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MIND, MORALS AND THE ORIGIN OF OUR IDEAS

Lecture 4

SCIENTIFIC IDEAS, ANCIENT AND MODERN: THE VACUUM

by

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SCIENTIFIC IDEAS ANCIENT AND MODERN: THE VACUUM - PART I

Professor Richard Sorabji

What is important about the vacuum? The importance was different in ancient and modern times. We can distinguish 6 questions that the ancient Greeks thought they needed to answer.

1 Is vacuum needed in order to allow for movement?
2 Must there be vacuum beyond the furthest stars?
3 How can we explain phenomena like suction?
4 How is vacuum distinguished from body?
5 Are matter and vacuum just space respectively with or without properties?
6 Is space dynamic or inert?

The Pre-Socratic philosophers of the 5th century BC already debated whether there was such a thing as vacuum, blowing up wineskins and debating whether they contained air or vacuum. Siding against vacuum, the Presocratic philosopher, Melissus, argued that vacuum was nothing, and a non-entity has no existence. On the other side, a few years later, the founder of atomic theory, Democritus claimed that all that existed was atoms randomly distributed through an infinite vacuum.

One philosopher who believed that vacuum was a logical impossibility was Aristotle in the 4th century BC, and his reason was a new one. Vacuum, he said, is thought of as empty space. But there is no such thing as space, as ordinarily conceived, since it would be redundant. We already have three-dimensional bodies, and their volumes are also three-dimensional entities. If we postulate three-dimensional space as well, we will have too many three-dimensional expanses coinciding in the same place. Aristotle here thinks of empty space as something which might, if it existed, interpenetrate with a body, although it would then no longer be called vacuum.

Things are made clearer, if we have a third word besides 'vacuum' and 'body', a word like 'space', to stand for what can either be empty or penetrated. Aristotle has three words, 'vacuum', 'body' and 'extension' (*diaste^ma*). The atomist philosopher Epicurus, who founded his school in Athens in 308 BC, shortly after Aristotle's death, also had three words, 'vacuum', 'body' and 'room' (*kho^ra*), and the Stoics soon afterwards also distinguished three such concepts, although they didn't give a name to space. Once the threefold distinction is made, it should be easy to avoid confusion. The space which was previously vacuum can be penetrated, and in that sense vacuum can be penetrated, although it will then no longer be called 'vacuum', and so in a merely linguistic sense might be called impenetrable. In the Middle Ages, however, vacuum was sometimes treated as being impenetrable in a stronger sense, as if it were a fluid, which would retreat elsewhere, if you tried to penetrate it. It has even been suggested that Epicurus in antiquity took this confused view about vacuum, that it was an impenetrable fluid flowing around bodies. But I do not take that interpretation myself, and certainly Aristotle's idea of vacuum was not like that.

Because Aristotle regarded vacuum as logically impossible, he was free to define body as what is three-dimensional without having to fear the objection that there is *also* three-dimensional vacuum. Those who believed in vacuum had to find another definition and sometimes defined body instead as what has *both* three-dimensionality *and* resistance (*antitupon*). Another answer was that the three dimensions of space are immobile, whereas bodies move. This would indeed distinguish <u>space</u> from bodies smaller than the universe. But it is not clear, however, that we could not conceive of bubbles of vacuum as moving. Yet another definition described body as what can act or be acted on. This account not only regarded vacuum itself as inert, but also denied that there were any *immaterial* forces.

What did Aristotle postulate instead of space? He said that all we need is the concept of a thing's *place*, and its place is its physical *surroundings*, or more exactly the *inner surface* of its physical surroundings. This is one of the topics on which Aristotle failed to persuade his fellow-Greeks, although his view was very influential on the later Middle Ages. In effect, by making place a surface, he made it two-dimensional, instead of three-dimensional. Moreover, he tried to make the idea of place do two incompatible jobs. First, he wanted it to be the precise space into which something fitted exactly. For this purpose, he said that your exact place is the inner surface of the surroundings in immediate *contact* with you. But he also wanted place to give your position. For this purpose he needed to make it *immobile*, or more precisely immobile in relation to the heavens. These two requirements of immediate contact and immobility led to problems. A moored boat needs to have the same water surface in contact with it, a drifting boat needs to have different water surfaces. Can Aristotle allow for this?

