take up
What motions mutually they give and take—
That gives you at once a simple explanation
Why things that were black a little while before
Can suddenly become as white as marble,
As the sea when strong winds beat upon its surface
Turns into white wave-crests of marble lustre.
You could say that often what we see as black,
When its matter has been mixed and the arrangement
Of atoms changed, some added, some taken away,
Immediately is seen as white and shiny.
But if the atoms of the sea's wide levels
Were blue, they could not possibly be whitened.
(II, 757-774)

This description is in accord with the modern view-colour is a macroscopic property which depends on interaction of billions of atoms with billions of photons of appropriate wavelength. However, the notion that a single atom (or a single molecule) is colourless can be disputed—each element has its absorption and emission spectrum. This contrasts Lucretius's idea that the atoms are colourless Also, our optical perception depends on the size of object: for smaller object it is more difficult to notice colour, so small grains of dust of thin threads appear colourless.

However, besides the ubiquitous colour which is a result of absorption, reflection and emission of radiation of a certain wavelength, there is yet another type of colour which is a result of a specific spatial arrangement of atoms: the interference colour. Splendid colours of butterfly wings, shiny feathers on pigeons' necks and rainbow-like sheen on puddles of oily water has nothing to do with absorption bands, so more closely resembles Lucretius's description.

Analogously, Lucretius claims that other macroscopic properties-smell, sound, temperature, etc. are also a result of behaviour of many atoms. However, he doesn't distinguish property and the sensory response to it, which contrasts to the modern models.

Do not suppose that atoms are bereft
Only of colour. They are quite devoid
Also of warmth and cold and fiery heat.
Barren of sound and starved of taste they move.
Their bodies emit no odour of their own.
(II, 843-845)
...
For the same reason atoms must not bring
An odour of their own in making things,
Nor sound, since they can emit nothing from themselves,
Nor similarly taste of any kind,
Nor cold likewise nor heat nor gentle warmth
And all the rest. All these are perishable—
The softness of their substance makes them pliant,
Its hollowness porous, its brittleness makes them crumble—
All must be kept well separate from atoms,
If we wish to lay a strong and sure foundation,
Immortal, on which the sum of life may rest;
Lest you find all things utterly returned to nothing.
(II, 854-864)

Light and Magnetism: Photons?

Until the 19th century, heat (or warmth) and light were considered as substances, and were even mentioned in Lavoisier's table of chemical elements (10). A corpuscular theory of light, regarding light as a stream of particles, developed in 17th century, and was championed by Isaac Newton (1642-1727). Lucretius held a similar view that light is composed of "very small" atoms:

For you could say that the heavenly fire of lightning
Is finer, being composed of smaller shapes
And therefore passes through apertures impassable
By our fire sprung from wood and lit by torch.
Besides, light passes through a pane of horn, but rain
Is thrown off. Why? Because the atoms of light
Are smaller than those that make life-giving water.
(II, 383-390)

Apparently, Lucretius confuses light and fire, however, this was also not uncommon before the 19th century. In fact, heat was correctly identified as a form of energy by James Prescott Joule as late as 1840s, although Davy and Rumford had suggested heat was motion some 40 years earlier.

Lucretius was probably the first philosopher to contemplate the speed of light, a concept virtually nonexistent before the 17th century. Only in 1676 did the Danish astronomer Ole Christian Rømer (1644-1710) prove that the light moves at a finite speed, after observing unusually delayed eclipses of a moon of Jupiter; from his measurements Christiaan Huygens (1629-1695) was able to provide a first estimation of speed of light. Today we know that it is not always the same: it travels fastest through vacuum, and that speed is a constant and is known as *c*. However, when passing through matter, light travels slower, and somehow "finds" the shortest possible way through the optically dense matter. Its refraction is a result of different speeds of light in different materials.

Lucretius gave a somewhat naive, but essentially correct conclusion that the light moves fastest through a "void" (i.e., vacuum), and slows down when passing through matter because the "atoms" of light collide with atoms of matter:

> But that heat and light serene the sun sends
>   forth
> Do not pass through empty void; and for this
>   reason
> They are compelled to go more slowly, and
> To cleave their way as it were though waves of
>   air.
> Nor do the particles of heat move separately,
> But in a mass all linked and massed together,
> So that at the same time they drag each other
>   back
> And meet external obstacles, and so move more
>   slowly.
> But atoms, which are completely solid and
>   single,
> When they pass through the empty void, and
>   nothing
> Outside of them delays them, then they move
> As single units on the course on which they
>   started.
> Therefore they must be of surpassing speed...
>   (II, 147-159)

This is similar to the modern view: we know that the light indeed travels fastest through vacuum (the physical constant *c*), and that it is also the highest attainable speed. Heat, however, does not travel through the void, but infrared radiation, which we feel as heat, does.

