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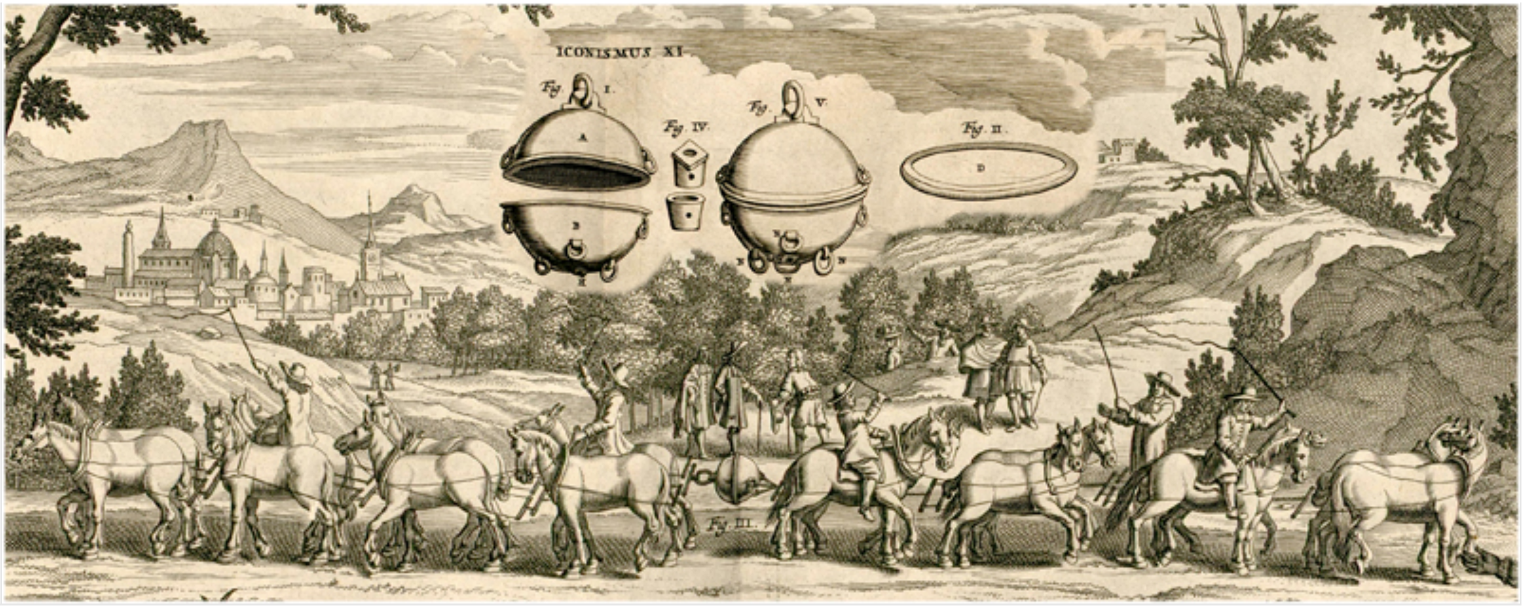
The Eternal Renewal of the Vacuum

by Tasneem Zehra Husain

There are some questions we just can't shake; the nature of space and time, or the identity of the building blocks of the universe; they pester us until we answer them, and then, as if on cue, the Universe proceeds to demonstrate the inadequacy of our proposed solutions. One such question, the asking and answering of which has spurred on the progress of science for millennia, is that of the vacuum. Almost universally, the human race seems to find the concept of complete emptiness fascinating. We have fantasized about this gaping void and spoken of it often, in science, philosophy and folklore, but while in principle it is possible to postulate a complete void - the physical equivalent of the mathematical concept of zero - in practice, this perfect nothingness eludes us.

The argument can be traced back at least to (circa) 500 B.C, when Parmenides declared that a vacuum - i.e. a region of space completely devoid of matter - simply could not exist. The Greek natural philosophers debated this possibility for decades, some declaring the void to be indispensable, others finding it repugnant, until a hundred or so years later, Aristotle issued the now famous dictum '*horror vacui',* or, 'Nature abhors a vacuum'.

