# LUCRETIUS, THE FIRST PYHSICAL CHEMIST

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## Introduction

The classical Roman poet and philosopher Titus Lucretius Carus (*ca*. 98 BC - *ca*. 54 BC) is today remembered by 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, which viewed the matter as continuous and postulated four "elements" as fire, air, earth and water. Perhaps unsurprisingly, the scientific revolution of the Renaissance roughly coincided with abandonment of the Aristotelean physics and re-discovery of *De rerum natura* with its atomism.

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 BC - 43 BC) and Vergil (Publius Vergilius Maro, 70 BC - 19 BC). According to a Cicero's letter to his brother Quintus dated 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 luxurious lifestyle of Roman high society. However, his verses also reveal that he had a broad knowledge on 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 the Roman history. The Roman republic, having outgrown itself, became corrupt, dysfunctional and virtually ungovernable. Intrigues, conspiracies, political murders and all kinds of violence were became common. Brutal civil wars were fought; a bloody dictatorship followed after a bloody dictatorship (2). 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 (3). 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 decline of the Roman empire, Lucretius and his work were forgotten. A copy of *De rerum natura* was found in a library of a German monastery by Italian humanist Gian Francesco Poggio Bracciolini (1380 - 1459), and its re-discovery heralded a beginning of a new era. Lucretius' 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 all natural sciences.

Interest in *De rerum natura* appears to have waned in the 20th century, one of the reasons likely being connected to fast advancement of all sciences and discovery of subatomic particles, which ran contrary to the ideas of classical philosophers. However, real appreciation of the natural philosopher's deep insight into the structure of the matter and dynamical phenomena in the Nature can hardly be properly understood without understanding of the modern molecular science.

Many of the fundamental concepts and mechanisms upon which the 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, and early form of proto-science, thrived between 1st and 3rd centuries AD (that is, it began more than a century after Lucretius' death) (4), however it was based on Aristotelean physics rather than atomism, and eventually gave rise to alchemy.

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.

## Conservation of mass

18th century chemistry was still based predominantly on Aristotle, pretty much as was alchemy in the Middle Ages. It regarded matter as continuous, i.e. 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 two things which were not readily available before 18th century: a sealed apparatus and a precision balance. And a great deal of imagination.

It is usually considered that the modern chemistry began when Antoine Laurent Lavoisier (1743 - 1794) postulated the Law of Conservation of Matter, which is regarded as the most basic law of chemistry. It was, however, only an empirical "law" discovered after numerous experiments, and its fundamental nature was realised only after John Dalton's (1766 - 1844) resuscitation of atomic theory in his 1808 book *New System of Chemical Philosophy* (5). 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 (6). Until advent of spectroscopy in 1860's mass was the only atomic property which could be determined.

Almost half a century before Lavoisier, the Law of Conservation of Mass 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 Menshutkin (1874 - 1938) (7).

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 simple: atoms are indestructible:

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 not explicitly stated, it is clear that each atom has a mass - after all, it is a physical particle. While the mass of a single atom is tiny and can't be measured, we can weigh macroscopic objects which are nothing more than a lot of atoms thrown together. Furthermore, Lucretius implicitly stated that every (chemical) change is a recombination 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 (4). Only in 17th century did Robert Boyle (1627 - 1691) in his *The Sceptical Chymist: or Chymico-Physical Doubts & Paradoxes* (1661) do away with this outdated concept and gave 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." (8) Therefore, the 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* (1789) (9). 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. Dalton re-defined the chemical element into "a pure chemical substance consisting of a single type of atom" (5). He distinguished atom types by their atomic weights, but today (i.e. since Bohr's model of atom and Moseley's X-ray measurements) they are distinguished by 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. Note similarity with Dalton's atomic theory:

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 19th century physicists, and was changed only in 1920's when quantum mechanics shoved 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. Therefore, physical objects must be composed of various kinds of atoms. However, unlike Dalton, he apparently had no idea what is the chemical element like (in this he is similar to Boyle), and did not consider existence of a chemically pure element (10):

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)

Here we should note that almost all educated people in 18th and early 19th century Europe were familiar with *De rerum natura*, and those almost certainly include John Dalton. Is it therefore a too far-fetched idea that he may have been actually inspired by Lucretius?

