On our inability to know what's really going on.

It is a truth universally acknowledged, that a single man in possession of precise knowledge of a particle's location, must be in completely ignorance of its velocity.

But what is a particle? If you were to take any object in the universe and zoom in to approximately 0.000001 times smaller than the breadth of a human hair, you would begin to see atoms. Atoms consist of tiny blobs called protons and neutrons, all bunched up together in a 'nucleus', with even tinier blobs called electrons orbiting them from a distance. Still, most of what you would see is empty space. If a hydrogen atom was expanded to the size of the earth, the nucleus (just one proton) would be a 200m diameter ball at the earth's core and the electron would be the size of a football.

Electrons are indivisible. Protons and neutrons, meanwhile, are built out of other indivisible objects called quarks. Electrons and quarks are examples of 'particles': simple, fundamental, teeny-weeny ingredients from which everything in the universe is constructed.

But still, you cry, that's not really answering the question! Well, to be perfectly honest we are still trying to work out what the answer to that question is. In fact, we continue to spend millions of pounds energetically and enthusiastically smashing them together in the hopes that we determine what they are and how they behave. What we do know is that they are governed by a very unintuitive and completely unexpected set of laws that have successfully dissuaded many people from studying physics since they were discovered in the 1930s.

In our daily lives, we tend to think of objects as being solid, demonstrably finite in volume, and having all their energy within that volume. Alternatively, we are aware of waves. These take some energy, sound, radio show or other information and transport it through space whilst being able to split into two or pass through walls, all whilst not really appearing to be anywhere in particular at any one time. Importantly – nothing seems to be both an object and a wave.

Where the problem started

Unfortunately for human intuition, two revolutionary experiments performed at the start of the 20th century would completely alter our understanding of what goes on at the atomic level. In 1905, Albert Einstein published a paper suggesting that light carried energy in discrete packets rather than one continuous wave, in order to explain several experimental observations in the latter half of the 19th century. His idea was tested in 1921 by Robert Milikan, who despite being thoroughly against the idea, proved it was correct.

Milikan shone a beam of light at a metal sheet, as shown in Figure 1. If the light has enough energy, it can hit electrons inside the metal sheet hard enough to knock them out of their atomic orbits. The electrons can then move around a circuit attached to the metal sheets, forming a measurable electric current. The number of electrons released can be measured by the size of the current, and the energy of the electrons can be measured by seeing how much voltage is required to stop the current. One would expect that if the power of the beam increased then more power would be transferred to the electrons – giving them a higher energy. What was instead observed was electrons at the same energy, but a larger current. Additionally, if the frequency of the light beam was increased, the current did not increase but the energy of the electrons did.

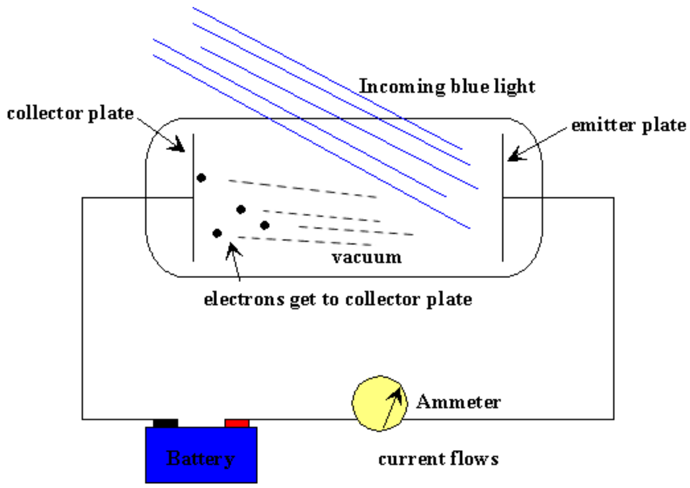

Figure 1: Schematic of photoelectric effect experiment [Image: galileo.phys.virginia.edu].

Einstein's idea to explain these phenomena was that the light beam consisted of many individual blobs of energy called photons – like particles, not waves. If the frequency of light increased then each blob had more energy, so each electron had more energy. If the power of light increased then the number of blobs increased, so more electrons could be whacked out of orbit. You can see why Milikan did not like this, since before the days of Newton everyone had been convinced that light is a continuous wave rather than a particle! As you will have learned at school, light as a wave explains things like diffraction; how glasses and telescopes work; and rainbows. However, the evidence here was quite clear; and convincing enough that it won Einstein the 1921 Nobel prize for physics.

Speaking of diffraction, in 1927 Clinton Davisson and Lester Germer somewhat inadvertently checked whether electrons were also behaving contradictorily. Intuitively, diffraction is something that happens to a wave (emphasis: wave) as it passes around or through narrow slits. A beautiful example of diffraction of water through gaps in a rock is shown in Figure 2. Davisson and Germer instead tried to see what would happen if they fired a beam of electrons at the surface of a nickel crystal. They were interested in the structure of the nickel's surface – but after literally cooking it in order to remove some air that had entered their experimental chamber, they had changed the nickel's surface into a repeating planar crystal structure akin to a series of slits. The electron beam was observed to produce a diffraction pattern!