Let us now consider the question whether there has to be vacuum beyond the furthest stars. There was a striking argument for and Aristotle had two striking arguments against. The argument *for* space beyond the furthest stars was put by a friend of Aristotle's teacher, Plato, namely the Pythagorean philosopher Archytas. If there is an outermost edge of the universe, could I stick my hand beyond it, or not? If I can, there is empty space there. If I cannot, there must be a body there stopping me. In either case it is not an outermost edge of space.

Aristotle's reply is put much later by his follower Alexander. You cannot stick your hand out, but not because of a body. Place is defined by Aristotle in terms of physical surroundings. The furthest stars have no physical surroundings. Therefore there is no place beyond them, and the reason why you cannot stick your hand out is that you would need a *place* to stick it into. Instead of a place, there isn't anything. The absence of any place for the stars is here turned into an advantage. Sometimes it had proved a disadvantage, as when it was asked in what sense the wheeling stars can be said to change their place, if they do not have any place at all. Presumably, they change their relation not to what surrounds them, but to things on earth.

Aristotle's second argument against vacuum beyond the furthest stars depends on a positive account of empty space as what *can* receive matter. Then, like almost all ancient and medieval thinkers, with a few exceptions, he supposed that the stars wheel round the earth, and he further supposed that they *cannot* fly off at a tangent, and so *cannot* be received further out. If matter *cannot* be received further out, there cannot be further out empty space, given that that is defined as what *can* receive matter. The argument is not stupid, because it is very difficult to get clear about correlative possibilities. Nonetheless, it received a decisive answer from a later Stoic, Posidonius. You might as well say, he retorted, that there cannot be an empty water vessel in an impenetrable desert. For what is here meant by an impenetrable desert? He means a desert which water *cannot* reach. And what does he mean by an empty water vessel? He means a vessel which *can* be filled with water. If that agument is absurd, so equally is Aristotle's.

Let us now consider the further question whether vacuum is needed, in order to make room for movement. Even before Aristotle, it had been shown by the Pre-Socratic philosopher Empedocles that vacuum is not needed, because of what might be called the teacup theory of motion. When you stir your tea, the tea and the spoon rotate in a circle, and the rotation is sufficient, without vacuum, to make room for all the moving components to move.

But Aristotle went further. Vacuum, he alleged, would actually make motion *impossible*. One type of motion, forced motion, depends on air as propellant. With another type of motion, natural motion, a moving body in a vacuum would have no reason to stop, and a stationary body would have no reason to move in one direction rather than another. Or would it explode in all directions in the manner of Stephen Leacock's *bon mot*? - 'Lord Roland... flung himself upon his horse and rode madly off in all directions'. Finally, with resistance reduced to zero, speed would, absurdly, rise to infinity.

Galileo congratulates one of Aristotle's ancient Greek opponents, Philoponus, for giving an adequate reply to this, 850 years after Aristotle's death. Philoponus had two replies. The first is that all motion takes time. What lack of resistance removes is not, as Aristotle supposes, the need for time, but merely the need for *extra* time spent in overcoming resistance. Secondly, Philoponus complained, Aristotle himself believes that the stars meet no resistance in wheeling round us, yet he does not conclude that their speed is infinite.

The ancient Greeks were very interested in suction, and two of them left us treatises explaining how to make wonderful automatic toys operating partly by steam and partly by vacuum. They often spoke of the force of the vacuum. But my colleague, Sylvia Berryman has recently shown that the force of the vacuum was cited not as an explanation, but as a thing needing to be explained. And there was no agreement on how to explain it.

The modern interest in vacuum, I think Michael Redhead will be telling us, has more to do with its possible incompatibility with the developing concept of matter. The ancient Greeks also discussed the relation between matter and space, whether empty or full space. Aristotle took his teacher, Plato, already to have had the idea, in his work the *Timaeus*, that we could think of matter as a three-dimensional space filled with properties. This adumbrates the modern idea that, at a certain microscopic level, it is better to think of matter as a *field* filled with properties. Plato thinks that the properties have been so organised that they come in geometrical packets, and it has been pointed out that, given the geometry of the packets, there would inevitably be interstices without properties between the geometrical packets. Plato does not draw attention to this, but the interstices would in effect be vacua. Aristotle rejected Plato's idea of a field, so that Plato's defenders urged that it had only been meant metaphorically. But Aristotle's Greek opponent, Philoponus, complained that something like this is what Aristotle *ought* to have meant by matter: a three-dimensional field endowed with properties. The field itself is called *prime* matter, but it is never found without the properties.