Two thousand years later, when experimental science had advanced sufficiently for abstract ideas to be put to the test, the vacuum was duly investigated. Scientists like Galileo, Pascal, von Guericke and Boyle devised mechanisms to pump the air out of glass vessels, creating vacua in order that their properties could be studied, and some rather striking demonstrations ensued. There were, for instance, the Magdeburg hemispheres designed by von Guericke in 1656.



These large copper hemispheres were joined together their rims sealed with grease, and the air within pumped out so that a vacuum was created within. The hemispheres could then no longer be pulled apart, even by thirty horses, until a valve was opened and air let back in. The incredible strength with which the metal globe clung together was attributable to atmospheric pressure; in other words, the ‘weight' of air - a force we feel all the time and yet are insensible of, because in most situations, the push and pull balances each other out. A vessel devoid of air, however, exerts no outward force – it only feels the air outside bearing down on it from all sides, holding it in an invisible vice.

Despite the fact that this – and similar - demonstrations were impressive and compelling, people soon realized that they did not necessarily prove the existence of a true vacuum. Even when most of the air inside a vessel could be evacuated, everyone was aware that the process was not perfect. No mechanism is efficient enough to ensure that every last bit of matter is removed, and while even an infinitesimal particle remains in a space, it cannot be termed a vacuum: the difference between nothing, and something might seem inconsequential in practice but the conceptual gulf between the two cannot be so easily bridged. Emptiness is a binary condition – space either is, or is not, a void.

As fallible mortals, who build necessarily imperfect realizations of ideal machines, we are used to our devices not performing precisely as they should. And for the most part, once we account for experimental error, if we find ourselves within the acceptable range of the answer dictated by mathematics, we are satisfied. The problem with a vacuum, of course, is that it is not enough to merely get close. We need to know if it is only our physical limitations that stand in the way, or is there perhaps a theoretical bound on ever attaining such a state.

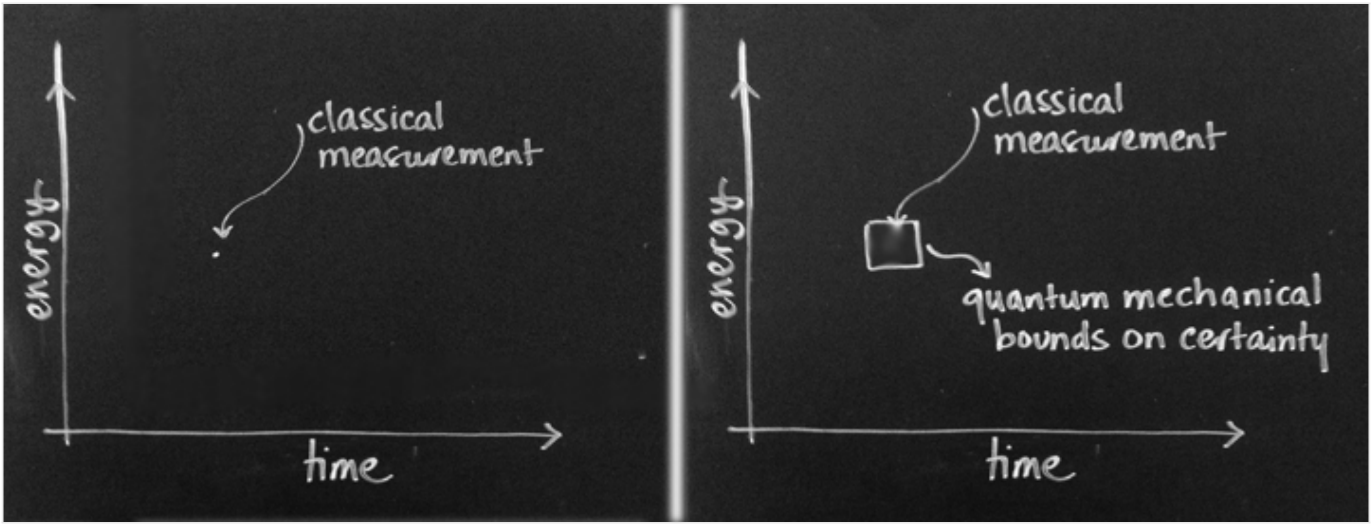
And so it was that despite persuasive and rather flamboyant demonstrations of (almost) vacua, we found ourselves once again on the horns of the same dilemma: is a true void possible in Nature? A counterpoint was provided by the aether: the massless, transparent, incompressible fluid which was postulated to fill space, providing a material which could mediate forces acting across distances - a phenomenon that was otherwise inexplicable. From the 17^{th} century onwards, prevailing wisdom declared that light waves propagated through the aether (much as water waves travel through water and sound waves through air), which permeated all of space, leaving no room for a vacuum.

