Quantum Theory

A Brief History

Quantum Theory is a theory about dead cats.

More seriously, it is a description of the way the small particles that make up the universe behave.

Their behaviour is quite different from the behaviour of the larger objects with which we are familiar from everyday life.

Thus quantum theory can seem quite counter-intuitive.

Quantum theory (or quantum mechanics) was developed mostly between 1900 and 1930
by European physicists including

Max Planck
Albert Einstein
Neils Bohr
Louis de Broglie
Max Born
Paul Dirac
Werner Heisenberg
Wolfgang Pauli
Erwin Schrodinger and his cat
Richard Feynman

As well as quantum theory,
these 30 years brought the discovery of relativity,
galaxies beyond the Milky Way,
and the expanding universe.

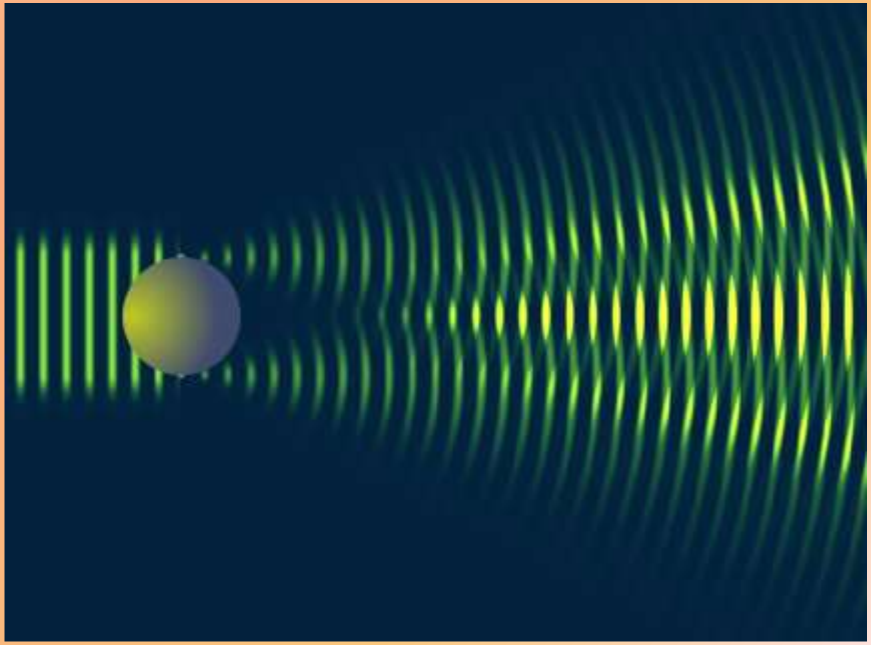
These discoveries laid the foundations of modern physics and cosmology.

In the 17th Century Newton came up with a theory of light.

He said that light is made of particles, each particle consisting of a particular colour of the spectrum.

This was just after coming up with his laws of motion and gravitation and developing calculus.

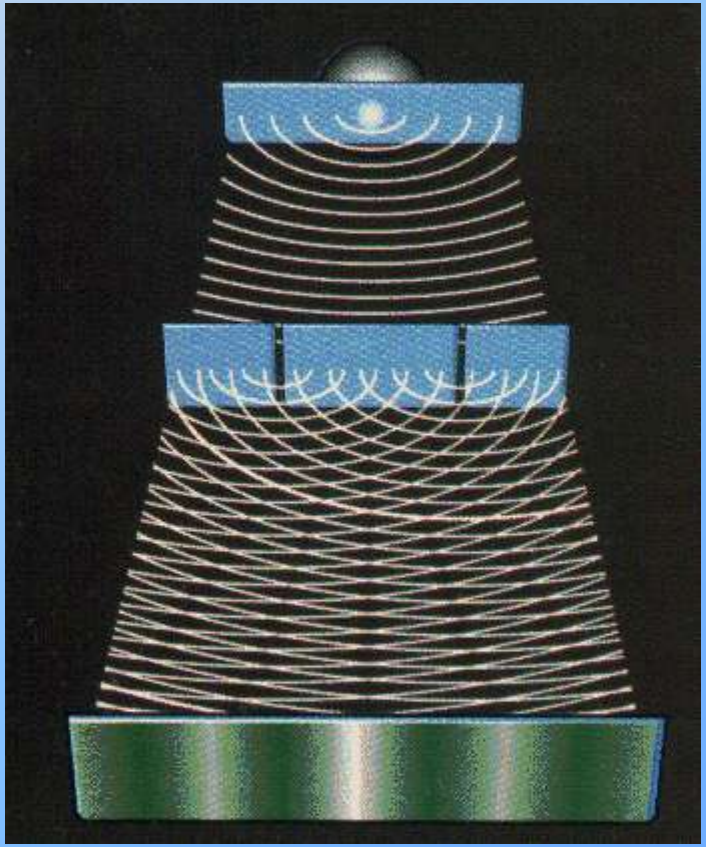
During the 18th Century, most scientists accepted this, though a few, like Robert Hooke, Christian Huygens and Leonhard Euler believed that light consisted of waves rather than particles.