### Bonding between atoms

By definition 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 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 the "force" (11). 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 (e.g. observing specks of dust in a ray of light), 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. This surprisingly modern concept has its parallel in quantum mechanics, where atoms can only be in their vibrational and rotational 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") 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 18th century.

The route from Aristotelean continuous matter to the modern concept of the chemical bonding was a long and winding one. In the last years of 18th century Germans Carl Friedrich Wenzel (1740 - 1793) and Jeremias Benjamin Richter (1762 - 1807) noted that the amount 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. In 1852 sir Edward Frankland (1825 - 1899) stated what had already became 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." (12) A few years later Kekulé and Couper independently of each other invented the structural formulae (13,14).

Conceptually, the early valence theory was not far from Lucretius' hooks, however it was more schematic and based on empirical evidence, rather than imagination. Lewis' theory of electron pairs (15,16) eventually revealed the nature of the covalent bonding: we can imagine every 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, flint (i.e. quartz) and iron are linked together by a 3D array of strong covalent 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's 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 quantum-mechanical description of chemical bond than to the 19th century valence (In the 19th century valence theory, existence of double and triple bonds were defined by 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 discovery of the electron at the close of the 19th century, a Croatian jesuite Ruđer Josip Bošković (1711 - 1787) (17) sketched the first potential between two elementary particles, which was eerily similar to the Morse curve, in his 1758 book *Theoria Philosophiae Naturalis* (18).

The idea of weaker-than-single bonds developed gradually during the first three decades of 20th century. In the early physical chemistry, first assessment of attractive forces between the unbound atoms and molecules was studied by van der Waals, and were for a long time termed "van der Waals forces" (19). 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" (20,21) and, eventually Huggins's "hydrogen bridges" (22,23,24), which are today known as hydrogen bonds (25). Weaker still forces were kept being discovered throughout the following century: weak C-H···O hydrogen bonds (26,27), interactions between π electron systems of conjugated rings (often erroneously called π···π interactions) (28,29,30), attractions of molecular dipoles, interactions involving halogen atoms ("halogen bonding") (31), etc. (32)

The most recent works showed that hydrogen bonds and halogen bonds are qualitatively similar to covalent ones (33,34,35) and that in fact there is no clear-cut distinction between strong hydrogen bonds and weak covalent bonds (30), 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 bond (and other electrostatic interactions also) is not, so it can't be represented as "hooks".

## Chemical affinity

Affinity of one substance towards another one is the very basis of the 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 in an essentially unchanged form. 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[3].

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) (36).

Reflecting on the possibility of different "kinds of atoms" (in today's language, different elements) combining with each other, Lucretius reaches the same conclusion: all atoms can't be combined in every possible way. However, 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 resurgence of atomism, is a ratio of mass and volume. Such an empirical measure says nothing of atoms and voids contained within an object. A more fundamental designation of density arrived with 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 "porous" frameworks containing voids (pores or channels) have low density. For example, the common hexagonal ice $I_h$ has a density of 0.92 g $cm^{-3}$, while the close packed ice VII has a density of 1.50 g $cm^{-3}$. 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)

## Microscopic and macroscopic properties

One of the modern definitions of chemical science is that it provides a link between 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 (37) and Pasteur's work on molecular chirality (37,38,39). More insights into atomic world had been gained in the close of 19th century through development of spectroscopy and statistical mechanics. However, 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 of 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 the 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. A single atom is therefore 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's wings, shiny feathers on pigeons' necks and rainbow-like sheen on puddles of oily water has nothing to do with absorption bands, so even more closely resembles Lucretius's description.

Analogously, Lucretius claims that other macroscopic properties - hardness, smell, sound, temperature, etc. are also a result of behaviour of many atoms.

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 19th century, heat (or warmth) and light were considered as substances, and were even mentioned in the Lavoisier's table of chemical elements (9). Corpuscular theory of light, regarding light as a stream of particles, developed in 17th century, and was championed by sir Isaac Newton (1642-1727). Lucretius held a similar view that the 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 19th century. In fact, heat was correctly identified as a form of energy by James Prescott Joule as late as 1840's.