Because the aether was by definition (or construction?) directly undetectable, it was not until the end of the 19^{th} Century that the American experimenters Michelson and Morley were able to prove that this purported substance did not, in fact, exist. The ensuing dilemma about the propagation - and indeed, the nature - of light, was resolved brilliantly by Einstein, who erected the shimmering edifice of his theory of relativity upon these grounds. As an added bonus, the equations of general relativity seemed to state that a void - defined now as space devoid of both matter and energy (since Einstein had proved the two were equivalent) - could in fact exist, and it began to appear that the troubling issue of the vacuum was at last laid to rest.

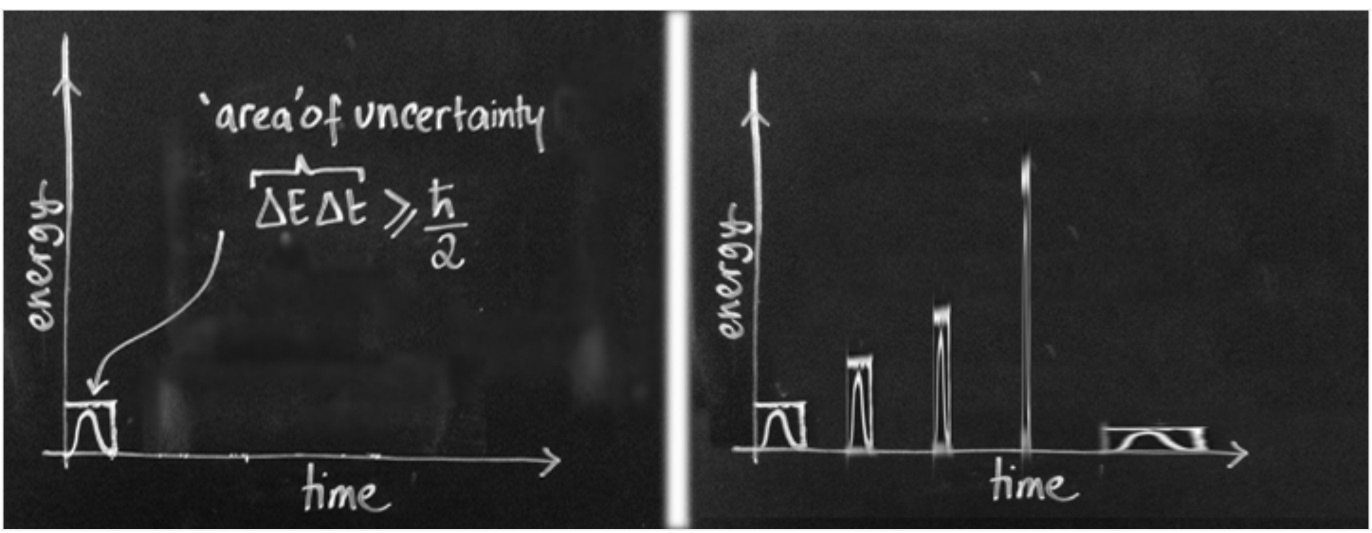
But, just when the vessel of space been finally emptied of the ether, it was filled up again with uncertainty. The new counter-intuitive discipline of quantum mechanics wrecked havoc with the idea of continuity. It questioned an age-old assumption that had been implicit in all our dealings with the universe - that no matter how close we were to something (be it a physical object, or a measurement), unless we were right upon it, we could keep edging ever closer. Quantum mechanics scoffed at this classical continuum and exposed the hard edges of Nature. At miniscule scales, both matter and its attributes have definite boundaries. There is a smallest possible unit - the quantum - beyond which you cannot divide any further.

Had this been true for matter alone, the fate of the vacuum might not have been so perilous. The fact that matter (and energy) can only exist in discrete aggregates does not in itself prevent us from emptying space. The real trouble lies with the uncertainty principle - the bizarre declaration that physical quantities cannot be measured with the infinite precision we had previously thought possible, but only up to a certain specified degree of haziness. Our perception of nature suddenly became pixelated.