Then in 1803, Thomas Young did his famous double-slit experiment.

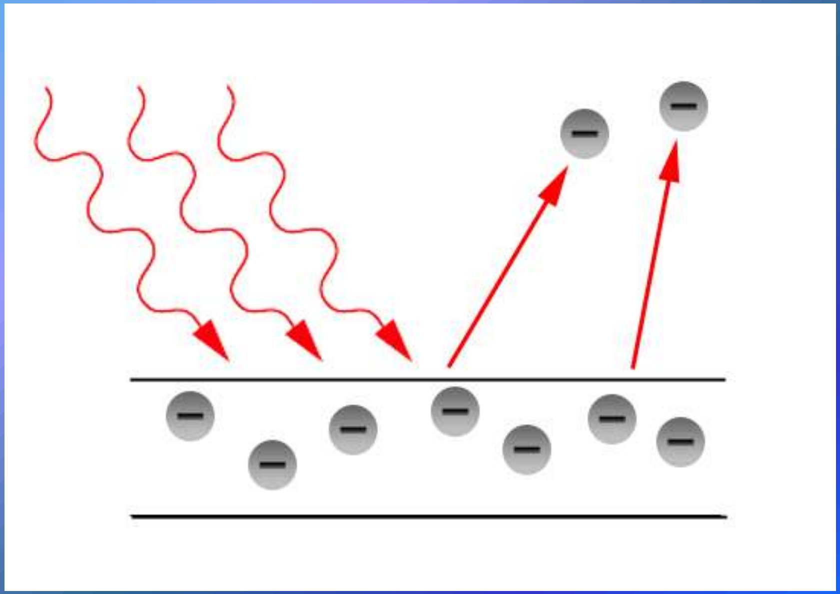
The interference Patterns produced were the same as those produced by waves on water.

After this it was generally accepted that light was made of waves rather than particles.



However, in 1905, Einstein produced a paper on the photo-electric effect, showing that light really was made of particles.

Light was used to provide the energy to dislodge electrons from a metal.



A certain amount of energy was required to dislodge an electron.

It was expected that once the brightness of the light reached a certain level, electrons would be released.

What he found, though, was that the brightness made no difference – what mattered was the colour.
Very dim blue light would release electrons while very bright red light would not.

It seemed that light was made up of particles of different colour, just as Newton had suggested. Einstein called them photons.

Bluer colours has shorter wavelengths and therefore higher frequencies and higher energies.

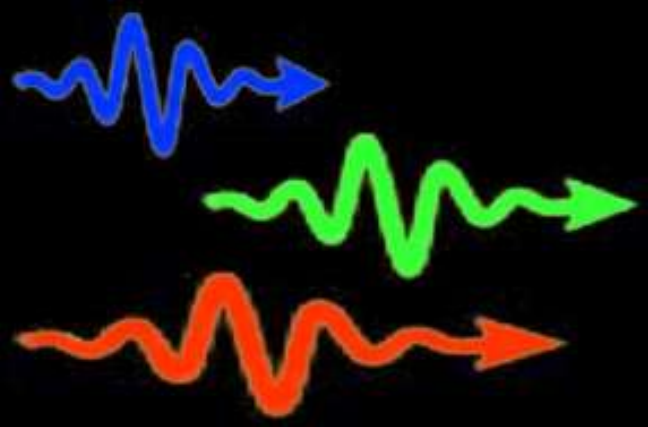
The energy of a photon was proportional to the frequency

$$E = hf$$

the constant of proportionality being called Planck's constant and having the value 6.6×10^{-34}.

