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The Idea of the Atom

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NATIONAL INSTITUTE OF ADVANCED STUDIES

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Abstract

The physical idea of finite divisibility of matter, and possibly that of space and time itself, is very old, and seems traceable to an even older idea of the arithmetic discreteness vis-à-vis the geometric continuum. In this talk, of admittedly limited range and depth, I shall summarize the Atomic Theory that was developed over nearly five hundred years before the Christian era by the three great Greek philosophers, namely, Leucippus, his pupil Democritus, and Epicurus, and the Roman philosopher-poet Lucretius, and by the great Indian thinker Kanada who founded the Vaiseshika School, ca. 6th century B.C.E. Their Atoms were indivisible, hard, solid (not hollow) particles of insensibly small sizes and weights, infinite in number, having various but finitely many shapes, moving incessantly every which way in the Void (vacuum), ever colliding, and occasionally compounding — thus giving the observed plurality of the sensible world. This atomistic world-view, based on logical arguments for the stability of matter and simple observations, rather than on any

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systematic experimentation, was, however, suspended and remained dormant for almost a millennium, throughout the (Dark) Middle Ages, under the damning influence of the greatest Greek of all, the continuist Aristotle (384-332 B.C.E.) who questioned the very existence of the actual or achieved infinities and infinitesimals in principle, and asked for the first and the final causes of the otherwise atheistic random Atomic motion in the assumed Void. He ruled polemically that "Nature abhors vacuum". The idea of the Atom, however, re-emerged forcefully in the post-Newtonian era, and informed much of the Daltonian chemistry and the Maxwellian physics (kinetic theory of gases), and finally received a more direct evidence in the Brownian motion of the plant pollen observed under the microscope, which was ultimately explained by Einstein as resulting from the molecular collisions of the many molecules (atoms) — of the Avogadro proportion. Lord Kelvin's theoretical construct (ultimately unsuccessful though) of discrete atom-vortices out of continuous ether may be viewed as an attempt at a concrete resolution of the ancient continuum-discrete dichotomy. Today, the quest for the Atom as the elementary building block of matter has gone far beyond the atoms of Bohr (~10^{-8} cm) listed in the chemists' Periodic Table, or their nuclei (~10^{-13} cm), and now points to the point-like quarks, and possibly to the tiniest strings (~10^{-33} cm). One may reasonably say that, while any specific model for the Atom may not survive in the 21st century, the idea of the Greek-Kanada Atoms as a metaphor for the ultimate constituents of the material universe will.

The idea of the atom ((Greek: a = No, tomos = cut) as an indivisible constituent of matter, informs, for all practical purposes, much of physics and all of chemistry that we know today, including presumably the biology of the living and the sentient too. This despite the fact that over the past century the atom has been resolved and actually *split*. Indeed, it has turned out to have an elaborate internal structure — with electrons orbiting the nuclei made of protons and neutrons, structured in turn on still finer scales that seem inward bound — an infinite regression perhaps. The atom has lost the certainty of its *sharp edges*, and has been replaced by the uncertainty of probabilistic waviness. In point of fact, the quest for the ultimate indivisible constituent has moved on far beyond the sensible and the naïve realism that appeals to our classically imprinted mind. One now speaks seriously of the reality of the Unobservable — of the point-like quarks and the tiniest of the *strings* ($\sim 10^{-33}$ cm) that may well be the stuff that our universe is made of. The indivisible atom has thus become a metaphor — extremely useful and creative for the *exposition of Nature, regardless of whether it existed or not* — an instrumentalist viewpoint held firmly by Francis Bacon (1561–1626), regarded by many as the Father of modern Science. And, of course, what good is a metaphor if it has to be literally one with the reality it points to!

