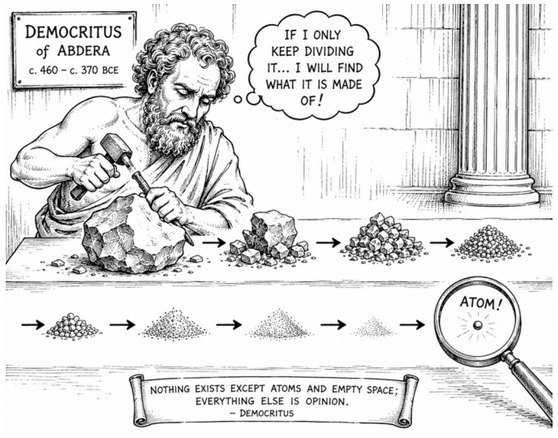



## People have always wondered what things are made of

The ancient Greek thinker Democritus imagined if you cut things up into smaller and smaller pieces there must be a point where you can't cut them up any more, you've reached the smallest possible thing. He called this thing the "atom", which in Greek means "uncuttable".

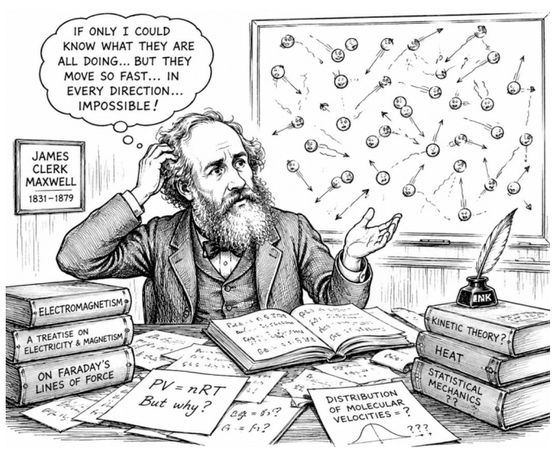
What we now call atoms aren't actually "uncuttable", they are made of smaller particles.

## There are a million trillion atoms in a grain of sand

That's a lot of atoms! Far too many to count and keep track of. But at least in a grain of sand they're sitting reasonably still – what if they're in a gas?

The atoms in a gas are flying around bouncing all over the place and hitting each other like snooker balls. How can we possibly make sense of all that?

There are just too many.




## Try probabilities instead

What you can do is use probabilities to work out what average atoms are likely to be doing. Multiply this by the number of atoms and you get a pretty good description of the behaviour of the gas, even though you don't know what any of the individual real atoms are actually doing.

It's a bit like tossing a coin. It's impossible to predict whether you'll get heads or tails, too many things affect the outcome. But we know on average we'll get heads half the time and tails half the time. So, if we toss a thousand coins we know around 500 will be heads and 500 tails – even though we don't know what any individual coin will do.




Using probabilities to predict the behaviour of particles was an important part of the development of quantum physics. The word "quantum" just means an amount (a quantity).

## So far so good….. but




Then something weird happened. A physicist called Niels Bohr realised these probabilities weren't just useful bits of maths, they were real. Individual particles are actually in lots of different states at the same time, perfectly matching their probabilities. They only have one specific state when you measure them. Einstein didn't believe it, but even though it sounds odd, experiments have shown that this strange behaviour is real.



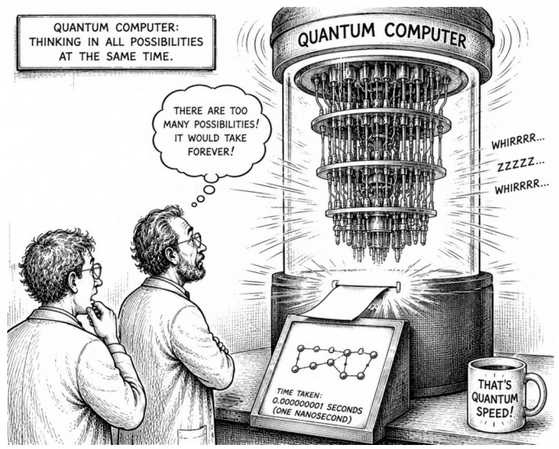

## Let's think about spinning coins again

When a coin is spinning, it looks like it's showing heads and tails at the same time. It only becomes one or the other when it stops. This is a useful analogy for something called "superposition" in quantum physics.