We can be tempted to regard Lucretius's "smallest atoms" of light as photons, but the very concept of photons emerged only after the work of Einstein in 1905 (50). However, Lucretius also considered magnetic interactions as streams of atoms, which is curiously similar to the modern view of magnetic fields which are made of photons. For a die-hard materialist, there can be no immaterial interaction (such as a field or Newtonian force), so every interaction must be explained in terms of atoms. However, modern field theories also posit particles to mediate forces: besides photons for electromagnetic fields, there are gluons for the strong nuclear force, and hypothetical gravitons

Nevertheless, the description of "streams of atoms" passing through the magnet, air and other objects, is somewhat reminiscent of magnetic lines of force.

> ... It is easy to move on and state the reason
> And make plain the cause why iron is attracted.
> Firstly, there must needs flow out of this stone
> A multitude of atoms, like a stream,
> That strikes and cleaves asunder all the air
> That lies beneath the iron and the stone.
> Now, when this space is emptied, and a large
> Tract in the middle is left void, at once
> The atoms of the iron gliding forward
> Fall in a mass into the vacuum.
> So the ring follows, its whole form moving for-
>   ward.
>   (VI, 1000-1008)
> ...
> This air of which I speak creeps subtly in
> Through all the many pores within the iron
> And reaching to its tiny particles
> Propels it on, as wind drives sails and ship.
> Moreover, every object must contain air
> Within its body since the structure is porous,
> And air encompasses and bounds them all.
> Therefore the air which deep within the iron
> Lies hid, surges continually, and thus
> Beats on the ring and drives it from within.
> For certainly the ring is carried forward
> By the course on which it has once launched
>   itself
> By its first plunge into the vacuum.
>   (VI, 1030-1042)

Lucretius's attempt to explain magnetism is certainly a bit (at least!) too far-fetched, but it was less erroneous than any other classical attempt, and was also the most coherent mechanistic attempt to explain the magnetic phenomena before Pierre de Maricourt's *Epistola de*

Magnete (51) (late 13th century); the modern study of magnetism actually began with William Gilbert's (1544-1603) *De Magnete* (52). In the classical age it was known that magnets can also repel iron, but the existence of its north and south poles was apparently unknown. (The magnetic needle was invented in China in the 11th century, and the compass eventually arrived in Europe sometime during de Maricourt's life.)

> It also happens at times that iron moves
> Away from this stone, having the tendency
> To flee and then pursue again in turns.
> I have even seen Samothracian irons jump,
> And iron filings in a copper bowl
> Go mad with this magnet stone placed underneath,
> So frantic seem they to escape the stone.
> In this connection do not be surprised
> That the stream from this stone has not the power
> To influence other things as well as iron.
> Some things stand firm by reason of their weight;
> Gold is like this, but others being of substance
> So porous that the stream flies through intact
> Cannot be set in motion anywhere.
> (VI, 1043-1060)

Brownian Motion

Brownian motion was first described by the Dutch biologist Jan Ingenhousz (1730-1799) who noticed irregular movement of coal dust particles on the surface of alcohol (53). However, the phenomenon was named after the Scottish botanist Robert Brown (1773-1858) who described movement of a grain of pollen in a drop of water observed under a microscope (54). Its jerky random movements with short stretches of linear motion, followed by sudden and random changes of direction, was consistent with a multitude of tiny bodies moving about randomly and colliding with each other. This is the basis of all future kinetic models of matter, which involve randomly moving and colliding particles, and which had by the end of 19th century morphed into statistical mechanics and statistical thermodynamics. Einstein gave a modern explanation of Brownian motion in 1905 (55).

Observing the behaviour of specks of dust in a ray of light (since the dust specks are of microscopic size, they can be seen only by reflection of strong light upon them—the same phenomenon was employed in the early 20th-century ultramicroscope), Lucretius made the same conclusions as Brown:

> … When the sun's rays let in
> Pass through the darkness of a shuttered room,
> You will see a multitude of tiny bodies
> All mingling in a multitude of ways
> Inside the sunbeam, moving in the void,
> Seeming to be engaged in an endless strife,
> Battle, warfare, troop attacking troop,
> And never a respite, harried constantly,
> With meetings and with partings everywhere.
> From this you can imagine what it is
> For atoms to be tossed perpetually
> In endless motion through the mighty void.
> To some extent a small thing may afford
> An image of great things, a footprint of a concept.
> A further reason why you should give your mind
> To bodies you see dancing in the sunbeam
> Is that their dancing shows that within matter
> Secret and hidden motions also lie.
> For many you will see struck by blows
> Unseen, and changing course are driven back
> Reversed on all sides, here, there, everywhere.
> There wandering movements, you may be sure, are caused
> In every case by atoms. Atoms first
> Move of themselves, next bodies that are formed
> In a small group and nearest to the force
> Of primal atoms are set moving by them,
> Driven by unseen blows from them; and they
> Attack in turn bodies a little larger.
> The movement thus ascends from primal atoms
> And comes up gradually up to our senses,
> And thus it is that those bodies also move
> That we can see in sunbeams, though the blows
> That make them do it are invisible.
> (II, 114-141)