However, it does come as a surprise that, until very recently, the idea of the atom was far from being accepted universally. It was certainly the case as late as the turn of the last century. Listen thus to Ostwald, the leading physical chemist of the late 19th century, who had won the 1909 Nobel Prize for Chemistry, and who contrived to write a whole text book of chemistry without using the word *atom*, which to him was a mere analogy. This is what he had to say of the unseen atoms in 1895 — " ... *thou shalt not make unto thee the graven image or any likeness of anything! Our task is not to see the world in a more or less clouded mirror, but to see it as directly as the constitution of our being possibly allows* ... ". Only bare facts! Analogies only *save appearances*. (The realization that there are no *bare facts*, and that all experiments are theory- loaded, came later, with Boltzmann in fact (ca. late 19th century, A.C.E.). Contrast this with what Feynman, one of the greatest physicists of our times, considered as the most important statement we could possibly make, "...*Everything is made of atoms ... everything that animals do, atoms do ... There is nothing that living things do that cannot be understood from the point of view that they are made of atoms acting according to the laws of physics.*" Add to this the permanence and the immutability of the atom that Dalton (ca. 1766-1810, A.C.E.), regarded by many the Father of Chemistry, claimed, "...*We might as well attempt to introduce new planet into the solar system, or to annihilate one already in existence as to create or destroy a particle of hydrogen*" *(A New System of Chemical Philosophy, 1808).*

The idea of the atom as centre of all material existence can be traced back to the early Greek and Indian thoughts of the five centuries before the Christian era. The Greek school was founded by Leucippus of Miletus, and propagated by his great pupil Democritus of Abdera in ca. 5th century B.C.E. Democritus was a great expositor of the Atomic Theory, and one of the most universal thinkers of the ancient world. (It is said that his public lectures on the atomic theory raised golden talents*, unmatched in value in the 19th century West!). Later, the Athenian philosopher, Epicurus of Samos (ca. 4th century B.C.E.) elaborated the Atomic Theory into a philosophical enquiry. This was followed by Lucretius, the Roman poet of ca. 1st century B.C.E., who *sang* the Epicurean philosophy (but not his ethics!) in his inimitable De Rerum Natura (on the Nature of Things). By then, the Greek Atomic Theory was complete.

The Indian Atomic Hypothesis was advanced by the sage Kanada (aka Kashyapa earlier) who founded the Vaiseshika School of atomism, ca. 6th century B.C.E. The Vaiseshika-Sutra (peculiarity aphorism) envisages *parmanu* (atom), the ultimate constitutuent, as point-like in space, indeed as a limiting image of a grain of rice (the *kana*) — indestructible, incessantly in motion, and with property peculiar (hence the Vaiseshika) to the primary substance that it constituted. The primary substances were the five Vedic Pancha Mahabhootas — Earth, water, fire, air with ether (space) added on later. He even spoke of *Dwinuka* (the diatomic molecule).

Clearly, both the Greek and the Indian thinkers of those ancient times were in quest of the ultimate constituent of matter — the One in terms of which the

(*talent = equivalent of monetary unit then.)

diversity and plurality of the Many could be resolved. This great reduction — of the many Why's and How's into a relatively small number of Why's and How's that may then be taken as the ultimate facts — had led them to Atomism as a minimal hypothesis. The basic tenets of the Atomic Theory of the ancient Greeks, and more or less of the ancient Indians, were:

1. Is matter infinitely divisible? No, they answered. Matter is finitely divisible. The sub-division must stop at the Atom that cannot be cut in two, terminating thus the infinite regression.
2. Atoms are all of one kind - having no essential property other than that of extension. All are made of the same primal substance. This was the monistic base of the early atomism, traceable to the Ionian philospher Thales (634-546 B.C.E.) of Miletus.
3. Atoms are of different, but *finitely* many shapes/sizes — insensibly small, interlocking shapes, concave/convex, and so on.
4. Atoms are infinitely many in number.
5. Atoms are hard, not hollow, and impassable.
6. There is *Void* (vacuum) — an independent permanent reality — separating the atoms. This allows atoms to move in the Void — the elbow room.
7. Void is infinite and accommodates infinitely many atoms.