A red photon did not have enough energy to dislodge an electron and no intensity of red light would do the job.

However, a single blue photon did have enough energy.

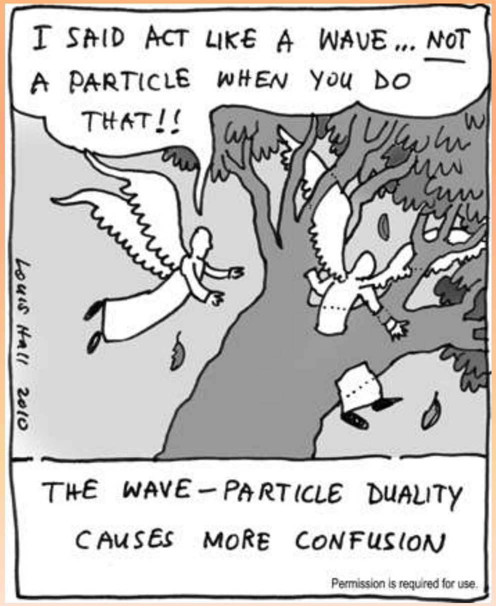


This showed that the energy of light came in discrete packets called quanta (plural of quantum).

Each quantum consisted of a fixed amount of energy.

So now it seemed that light was both a wave and a particle. Eddington suggested calling it a wavicle, though this idea didn't really stick.

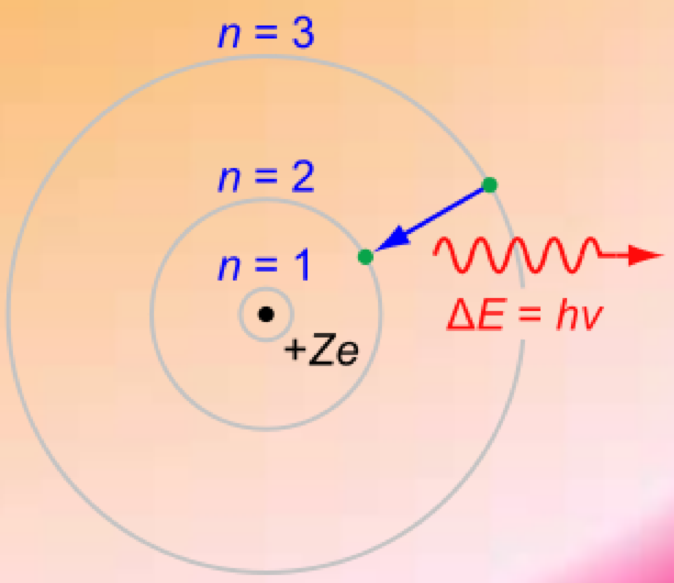
It is now well accepted that photons behave in some ways as waves and in other ways as particles.



This was not actually the start of quantum theory. It started 5 years earlier in 1900 when Max Planck published a paper showing that black body radiation was quantized.

The idea behind this is harder to understand though.

In 1913, Niels Bohr came up with a model of the hydrogen atom which explained experimental observations.
In his model, electrons could orbit the nucleus only at certain distances.
When energy was absorbed or emitted, it did so only in quantities equal to the difference between the energy levels of the orbits.



Thus a hydrogen emitted light only at certain discrete frequencies.

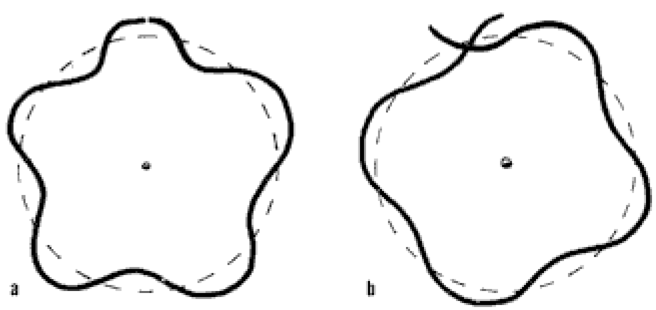
There was a serious problem, however, with Bohr's atom.