For example, electrons have a quantum property called "spin", which can be measured as either "up" or "down". Before it's measured, an electron can be in a superposition of both these spin states at the same time, but when we measure it, we find just one state - up or down.

## Why does superposition matter to me?

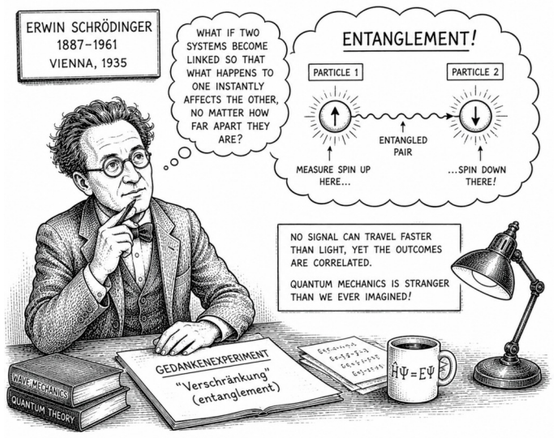
Superposition is really useful. It's one of the things that makes quantum computers so fast, because they can consider lots of different possibilities at the same time.



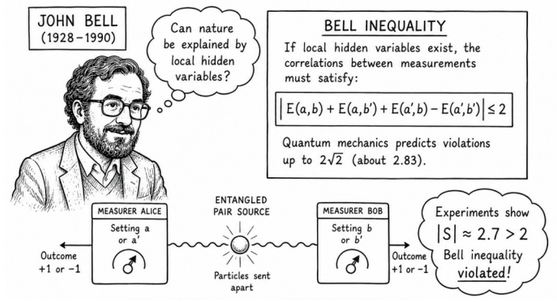

In 2019 Google's quantum processor completed a calculation in 200 seconds that would have taken the world's most powerful conventional supercomputer around 10,000 years.

## And now it gets really weird…

Quantum physics predicts that pairs of particles can be "entangled" so when their behaviour is measured, it matches much more often than should be possible - even if the particles are so far apart there can't be any communication between them.




Einstein thought the particles must have decided in advance what they were going to do, but in the 1960s, a physicist called John Bell devised a test that proved this was impossible.




In Bell's test, there was no communication between the particles, and because they were in a state of superposition, their behaviour wasn't decided until it was measured, but it still matched much more often than conventional physics said was possible.

Entanglement isn't just a clever theory. Quantum encryption uses pairs of entangled photons to allow people to share secret codes. Quantum imaging can make incredibly sharp pictures by using one photon to look at an object while its partner helps build the image. And quantum sensors use entangled atoms to measure things like magnetic fields much more precisely than normal tools.