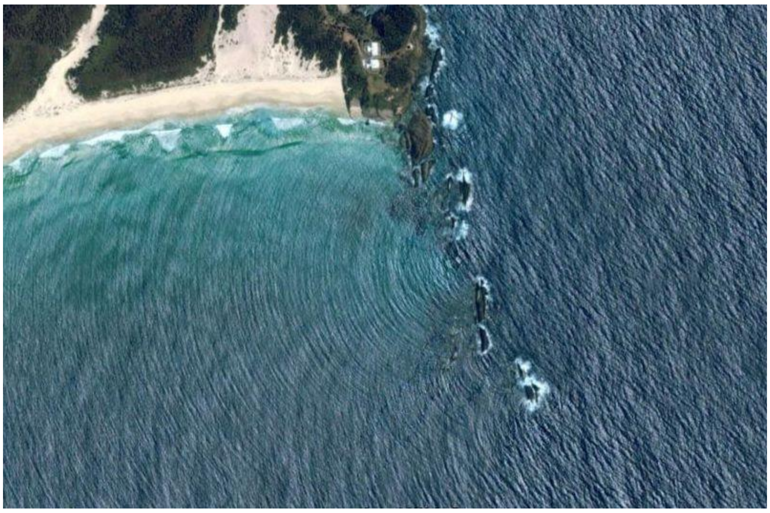

Figure 2: Example diffraction patterns in the ocean off the coast of Australia [Image: https://www.physicsforums.com/threads/beautiful-natural-oceanic-diffraction-patterns.557139]

This result was interpreted as confirming a hypothesis proposed by Louis de Broglie in 1924. His hypothesis was (yes reader, you've guessed it!) that electrons, or all particles generally, can also be considered as waves. After this confirmation, de Broglie won the 1929 Nobel prize. In summary, it turns out that the fundamental ingredients of our universe are both waves and particles.

Reader, I urge you at this point not to think 'right that's it, physics makes NO sense' and continue reading… I assure you, physicists are also confused but we can still use the beautiful (don't scoff) language of maths to describe and understand the situation and accept that it's a bit odd. I suggest you pause to get a cup of tea, as we are about to start using the phrase "quantum mechanics".

Quantum Mechanics

Quantum mechanics is a theory that attempts to explain how, on very zoomed in scales, objects can be both particles and waves. This is only consistent way found, so far, to explain all the bizarre observations made in the 1920s and to recover the expected sensible physics you were taught as school as we zoom out.

The basic idea is that rather than being a particle or a wave at all, our electron or photon is some partially localised wave-packet as illustrated in Figure 3. When left to its own devices it acts more like a wave, but when it interacts with something like a sheet of metal or is 'measured' in any other way at all it suddenly behaves like a particle again.

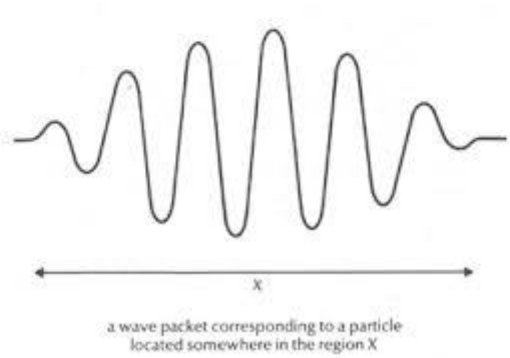

Figure 3: Schematic of a wave-packet [Image: srjcstaff.santarosa.edu]

The 'wave', now called a 'wavefunction', describes the probability distribution of the object, namely where in space it is more likely to be found. For example, the probability distribution of your current location is shown in Figure 4. This is both wavy looking and finite. The author has no idea where you actually are until she asks you, so you are effectively not *really* in any of these locations at all – and when she does, she will find you in only one of these locations. Once she's found you, your probability distribution will be a single spike of height 1.0 in your location. You will have become particle-like!