It turned out that some physical quantities operate in tandem - position and momentum are one such pair, energy and time another - and the amount of uncertainty in the measurements of the two is correlated. In our days of classical innocence, we had assumed we could pinpoint, with arbitrary accuracy the position and momentum of an object in motion. Quantum mechanics said that the best we can do is to put down one of our little ‘squares' of uncertainty and say that the position - and momentum - of the object lie somewhere within its bounds.



There is a twist to this tale. The squares have a definite, fixed area, but they are remarkably pliable and can be deformed into rectangles of practically any size; with the caveat, of course, that the more one edge is stretched, the more the other edge shrinks. Thus, one can 'trade' uncertainties: if I choose to make my measurement of the position of an object extremely precise, the information I can gather about its momentum becomes rather ambiguous, and the same holds for energy and time. Since energy cannot be measured with complete precision, we can never say for sure that the energy in a space vanishes completely - and so, the uncertainty principle blurs even the vacuum.



Where the classical vacuum was a place of complete silence and stillness, the quantum vacuum is a beehive of activity. It is defined to be the state of lowest possible energy, where everything that could possibly be removed has been sucked out, and yet something essential and inextricable - a degree of haziness - remains. Our knowledge is limited to the boundaries of our pixelated measurements. Within the elastic confines of these little boxes, the standard rules of physics cease to apply. Even the sacred law of energy conservation need no longer be respected! Energy can appear practically out of the blue, as long as it disappears again, fast enough to be contained by the rectangle of uncertainty. It follows, of course, that the larger the amount of energy 'borrowed' from the universe, the more quickly it must be returned, because these delinquencies can never make it out into the realm of physical measurement; within those protected borders, however, all kinds of lapses and misdemeanors are tolerated.

From Einstein, we have learnt that mass and energy are interchangeable, so it is only natural to wonder if these flashes of energy are manifested as particles - and indeed, they are; pairs of particles, in fact, which are created together, and have the ability to annihilate each other, vanishing into a burst of energy. Like exceptionally short-lived soap bubbles, these so-called virtual particles rise and burst constantly. Lighter particles are allowed to live longer than the heavier ones, but they live one and all on borrowed time; their very existence conditional on them adhering to the constraints of their situation, and decaying before their allotted period is over.

But since no one can peer inside the walls of uncertainty, and these ghost-like particles must of necessity refrain from leaking out, how do we know that they do in fact exist? Quantum field theory, the mathematical framework that incorporates the dictates of both quantum mechanics and special relativity, provides a spectacularly successful structure for understanding nature at the miniscule level. It provides us with a mechanism to model the behavior of particles as they interact via electromagnetic or nuclear forces. The mathematical calculations made using quantum field theory depend crucially on the existence of virtual particles, and are found to be in unprecedented agreement with experimental findings. In fact, the precision of our answers increases, as we include contributions from progressively more elaborate virtual particle gymnastics. So, while these flamboyant indulgences are never directly seen, their presence is – at least indirectly – felt.

Over the centuries, the eternal renewal of the vacuum has plagued us repeatedly, and it has often seemed that we will never reach a conclusion but are merely doomed to loop around for ever. In the mid seventeenth century, Otto von Guerike declared "Nothing contains all things. It is more precious than gold, without beginning and end... Nothing always inspires. Where Nothing is, there ceases the jurisdiction of kings."

More than three hundred years later, Heinz Pagels wrote "The vacuum is all of physics. Everything that ever existed or can exist is potentially there in the nothingness of space." Upon a superficial comparison it may seem as if we have merely circled back around, but reading between the lines, it is clear how much deeper we have spiraled into the truth.

From where we stand now, it appears that Aristotle was right - Nature does abhor a vacuum, but in a wholly different way to what he had envisioned. The quantum vacuum is a place seething with possibility, a place where all known rules break down for brief instants of time, and virtual particles - rather than dwelling on their imminent and inevitable fate - spend their mayfly existences living out all sorts of wildly implausible, completely fantastical scenarios instead. And, in a strange way, these ostentatious and preposterous happenings seething beneath the surface are crucial to making our familiar every-day, law-abiding universe function as it should.

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