## Quantum physics is strange but amazing

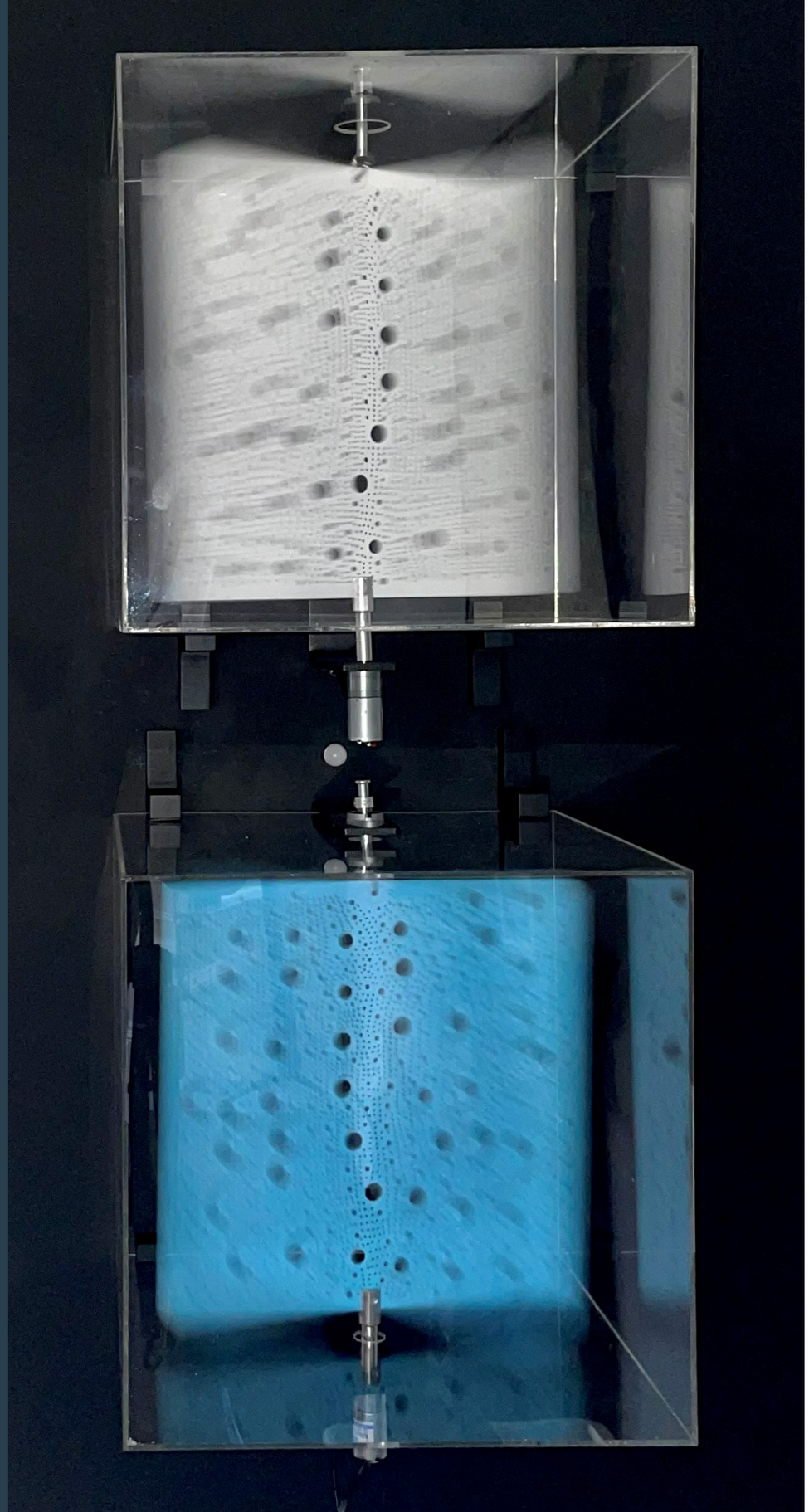
Think quantum physics is too complicated for you?

Think again

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# Superposition



## The Superposition art installation

Artist Gregor Harvie worked with the Quantum Theory Group at the University of Glasgow to develop an art installation about quantum superposition and entanglement.

He cut thousands of holes through panels of aluminium, creating tiny little packets of space, laid out so they combine to form patterns of lines, waves and circles.

The two sides of each panel are mirror images, one side the opposite of the other. But when someone approaches them the panels start to spin and everything changes. The holes tunnel through space and the two faces merge to create a new, 3D symmetrical pattern; a superposition of art that is not one side or the other, but both at once.

In this dynamic spinning state, there is a confusion of forms. Some holes seem to have definite positions, but others seem to be spreading, overlapping, leaping from one place to another, jumping between states, and leaving ghosts of forms where they were before.

When the spinning stops, the faces of the panels separate again and the symmetry is broken. The superposition reverts to simple, stationary holes. Really there is nothing there.

## The entanglement trick

One side of each panel is white and the other side is coloured. When the panels stop spinning they are equally likely to show the white side or the coloured side.

Each panel also has an identical twin above it or below it. When the twins stop spinning, they either show the same side (both white or both coloured) or opposite sides (one white and one coloured). Whether they show the same or different sides is completely random.

If you watch them for long enough you'll notice that on average the twins show the same side half the time and opposite sides half the time, even though their stopping positions are random. If you think about it, that's what you would expect. How could it be any different?

But one of the sets of twins is different.

On average this pair shows the same side three quarters of the time - and that shouldn't be possible. Somehow these twins know what their partner is doing.

If you only look at one of this special pair of twins, its stopping position still seems completely random, it's only the correlation between the two twins that tells you something weird is going on.