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INFINITY IN THE PALM OF YOUR HAND

You could fit the entire human race in the volume of a sugar cube

To see the world in a grain of sand
And a Heaven in a wild flower
Hold Infinity in the palm of your hand
And Eternity in an hour

William Blake

You could fit the entire human race in the volume of a sugar cube. The reason for this is that matter is mind-bogglingly empty. Probably, you have a picture in your mind from school of an atom, the fundamental Lego brick of all matter. Most likely, it is an image of a miniature Solar System, with a "nucleus" sitting at the centre like a sun around which electrons orbit like planets. However, this image fails to convey just how much empty space there is inside an atom. The playwright Tom Stoppard said it best: "Now make a fist, and, if your fist is as big as the nucleus of an atom, then the atom is as big as St Paul's, and if it happens to be a hydrogen atom then it has a single electron flitting about like a moth in an empty cathedral, now by the dome, now by the altar."

As a percentage, the amount of empty space in an atom is about 99.9999999999999 per cent. You are a ghost. I am a ghost. We are all ghosts. And, if you could squeeze all the empty space out of all the 7 billion people in the world, the human race would indeed fit in the volume of a sugar cube (Mind you, it would be a very heavy sugar cube!).

This is not mere theoretical fantasy. There are objects out in the Universe whose atoms have had all the empty space squeezed out of them. They are called "neutron stars" and they are the endpoint of the evolution of very massive stars. When such a star blows its outer layers into space as a "supernova", its core, paradoxically, implodes (In fact, it is the implosion that is believed to drive the explosion). The resulting neutron star is about the size of Mount Everest but contains about the mass of the Sun. And, if you could travel to a neutron star, and dig out a chunk the size of a sugar cube, it would indeed weigh as much as the human race.

But why are atoms so empty? The answer is provided by "quantum theory". Quantum theory is our very best description of the microscopic world of atoms and their constituents. It is fantastically successful. It has given us lasers and computers and nuclear reactors. It explains why the Sun shines and why the ground beneath our feet is solid. In fact, it is the most successful physical theory ever devised, predicting what we observe in experiments to an obscene number of decimal places. But, in addition to being a fantastic recipe for building things and for predicting things, quantum theory provides a unique window on an Alice in Wonderland World that exists beneath the skin of reality. It is a place where a single atom can be in two places at once – the equivalent of you being in London and New York at the same time; where things happen for absolutely no reason at all; and where two atoms can influence each other instantaneously even if on opposite sides of the Universe.

All this quantum insanity stems from a simple observational fact: the fundamental building blocks of matter have a weird dual nature. They can behave as localised "particles" like tiny billiard balls and they can behave as spread-out "waves" like ripples on a pond [1]. Don't even try to imagine how this can be. It is impossible. The truth is that the electrons and photons and so on that make up the world are neither particles nor waves but something for which we have nothing to compare them with in the everyday world and for which we have no word in our vocabulary. Like an object we can never see directly but can know only from the shadow that it casts on two adjacent walls, we can never see directly the denizens of the quantum world, only the shadows they cast in our experiments: one of a tiny bullet, the other of a dancing ripple.

The key thing is that the smaller the particle, the bigger its quantum wave [2]. And the smallest particle of familiar matter is the electron. It therefore has the biggest quantum wave. And it is because the electron wave needs tons of elbow room that atoms have to be so big relative to their nuclei – that they contain so much empty space [3].

In fact, it is the wave nature of the electron which is why actually atoms exist. As the American physicist, Richard Feynman, said: "Atoms are completely impossible from the classical point of view." What Feynman meant is that, according to the theory of electromagnetism, an electron whirling around a nucleus in an atom should constantly broadcast "electromagnetic waves" like a tiny radio transmitter. This should cause it to lose energy and spiral into the nucleus in less than a hundred-millionth of second. Atoms should collapse in on themselves. They should not exist.

This rather contradicts reality where atoms have existed for at least the age of the Universe – 13.82 billion years. This is about 1 followed by 40 zeroes longer than predicted by the theory of electromagnetism! [4]

Quantum theory comes to the rescue because electron waves are spread out and always take up a minimum amount of space. They cannot be squeezed down into a nucleus. Thus, atoms – thank goodness, since we are all made of atoms – are able to exist.

If there is one thing that perfectly encapsulates the madness of the quantum world it is this… The British physicist "J. J." Thomson won the Nobel prize for showing that the electron is a particle. His son, George Thomson, won the Nobel Prize for showing that it isn't. I imagine Thomson family get-togethers =as raucous affairs, with "J. J" shouting - "It's a particle!" – and his son shouting back - "No, it isn't!"

[1] Actually, a quantum wave associated with a particle is a weird type of wave. It is an abstract, mathematical entity which is imagined to fill all of space. Where the wave is big – strictly speaking, has a large "amplitude" – there is a high chance, or "probability", of finding the particle, and where the wave is small, a low probability.

[2] The reason for this is that a low-energy/low-mass particle like the electron naturally has a low-energy quantum wave associated with it. Imagine a low-energy wave the surface of a pond. It is sluggish and its characteristic size – the distance between successive wave peaks – is large.

[3] Actually, in an unexpected twist, quantum theory tells us that empty space is not completely empty. It is a roiling sea of the "zero-point fluctuations of the quantum fields". But that's another story!

[4] This was the biggest discrepancy between a prediction and an observation in the history of science until 1998. That year marked the discovery of the "dark energy", which fills all of space and whose repulsive gravity is speeding up the expansion of the Universe. When quantum theory is used to predict the energy of the vacuum – the dark energy – it yields a number which is 1 followed by 120 zeroes bigger than observed. This is a strong indication that our current theory of physics is inadequate!