8. Atoms are constantly moving, colliding, and interacting only by contact — *elastically* — their Motion taken as an ultimate fact. No arguments regarding its causation. No external forces, or innate tendencies.
9. Primary qualities, e.g., hardness, impassability, etc., are the objective, *true* attributes of matter made of the atoms.
10. Perceived qualities (or qualia or affections), e.g., colour, smell, taste, sound, are subjective and secondary:

    Colour exists by convention,
    Sweet by convention,
    Bitter by convention.

    Nothing in truth exists, but the Atoms and the Void — the reality (Thus chanted Democritus, quoted verbatim by the Greek physician Galen, ca. 2nd century A.C.E.).
11. Objective basis of sensations — simply and solely by contact with the unseen atoms.

Needless to say that the Greek/Indian atomism was not derived inductively from any detailed, systematic experimental observations/empirical data, nor arrived at deductively from a set of given/assumed axioms. It was, therefore, not scientific in the modern sense of the word. It was nevertheless a serious attempt at rationalization of Natural Philosophy that had logic to it. The compelling reason of these ancients for their atomism was to be found in the general question of the observed stability of matter — how could the perceived small changes in the sensible objects around us be consistent with the unchanging, essential (taxonomic) identity of the objects themselves. Only an object made of a large number of unchanging *smaller-units* can change without changing essentially. This *change-without-changing* was the real reason for their Atomism. The sharp discreteness of the Atom, as opposed to a fuzzy continuum, was ultimately responsible for their stability. (In the modern context, just think of the discreteness of quantized orbits that stabilize Bohr's atoms against decay into the otherwise classical continuum. It is also much the same as the idea of polymorphic stability of a population/species despite the allelogenetic variations, as in modern molecular biology of the genome. Or more generally, it is perhaps a question of the digital robustness against the analogue fuzziness).

One may well be inadvertently biased towards reading much more into the records of the ancients than what there actually was. But, at the risk of making this systematic error, one can reasonably say that the stability of matter was very much in their thoughts. A related issue was that of the conservation of matter: Atoms, just like integers (or now as rational fractions too!), could be counted and accounted for in any reckoning. Such a book keeping was hardly possible for a continuum (or now for the irrationals too): Such fractions could be lost irretrievably! Another significant point to be noted here is the *finiteness* of the number of *shapes/sizes* of the atoms envisaged by them (After all, the Period Table of Mendelev (ca. 1869 A.C.E.) too contains only finitely-many types of atoms — 92, or some more if one counted the 25 odd transuranium elements, occurring naturally or created artificially). Still another point of note is that the Atoms interacted only by the hard-core contact (excluded volume effect) — reminiscent of the force-less mechanics of Heinrich Hertz (1857-1894), subject only to constraints. And yet they spoke of the compounding of the Atoms — due to the Atoms scattering multiply against one another giving a long-lived Epicurean *Concilium* — a molecule in communal motion in the narrow space bounded by the neighbours. Again, strongly reminiscent of the modern idea of the Ruelle-Pollicot resonances of the 20th century! As to how an object of sensible magnitude, made of these Atoms racing at high velocities, could move rather slowly, they simply pointed to the clouds! And, as for the evidence for the Atomic motion itself, they pointed to the mote (of dust) dancing in the sunbeam. Interestingly, but for the effects of air convection, this zig-zag motion was no different from that of the plant pollen observed by the Scottish botanist Robert Brown (1773-1858) some two thousand years later.

There were, of course, variations on the main Atomic theme of the ancient Greeks so as to accommodate other features as they occurred to them. Thus, one such feature was the Epicurean *swerve* wherein the Atomic motion, originally deterministic, was made intrinsically random and unpredictable in principle, to preserve reverence for the human freewill. The greater the *swerve,* the greater the degree of spirituality. Critically poised atoms (the *clinamen*) were explicitly introduced for this purpose. Present day efforts to derive freewill from deterministic chaos bear a close resemblance to these *clinamen.* The atoms could also be viewed as comprising the primal substances — the air, water, earth and the fire — of Empedocles (ca. 490-430 B.C.E.), but without invoking his forces of love and hate for interaction. But the general picture was that of the Atoms of Democritus (the *ameres*) moving in the Void, or perhaps in the continuum of ether (the *apeiron* of Anaximander of Miletus, ca. 600 B.C.E.).