The idea of space had been complicated by some of Philoponus' near-contemporaries, who held that space was *dynamic*. Space holds things apart and prevents their colliding. Space also holds things together and prevents them disintegrating. One Neoplatonist contemporary of Philoponus speaks of the particular place you occupy as if it were a flexible mould fitting tightly round you and moving with your every movement. This may seem very surprising. But in modern Physics too space is given dynamic properties. Gravity is equated with the curvature of space in ways that Michael Redhead could explain better than I.

Aristotle's friend and immediate successor Theophrastus, as I interpret him, had denied any dynamic power to place. We do not appeal to the power of a place in order to explain why my head returns atop my shoulders, if it has been jerked sideways. It is resuming its natural relation to the *shoulders*, not to some two-dimensional place. Similarly, if stones are artificially raised aloft, on release they return to earth, to resume their natural relationship with other *bodies*, not with a two-dimensional place. Some interpreters have gone further and think that Theophrastus is making place into no more than a set of relations among bodies.

What Michael Redhead is going to tell us is that in modern Physics, matter is sometimes thought of as a field which has dynamic properties and is always active. It is because these activities can never be fully eradicated from the field that a complete vacuum cannot be obtained. The closest to this idea among the Greeks is once again in Philoponus, who has emerged as the hero of the story, to Aristotle's anti-hero. He was not one of those who regarded space as dynamic. But what he did say, like many other Platonists, is that so far as its own definition is concerned, there is nothing to stop space from being vacuous. Thus far he disagrees with Aristotle. But he agrees that it is impossible to get vacuous space in fact.

READING
Richard Sorabji, *Matter, Space and Motion*
Edward Grant, *Much Ado About Nothing*

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The Vacuum in Antiquity and in Modern Physics Part 2

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With the scientific revolution in the 17th century AD, the arguments continued. Descartes, for example, believed that extension was a necessary concomitant of matter (*res extensa)*, so if you tried to remove all the matter from inside a flask, you could not possibly succeed, because you would end up with the flask containing an empty volume, which Descartes regarded as a *reductio ad absurdum.* On the other hand Pierre Gassendi revived the views of the ancient atomists, and people like Robert Boyle and most famously Isaac Newton entertained the corpuscular hypothesis concerning the ultimate nature of matter. For Newton, in particular, the void in the guise of absolute space was given a theological interpretation as the sensorium of God. But many people objected to Newton's account of gravitation, and other influences such as electric and magnetic effects, as acting at a distance across a vacuum. In the famous queries appended to his Opticks, Newton speculated about a subtle medium, the aether, as ultimately responsible for transmitting these influences. But the aether itself might be corpuscular (which would just reset the problem of how action could be transmitted) so, the alternative view was of 'effluvial' theories modelled on Newton's own conception of a corpuscular theory of light.

It was the rise of the wave theory of light at the beginning of the 19th century that led back to the view that truly empty space did not exist. If you could empty a flask of aether it would become opaque to light and no such effect had ever been observed, even with the best available vacuum pumps! Somehow the aether was so subtle it could just flow back unimpeded through the walls of the flask.

But then came the famous negative result of the Michelson-Morley experiment (1887) designed to measure the velocity of the earth through the aether, and with Einstein's special relativity theory (1905) the rejection of the whole concept of a material aether. So were we back to the void of antiquity? There were two reasons why this was not so.

(1) In Einstein's general relativity theory (1915) space (or more accurately spacetime) became a dynamical object in its own right, acting (gravitationally) on matter and being reacted on by matter. So the void was causally efficacious, a totally different view from the unchanging, featureless backdrop against which events unfold, contemplated with Newtonian absolute space.

(2) But the new quantum theory, introduced by Max Planck in 1900 was to lead to an even more dramatic revision of the physicist's conception of the vacuum. To understand this there are two basic ideas that we need to get across:

<u>Wave-particle duality</u>
Material particles like electrons are to be thought of as possessing a wave-like aspect as well as a particle-like aspect.

Perhaps the best way of thinking of this is to think of an electron as a 'discrete' excitation of a continuous matter field spread throughout space. The idea of a <u>discrete</u> excitation is where the quantum mechanics comes in, the excitations are'quantized' as one says, so you can't have a half electron or a quarter electron, but only a whole electron as a possible excitation of the field. It is the same with all the other particles like protons and neutrons (now thought to be made up of still more fundamental particles, the quarks) and also the fields of force between the material particles, like the electromagnetic field, which, reciprocally, have also a particle aspect, so the interactions can be given effectively the old-fashioned effluvial interpretation, i.e. as mediated by streams of particles (in the case of electromagnetism these are called photons), but remember these 'particles' have also a wave aspect, allowing for interference and diffraction effects, so there is also a continuum(i.e. plenum) way of talking about the interactions!