However, it may be noted that dust specks in air are buffeted by currents including breeze and convection, which are absent in a small drop of water under a microscope. Therefore, the "mingling" which Lucretius observed may be more due to convection than random collisions between small particles.

We may speculate that Brown was familiar with *De rerum natura*, so that "his" motion may not be not very original...

Kinetic Model

Stemming from Brownian motion and the basic gas laws discovered in the 17th through 19th centuries (which are now conveniently combined into the "general" gas equation, $pV = nRT$), are the first quantitative kinetic models of matter, namely the kinetic model of gases and models of diffusion in solutions (Fick's law, 1855). A decade later James Clerk Maxwell gave an explanation of gas viscosity in terms of a distribution of particle velocities in the gas, and the finite size of the particles, which eventually developed into the Maxwell-Boltzmann distribution and statistical mechanics. The basic principles underlying those early models were:

i) there are only atoms (or molecules) and open space through which they move;

ii) there are no interactions between atoms other than elastic collisions;

iii) between the collisions atoms travel in straight lines.

The first step beyond these simple limitations was done by Johannes Diderik van der Waals (1837-1923), who attempted to include interatomic/intermolecular forces in his improved version of the gas model (1873) (56). However, some 1900 years earlier, Lucretius provided a picture qualitatively equivalent to the early kinetic model of gas:

> Yet all things everywhere are not held in packed tight
> In a mass of body. There is void in things.
> To grasp this fact will help you in many ways
> And stop you wandering in doubt and uncertainty
> About the universe, distrusting what I say.
> By void I mean intangible empty space.
> If there were none, in no way could things move.
> For matter, whose function is to oppose and obstruct,
> Would at all times be present in all things,
> So nothing could move forward, because nothing
> Could ever make a start by yielding to it.
> But in fact through seas and lands and highest heaven
> We see before our eyes that many things
> In many different ways do move; which if there were no void,
> Would not so much wholly lack their restless movement,
> But rather could never have been produced at all,
> Since matter everywhere would have been close-packed and still.
> (I, 329-345)
> ...
> Now if you think that atoms can be at rest
> And can by resting beget new movements in things,
> You are lost, and wander very far from truth.
> For since the atoms wander through the void,
> All must be driven either by their own weight
> Or by some chance blow from another atom.
> For often when, as they move, they meet and clash,
> They leap apart at once in different directions.
> No wonder, since they are extremely hard
> And solid, and there is nothing behind to stop them.
> To see more clearly that all particles of matter
> Are constantly being tossed about, remember
> That there is no bottom to the universe,
> That primal atoms have nowhere to rest,
> Since space is without end or any limit.
> (II, 80-93)

It is difficult not to notice analogy with the early kinetic models. Lucretius also ingeniously concluded that while the bodies are in a constant movement, we don't notice it because they are so small, so it seems like we view it from a great distance:

> And here's a thing that need cause no surprise:
> That though all atoms are in ceaseless motion
> Their total seems to stand in total rest,
> Except so far as individual objects
> Make movements by the movements of their bodies.
> For all the nature of the primal atoms
> Lies hidden far beneath our senses; therefore since
> You cannot see them, you cannot see their movements.
> Indeed things we can see, if some great distance
> Divides them from us, oft conceal their movements.
> You see sheep on a hillside creeping forward
> Cropping the fresh green grass new-pearled with dew
> Where pastures new invite and tempt them on,
> And fat lambs play and butt and frisk around.
> We see all this confused and blurred by distance,
> A white patch standing still amid the green.
> (II, 308-323)

Chemical Equilibrium? Or just Crystal Growth?

There can hardly exist a concept more central to physical chemistry than chemical equilibrium. Its modern version was first conceived by Claude Louis Berthollet (1748-1822) who discovered about 1800 that some chemical reactions are reversible. The first quantitative model of equilibrium was proposed in 1864 by Norwegians Cato M. Guldberg (1836-1902) and Peter Waage (1833-1900) (57, 58); a decade later J. H. van't Hoff formulated an equivalent theory (59).