Despite, however, its great appeal to physicists, the Atomism of the ancient Greeks lost out to the continuism of Aristotle (384-322 B.C.E.), who was totally opposed to Atomism. Aristotle was a realist/empiricist who questioned the reality of the sensibly unobservable Atom. He opposed the actual or achieved infinitesimal and infinity in principle, and admitted only the sensible objects. The Void separating the Atoms too was inadmissible — *Nature abhors vacuum*! And finally, the random motion of the Atoms, without any divine assistance and without the *innate tendencies* and *potentialities* within the matter as the final cause, was down-right atheistic to him.

To Aristotle, chance and disorder was an abnegation of the created order. Also, Aristotle viewed space not as a vacuum, but as filled with *plenum* — universal material. Matter was identified with extension. As to how motion was possible at all within such a continuum, he proposed the idea of *antiperistalsis* — motion by exchange of places, of what is *a priori* (to the fore) with what is a *posteriori* (to the aft). Parts moving into one another. (Just imagine a fish swimming through water by displacing it as it moves). This is what the fluid-dynamicists of today would call the back-flow.

Some of this continuist viewpoint can be detected in the rather sophisticated thinking of Anaxogoras, ca. 500-428 B.C.E., who considered a continuum which was infinitely divisible and, very importantly, infinitely differentiated. This could give the observed plurality of things that are nevertheless sensibly homogeneous — his *Homoeomeria*! This plurality can be pictured rather vividly as a re-arrangement of a pointillistic quasi-continuum (Just imagine a variegated silly putty or plasticene!).

Aristotle, however, did allow for the *minima*, e.g., the *cells* for the living things below which size there is loss of identity. This idea was preserved and perfected through the Middle Ages, even though the Greek Atomism *per se* was vehemently opposed. (By the Middle ages, the Atom had in fact become latinized to mean the smallest unit of time.) He was also struck by the analogical *letter-atoms* (the *stoicheio*) and the word-compounds. Because, after all, weren't tragedy and comedy both composed of letters from the same alphabet! Order (sequence) of letters in a word matters, much as the arrangement of the Atoms in a concilium (compound). There, the meaning (of the word) as also the property (of the *concilium*) is encoded in the order of the letters/atoms. Such an information-theoretic viewpoint is quite modern! Physical Atoms were, however, not acceptable to Aristotle.

And, so great was the damning influence of Aristotle that the Atomism of Leucippus, Democritus, Epicurus, and *Lucretius was suppressed completely* by the turn of the first Christian era, and remained so for almost 1000 years through the Dark Ages and the most of the Middle Ages, while theology and scholasticism prevailed, firmly opposed to Atomism. (Much as the Darwinian idea of evolution is still being opposed in some of the southern states in the USA). It was revived by William of Occam in the late Middle Ages. There followed the rediscovery and reprinting of the ancient texts in the early 15th century, and the Atomism eventually became a force in the course of the renaissance (14th-16th century) and the post-Newtonian period, and, of course, in the modern era.

The Greek Atomism and the associated mechanical world-view exerted a deep influence on the chemists and the physicists of that time and beyond. Of course, initially at least, one had to introduce here the external Cosmic Law-Giver (to replace the Aristotelian innate tendencies and the final causes) so as to order the random motion of the atoms. This helped remove the traditional, somewhat repugnant atheistic association of the past and made the thus tempered mechanical world-view more acceptable. But still, there was fierce disagreement and debate though. Thus, in his Optiks, Isaac Newton (1642-1729) wrote, *"It seems probable to me, that God in the Beginning form'd Matter, in solid massy, hard, impenetrable, movable Particles, of such Size and Figures, and with such other Properties, ..., so very hard, as never to wear or break in pieces; no ordinary Power being able to divide what God himself made one in the first Creation"*. Quite inevitably, Gottfried Wilhelm Leibniz (1647-1716) differed. He was for continuum, and held that matter is infinitely divisible and the universe infinitely extensive: *"Atoms are the effect of the weakness of our imagination, for it likes to rest and therefore hurries to arrive at a conclusion in sub-division or analyses; this is not the case in Nature; which comes from the infinite and goes to the infinite. Atoms satisfy only the imagination, but they shock the higher reason"*.