Lucretius was probably the first philosopher to contemplate speed of light, a concept virtually nonexistent before 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 Jupiter's moon; 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 speed of light in different materials.

What did the classical philosophers know about optics and the nature of light? In the extant texts, there is barely a mention of the phenomena. However, 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)

We can be tempted to regard the Lucretius' "smallest atoms" of light as photons, but the very concept of photons emerged only after the works of Einstein in 1905. 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. However, for a die-hard materialist, there can be no immaterial interaction (such as field or Newtonian force), so every interaction must be explained in terms of atoms. Nevertheless, description of "streams of atoms" passing through the magnet, air and other objects, somewhat reminds 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 forward. (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' 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 seriously scientific attempt to explain the magnetic phenomena before Pierre de Maricourt's *Epistola de Magnete* (40) (late 13th century); the modern study of magnetism actually began with William Gilbert's (1544 - 1603) *De Magnete* (41). In the classical age it was known that magnet can also repulse iron, but existence of its north and south poles was apparently unknown. (Magnetic needle was invented in China in 11th century, and the compass eventually arrived to 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. 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) (42). 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.

Observing 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)

We may contemplate that Brown was also familiar with *De rerum natura*, so that "his" motion is in fact not very original...

## Kinetic model

Stemming from Brownian motion and the basic gas laws discovered in the 18th century (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). 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 Diedrik van der Waals (1837 - 1923), who attempted to include interatomic/intermolecular forces in his improved version of gas model (1873) (43). 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 the 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) (44,45); a decade later J. H. van't Hoff formulated an equivalent theory (46).

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 (47), while early thermodynamics also applied to equilibrium states. The very notion of the saturated solution 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 from it.[37]

## Conclusion

The physical chemistry as an independent branch of chemical science was firmly established by 1890's, 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. 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 the physical chemistry.

Since its re-discovery during the Renaissance, *De rerum natura* had been influencing generations of naturalists and we can truly wonder how many "novel" concepts developed between 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 age. Indeed, the work of Lucretius was not just centuries, but full two millennia ahead of its time.1

## About the Author

Krešimir Molčanov is a chemical crystallographer working at the Ruđer Bošković Institute in Zagreb, Croatia, and his research includes study of intermolecular interactions in the solid state and crystal engineering using organic radicals. His other interests are popular science, education and history of science.

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2. A number of murderous dictatorships occurred during the life of Lucretius: Lucius Cornelius Sulla (88 BC), Gaius Marius (87 BC), Cornelius Cinna (87 - 82 BC), Sulla again (81 - 79 BC) and the first Triumvirate of Pompey, Crassus and Julius Caesar (*ca*. 60 BC - 53 BC). Also, there was the war with Italian allies (the Social War, 91 - 88 BC), the rebellion of Spartacus (also known as the Third Servile War, 73 - 71 BC) and the conspiracy of Catiline (63/62 BC). Detailed accounts of the dictators and the civil wars are found in Plutach's *Parallel lives* (lives of Marius, Sulla, Crassus, Pompey the Great, Julius Caesar, Cicero and Cato the Younger); available on-line free of charge from http://penelope.uchicago.edu/Thayer/E/Roman/Texts/Plutarch/Lives/home.html.
3. Gaius Memmius, sometimes referred to as Gemmelus, was a minor politician and a poet, although none of his verses survived to modern times. His greatest achievement was the office of tribune of the people, which he held in 66 BC. Initially a Pompey's supporter during the civil war, he quickly changed side and went over to Julius Caesar. After a corruption scandal during the elections in 54 BC he was forced to leave political life and retired to Greece where he died around 49 BC. Today he is remembered solely due to Lucretius' dedication. Some notes on Memmius's political career can be found in Plutarch's *Parallel lives* (*Life of Cato the Younger*).
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11. Interestingly, Newton's mechanics, which involves non-material force, was criticised for the same reasons by his contemporaries.

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