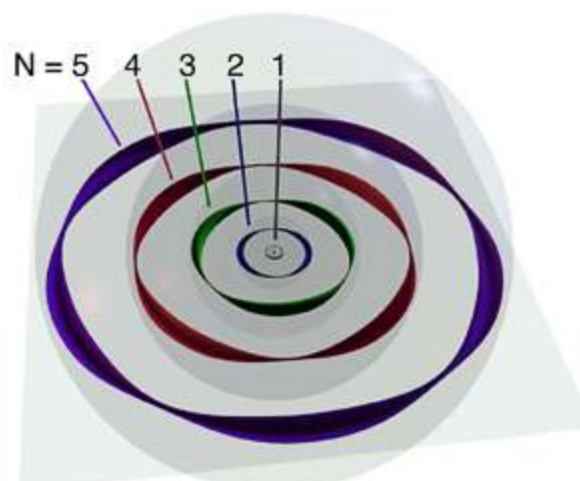
It wasn't that it was Bohring . . .

It was that it was well known that an accelerating charged particle will emit electromagnetic radiation. This would cause the electron to lose energy and to sink into the nucleus in a small fraction of a second.

In 1924 Louis de Broglie suggested that, if light could have properties of particles and waves, then so, maybe, could electrons.

He developed a model of the atom in which the electron was a wave around the nucleus.
If the circumference of the orbit was a whole number of wavelengths, then the wave would be a standing wave that doesn’t change with time.





Bohr-de Broglie electron matterwave orbits shells 1-5

Such a wave would not emit energy and so would be stable.

His model correctly predicted the energy levels of the different orbits as known from the emission spectrum.

Shortly afterwards, Erwin Schrodinger developed the Schrodinger wave equation.

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[\frac{-\hbar^2}{2m}\nabla^2 + V(\mathbf{r},t)\right]\Psi(\mathbf{r},t)$$

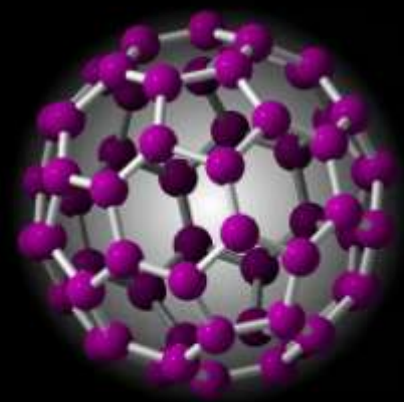
With this, the model could be placed on a sound mathematical basis.

Of course, if it was true that electrons did in fact behave as waves, then they should produce the same interference patterns that Thomas Young produced with his double slit experiment.

The experiment was repeated with electrons instead of photons and . . .

Sure enough, the same interference patterns resulted.