The great Rene' Descartes (1596-1650) who gave us the Cartesian coordinates, too was a continuist, opposed to Atomism and Void. (For him the space was filled with a plenum — in fact in a vortex that moved the entire planets). Also, the positivists like Ernst Mach (1838-1916) could never reconcile to the insensible atoms. The Machian *sensationalism* was rejected by Boltzmann (1844-1906) and Maxwell (1831-1879) who at once took to

Atomism. Indeed, Maxwell's kinetic theory of gases was manifestly Atomic. There was also an ingenious attempt by the 19th century physicists von Helmholtz and Lord Kelvin at deriving a stable atom-like dis*crete* object from the fluid *con*tinuum in motion — a *con-crete* unification of the otherwise conflicting atomism and continuism. The resulting Helmholtz-Kelvin Vortex-Ring Atom was finite, permanent and could form a compound through entanglement that was stable topologically against decay or dissociation. This, however, required an ideal inviscid ether-fluid, and had to be finally abandoned.

There were also remarkable novel applications of the Greek Atoms and the Void, notably the one proposed by George-Louis La Sage in the 19th century, to Gravitation. He postulated such Atoms (the *ultramundane corpuscules*) racing around in the Void at random and colliding with any sensible object elastically. Mutual shadowing of any two such objects then resulted in a force of attraction that had the Newtonian form. Detailed consideration, however, led to a cancellation of the effect for the simple models. This was a bold first attempt to derive a force of interaction from exchange of particles.

An important development of note that helped the general public acceptance of Atomism was the publication of Hooke's *Micrographia* in 1665, revealing the finer-scale details of tiny life-forms imaged with the help of the newly developed microscope — demystifying thus the unseen minuteness ($\sim 10^{-4}$ cm) and by extension the unseen Atoms. For the 19th century chemists like Dalton, Cannizzaro and Avogadro, Atomism had great, instant appeal. So was the case with the 17th century chemist Robert Boyle (1627-1691) with whom started modern chemistry. Dalton introduced his Lego-like models of molecules made from the *atoms*, and published A New System of Chemical Philosophy at the turn of the 19th century, to which the Atomic Hypothesis was central. Lavoisier (1743-1794), however, found the Atoms impossible in principle but convenient in practice. (It has been suggested that this resistance to the Atomic picture correlated with the sudden demise of the French science in the early 20th century).

Finally, the reality of the unseen Atoms/Molecules was unambiguously confirmed by the phenomenon of and the theory for the Brownian motion as developed by Einstein in 1905 (though he wasn't really aware of the work of the Scottish Botanist Robert Brown (1773-1858) who had observed the thermal motion of the floating plant pollen under a microscope). The scientific revolution of the late 19th and early 20th century changed dramatically the course of history of the Atoms. Thus, J.J. Thomson's discovery (1897) of the negatively charged light particle, the electron, detachable from the atom, and Lord Rutherford's discovery (1911) of the positively charged, heavy atomic nucleus, pointed to an internal structure of the Atom. Early attempts to successively refine the model structure were somewhat like the great Ptolemy adding on his epicycles. And then came the revolution with the new Framework Theories — Relativity and Quantum Mechanics. Relativity did away with the ether (the *apeiron*) in which the atoms (*ameres*) would move, and quantum mechanics took away the *sharp-edges* of the Atoms, replacing these with a probabilistic fuzziness/waviness. Stability was now provided by the discreteness of the allowed quantum *numbers* — the Bohr atom. The subsequent history is known all too well. Today, the Atoms can really be *seen* and *touched* — by the *finger-tip* of a Scanning Tunneling Microscope. But the ancient quest for the Atom as the ultimate constituent of matter has moved on to a different domain of the subtle and the minute — to the point-like quarks and the tiniest strings ($\sim 10^{-33}$ cm, the Planck length) — far from the madding laboratory scales, where experiments may no longer be do-able. Self-consistency, beauty and simplicity — almost pure thought — may well be the only guide. A situation not very different from the one in which the Ancients with their obvious limitations found themselves in — but nearly two thousand years ago! But that is a different story.