The first physico-chemical studies of 19th century, early electrochemical (mostly potentiometry and conductometry) and spectrophotometric studies, dealt almost exclusively with equilibria in aqueous solutions (60), while early thermodynamics also applied to equilibrium states. The modern concept of the saturated solution (taught in schools!) implies a dynamic equilibrium between a solid and a liquid phase—that is, the crystals grow and dissolve all the time, but in the saturated solution rates of growth and dissolution are equal, so it appears that nothing is changing. It is a small wonder that teaching of physical chemistry still begins with equilibria.

It appears that Lucretius had at least a vague idea that such a dynamic equilibrium may exist at the atomic level. There is a rather ambiguous paragraph saying that perishable matter consists of indestructible atoms; however, it also states that everything is in a constant motion:

> Come, listen now, and I'll explain the motions
> By which the generative bodies of matter
> Beget the various things and, once begotten,
> Dissolve them, and by what force they are driven to do this,
> And what power of movement through the mighty void
> Is given them. Do you now mark my words.
> Matter, for sure, is not one solid mass,
> Close packed together. We see that everything
> Diminishes, and through the long lapse of time
> We note that all things seem to melt away
> As years and age withdraw them from our sight.
> And yet the sum of things stays unimpaired.
> This is because when the particles are shed
> From a thing they diminish it as they leave it,
> And then increase the object that they come to.
> (II, 62-74)

If nothing else, there is the earliest, briefest and surprisingly correct "mechanism" of crystal growth: bodies grow as atoms are attached to them, and diminish as they are removed (47). It is not impossible that Lucretius had actually seen crystals grow from a solution, and gave an atomistic explanation. Although he did not mention it in *De rerum natura*, he must have been aware of the classical method of obtaining salt by evaporation of sea water in shallow pools. (This method is still used in the Mediterranean, and the *sea salt* is considered by gourmets as more palatable than the mined *rock salt*.) Also, one of the most widely used Roman spices, called *liquamen* or *garum*, was essentially a fish-flavoured saturated solution of salt. It is almost certain that salt crystals would grow in vials of *liquamen* upon standing in air.

Conclusion

Physical chemistry was firmly established as an independent branch of chemical science by the 1890s, and most of its basic concepts emerged during the 19th century. However, in their most basic form, they can already be recognised in the work of Lucretius written two millennia earlier: conservation of matter (i.e., atoms), bonding between atoms, chemical affinity, kinetic model of gases (and Brownian motion) and chemical equilibrium, explanation of macroscopic properties by arrangement and motion of atoms (e.g., hardness, density…), corpuscular nature of light and magnetism. While *De rerum natura* can't be regarded as a true scientific work in its modern sense, since it was, like most of classical philosophy, based on observation and deductive reasoning, rather than on experiment and inductive reasoning, it is nevertheless the most complete pre-19th century work on the subject which can today be recognised as physical chemistry.

Since its rediscovery during the Renaissance, *De rerum natura* has been influencing generations of naturalists, and we can truly wonder how many "novel" concepts developed between the 16th and 20th centuries actually stem from Lucretius. We can only speculate that many of them were not original after all, but mere re-writing of his old verses and providing experimental evidence for support.

To conclude, atomism as laid out by Lucretius, is more akin to modern physico-chemical science than to Aristotelean science which had been prevalent until the Renaissance (3).

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HIST to Celebrate 100th Birthday

The American Chemical Society (ACS) Division of the History of Chemistry (HIST) will celebrate its hundredth birthday as an ACS Division in 2022. Today, HIST has over 1,000 members from every sector of the ACS, mounts symposia regularly at ACS National Meetings and at many regional meetings, publishes two Newsletters per year, and since 1988 has published this journal, the *Bulletin for the History of Chemistry*. HIST's publishing record also includes 37 history-related volumes published over the course of the past 60 years that include topics in archaeological chemistry, biography, anniversaries of important chemical events, and history of chemical sub-disciplines.

Two major projects to celebrate its Centennial Year are currently in development:

1) The Centennial History of the Division of the History of Chemistry: A thorough treatment of what happened before, during the foundation, during its evolution and up to the present. The project will be open access and published online. Gary Patterson, Historian of HIST, is organizing the project. Further information, including a projected table of contents, can be found on the HIST website at acshist.scs.illinois.edu/centennial/index.php

Gary welcomes contributions: please send him written material, photographs, ephemera, etc. at gp9a@andrew.cmu.edu. You too can author a full or partial chapter!

2) The *Bulletin for the History of Chemistry* is preparing a special issue in honor of the centennial. Guest editor Jeffrey I. Seeman and Editor in Chief Carmen Giunta have obtained commitments from several recipients of HIST's major awards and current leaders in the history of chemistry to write on the theme "Novel Insights in the History of Chemistry: Looking Back Yet Mostly Looking Forward." The issue will be open access to all online; HIST members will receive hard copies.