If you find all this confusing, don't worry, famous physicists have wrestled with these novel ideas for the past 70 years or so, and although the empirical predictions are wonderfully vindicated, there is still a deal of argument about what the equations mean!

The uncertainty principle

Consider a pendulum in a grandfather clock. If you set the bob in motion it acquires kinetic energy, but as it swings up to the endpoint of its arc the kinetic energy has all been converted into potential energy, and then as it swings down the potential energy gets converted again into energy of motion, i.e. kinetic energy, but in the absence of friction the total energy remains constant, the famous law of the conservation of energy.

Suppose you now try to bring the pendulum to rest, with the bob hanging vertically, so classically it would have zero energy.

According to quantum theory this is not possible to do. If you try to reduce the potential energy by moving the bob to the vertical position, you inevitably introduce 'fluctuations' in the speed of the bob so the kinetic energy goes up. On the other hand, if you try to bring the bob to rest so that the kinetic energy is reduced, 'fluctuations' will occur in the position of the bob, so increasing its potential energy. This is an example of the celebrated Heisenberg uncertainty principle, which says roughly that doing one sort of thing to a physical system prevents you at the same time doing other sorts of thing.

In the case of the pendulum there is effectively a trade-off between reducing the two sorts of energy, so that the minimum total energy of the bob is not zero, as we would expect classically, but is given by the famous formula $1/2\ h\ f$, where f is the frequency of the pendulum, the number of complete oscillations it makes in one second, and h is known as Planck's constant. Now h is very small indeed, e.g. with a pendulum making one oscillation per second, so $f = 1$, the minimum, often called the zero-point energy, comes out at approximately 10^{-34}Joules. For comparison the typical energy of the pendulum in a grandfather clock is about 1/10 Joule, so it is not surprising that for macroscopic objects like a pendulum in a grandfather clock, the zero-point energy can safely be ignored!

But when we are dealing with atomic particles like electrons, the zero-point fluctuations become very important. From the field point of view we can say that the oscillations of the field can never be brought entirely to rest. The vacuum in quantum theory is defined as the state of lowest energy for the field. Classically this would be the state where the field was not oscillating at all. But quantum-mechanically there is no such state. We are always going to be left with the zero-point energy.

Let us look at the situation from the particle point of view. The vacuum fluctuations in the field and the associated zero-point energy can now be described in terms of the creation and annihilation of so-called 'virtual' particles. These are literally created out of nothing, well it would be better to say out of the vacuum of the quantum field. But according to Einstein a particle of mass m carries energy mc^2, where c is the velocity of light. So where has the energy come from to create the virtual particle? The answer lies again in another application of the uncertainty principle. In the quantum theory energy need not be conserved in creating a particle of mass m, so long as it is 'paid back' over a time not longer than h/mc^2. To conform to this principle virtual electrons, for example, have to annihilate, i.e. 'disappear' (back into the vacuum) in a time which comes out numerically at about 10^{-21} seconds. But if the electon is moving very fast, near to the speed of light, then it can cover a distance of about 10^{-11}cm during its lifetime, and this is detectable since it lies between the scale of atomic dimensions (10^{-8} cm) and nuclear dimensions (10^{-12} cm). So virtual particles can produce all kinds of important effects in atomic and nuclear physics. Theoretical predictions of these effects are in amazingly close agreement with experimental data. Indeed the predictions have been verified up to ten significant figures in the most favourable case, which stands as one of the most outstanding triumphs of the theory of quantum physics.

If we did the same calculations for virtual billiard balls, the lifetimes come out at around 10^{-48} seconds, far beyond the limit of any possible detection, so the possibility of virtual billiards can definitely be ignored in everyday life!

So, back to the problem of trying to empty a flask. We can, in principle take out all the 'real 'particles, but we are always going to be left with the seething activity of the virtual particles which we cannot get rid of, unless, *per impossibile*, we pumped out the fields themselves. But, remembering that the gravitational field, and possibly other fields as well, are part of the geometry of space, this would mean pumping space out of space, so to speak, and that sounds like a conundrum for the ancients, which is where we came in ...

READING Henning Genz, Nothingness: The Science of Empty Space