Philosophically speaking, the conflict between Atomism and Continuism goes much deeper, perhaps into the mathematics of number theory. And it goes back to Pythagoras (ca. 585-495 B.C.E.) — the arithmetic discreteness of integers, rational fractions, the commensurable, and the countable — and to Zeno (ca. 490-430 B.C.E.) with his celebrated paradoxes — the geometric continuum of a line interval, the irrational, the incommensurable and the uncountable. It may have been extended to space, time and matter by some kind of transference. It also reminds one of the analogue- digital divide of today. Or the two-valued versus multi-valued (or fuzzy) logic. The introduction of the quantum of field in modern physics has raised the conflict to a much higher level of abstraction indeed.

The Atomic worldview of the Ancient Greeks and Indians, that tried to assemble the sensible universe out of the insensible Atoms, however, stands basically unchanged. Nature seems to have no architectural (*aufbau*) excesses. It repeats it just the same, over and over again:

> *Now the smallest particles of matter may cohere by the strongest attraction, and compose bigger particles of weaker virtue; and many of these may cohere and compose bigger particles whose virtue is still weaker; and so on for diverse successions, until the progression ends in the biggest particle on which the operations in chemistry and the colour of natural bodies depends and which by cohering compose bodies of a sensible magnitude.*
> *Isaac Newton in Optiks (ca. 1700)*

Postscript

THE IDEA OF THE ATOM is based almost entirely on my general acquaintance with the ancient Greek and Indian thoughts on the subject, that I have gathered informally as a theoretical Physicist, and not formally as a professional historian of science. The selection of issues discussed, as also the discussion itself, reflects my personal bias. There are serious omissions too — notably of the Jain, the Arab and the Chinese world-views. One may note in passing, however, that clearly the Indians, but also the Arabs, much like the Greeks were generally receptive to the idea of Atomism. Indeed, it was the century Arab philosopher Averroes who considered the 12th physical infinite divisibility (as distinct from the mathematical infinite divisibility) unphysical as it could not be realized in practice. The Chinese under the holistic influence of Confucius (ca. 600 B.C.E.) believed in the harmony of homogeneity and continuity, and were thus opposed to the atomic discreteness. Indeed, the moods were different — the mood of the Chinese was in the imperative (ethical/moral), while the mood of the Greeks, and certainly of the Indians, was in the infinitive (a-moral). The Chinese had difficulty with the idea of the externally imposed universal laws of Nature governing the universe. Only the ethical/moral (legal) laws were admissible to them. The Jain system with its great elements and the elaborate cosmology was, however, very different; but I must let it pass for now. Completeness of any kind, is of course, out of the question here. None was intended. I have, however, checked for correctness on the dates, the places and the people, and their ideas quoted here. For this, I have depended heavily on the following texts: (1) S. Sambursky, *The Physical World of Late Antiquity* (Princeton University Press, New Jersey, 1961); (2) S. Sambursky, *The Physical World of the Greeks* (Princeton University Press, New Jersey, 1956); and (3) John D. Barrow, *The World Within the World* (Oxford University Press, Oxford, 1988). And, of course, the World Wide Web.

Dr Narendra Kumar is an electrical engineer-turned-theoretical physicist known for his researches in condensed matter and statistical physics, specialising in disordered systems, superconductivity and magnetism. His other interests include chaos theory, complex systems, cosmology, and physics in everyday life. He has authored 160 research papers and several books. He has been professor of physics at the Indian Institute of Science and is presently the Director of the Raman Research Institute, Bangalore.

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