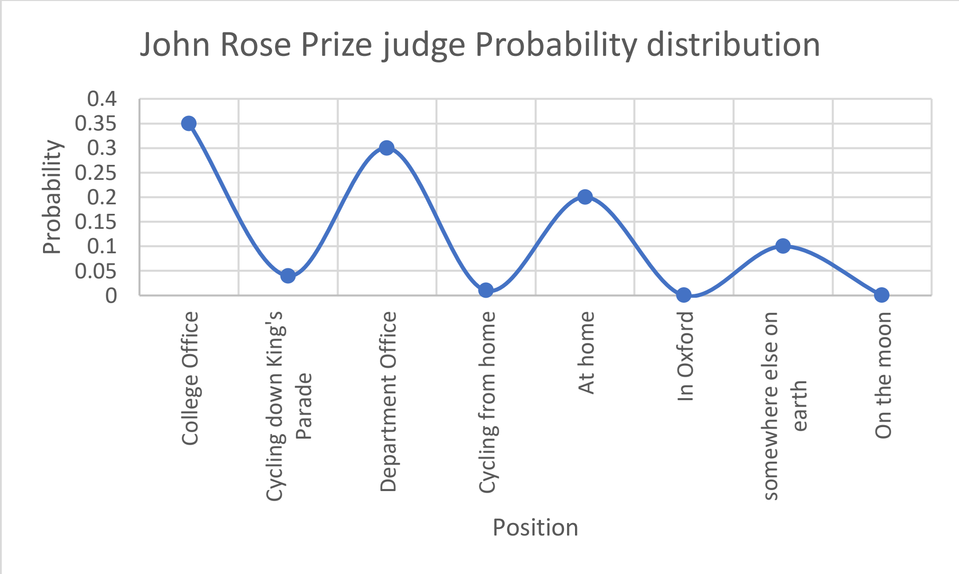

Figure 4: John Rose Prize judge's location probability distribution before being observed.

The most famous example to illustrate this point was created by Erwin Schrödinger, one of the most important figures in the development of quantum mechanics. He had this to say on the subject:

> *"I do not like it, and I am sorry I ever had anything to do with it."*

Schrödinger, a presumed 'dog person', posed a thought experiment whereby an unfortunate cat is trapped within a box. Along with the cat is a radioactive source which has a 50% chance of emitting some radiation that will immediately kill it. The cat can justly be thought of as both alive and dead simultaneously, described by a wavefunction, until the observer lifts the lid and measures the cat's fate.

An important point to clarify is that both these examples consider a sentient being in a wave-like state. One must pretend that neither you, the John Rose Prize judge, nor the unfortunate cat, know what is going on either. Really it is objects like electrons and photons that get stuck in these wave-like states and they are not sentient.

In short: the act of observing something not only changes your knowledge about that thing, but the behaviour of the thing itself. You can never observe what it was doing before you arrived. 'It' also doesn't know what it was doing before you arrived. Nobody can know anything that's going on unless they actively try to observe it. All we know is how likely each possible outcome of the observation is, in the same way that if we flip a coin all we know is that it is 50% likely to return heads or tails.

Before we move on, a quote from another marvellous physicist, Richard Feynman, seems appropriate to summarise both the author and the reader's inevitable position on the matter:

> *"I think I can safely say that nobody understands quantum mechanics."*

The Heisenberg Uncertainty Principle

In trying to measure the position of an electron, we try to take the wave-packet and extract where the electron is. However, we can't do this. Instead we measure some position with an associated uncertainty stemming from the finite extent of the wave-packet. One can consider all the ways in which you can actually observe the position of something. You either poke around with a stick until you feel your object resist, or you shine some light on the object and observe it once the light has reflected into your eye. Either way, you will disturb the object and transfer some momentum to it which makes its position change somewhat. Or you can consider that some small amount of time will pass between your stick/light interacting with the object and you interpreting it, during which the object can again move.

The analogous issue of uncertainty arises if you tried to measure the momentum of your object, for precisely the same reason. What Werner Heisenberg found is that the more precisely you know the position of your object, the less precisely you can know its momentum; and visa versa. In fact, mathematically we can say that the product of these two uncertainties is at least some value experimentally measured to be 0.00000000000000000000000000000000005272859 m^2 kg / s. This is a very small number, which explains why the effect is not something we observe on a macroscopic level.

Reader, before you now go and a fetch a drink that is stronger than tea, let me reassure you we can obtain some sensible results. Firstly, we can return to atoms. You might assume that since they consist of an electrically positively charged nucleus and negatively charged electrons, that the electrons would fall into the nucleus. However, this would mean that the electrons' position is known so precisely that the uncertainty on their momentum grows enormously. The electrons' momentum could then be so high that they whizz off away from the nucleus completely.

Another example is nuclear fusion inside the sun. In order to fuse protons together they need to overcome their enormous electrostatic repulsion. However, through the uncertainty on their position, there is a non-zero probability of them being found close enough together to fuse and release the huge amounts of energy that allow the star to shine.

Conclusion

To conclude, nobody really knows what's going on when we zoom in far enough. Not because we aren't smart enough but because the fundamental physics is entirely probabilistic and based on physical uncertainty. Reader you may now finish your drink and relax in the consolation that at the very least, we have a good understanding of what it is that we don't understand.

Bibliography

Milikan, R. (1914). "A Direct Determination of h". *Physical Review*. **4** (1): 73-75.

Einstein, A. (1905). *"*On a Heuristic Viewpoint Concerning the Production and Transformation of Light". *Annalen der Physik*. **17** (6)*:* 132–148.

De Broglie, L. (1924). "A Tentative Theory of Light Quanta". *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science.* **47**(278): 446-458.

Davisson, C., Germer, L. H. (1927). "The Scattering of Electrons by a Single Crystal of Nickel". *Nature* **119** (2998) 558.

Schrödinger, E. (1935). "The Present Situation in Quantum Mechanics". *Naturwissenschaften*. **23** (48): 807–812.

Heisenberg, W. (1927). "The Actual Content of Quantum Theoretical Kinematics and Mechanics". *Zeitschrift für Physik*. **43** (3-4): 172-198.