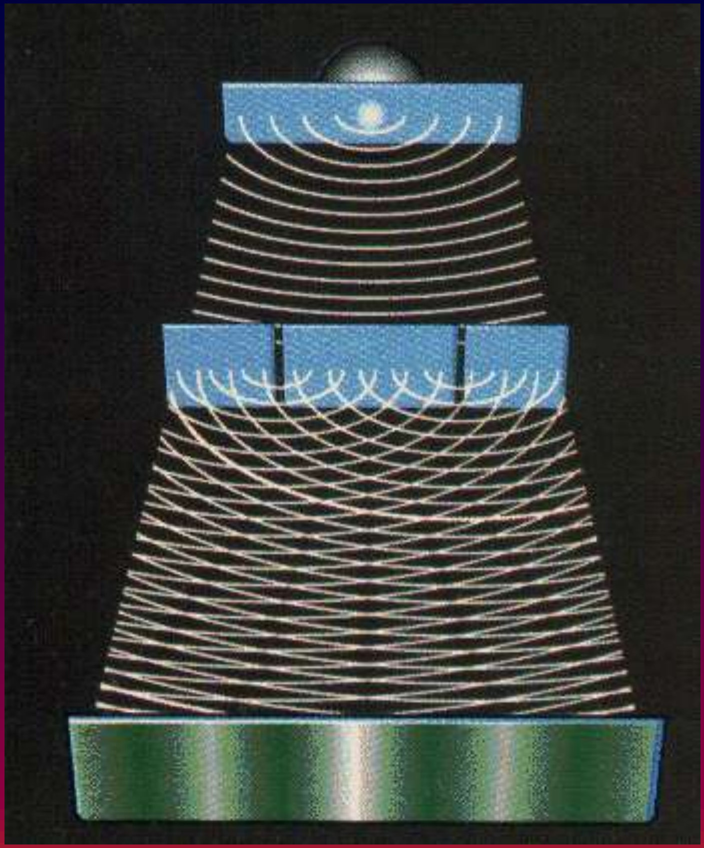
Similar experiments have been carried out with neutrons and other subatomic particles and even with atoms and quite large molecules and the same sort of behaviour is observed.



It seems that all matter can exhibit wave-like behaviour, though the larger the particle, the less obvious it is.

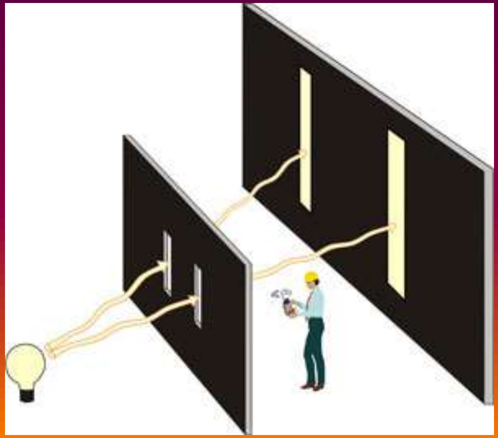
Now this is where the weirdest thing in quantum theory comes in.

The interference patterns in the double-slit experiment are produced by two photons or electrons passing through the two slits (one through each) at the same time and interfering with one another.

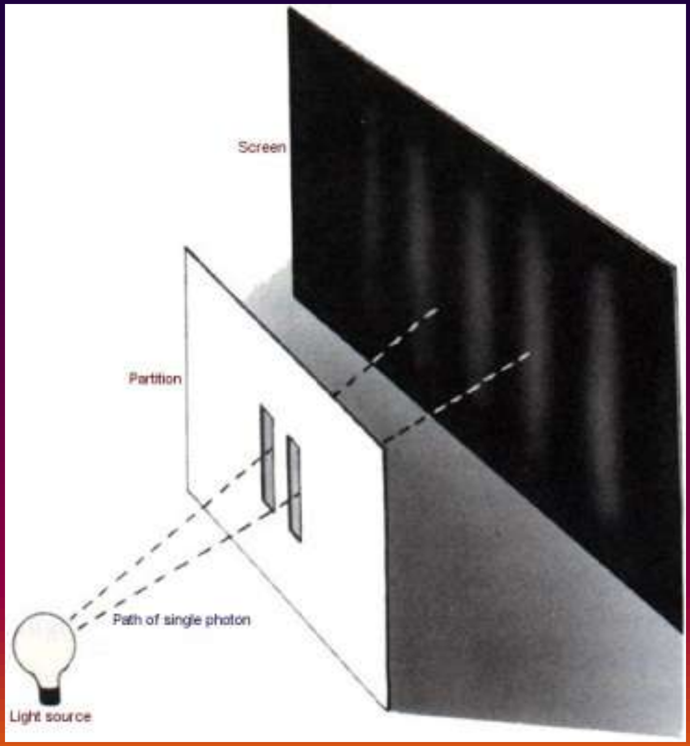


The experiment was repeated with electrons being produced so slowly that only one would be going through the slits at any one time.

It would, of course, be expected that the electron would pass through one of the slits and, as there was no electron passing through the other, no interference pattern would result – just two lines, one behind each slit.



But, to people's surprise, the interference patterns were still produced.



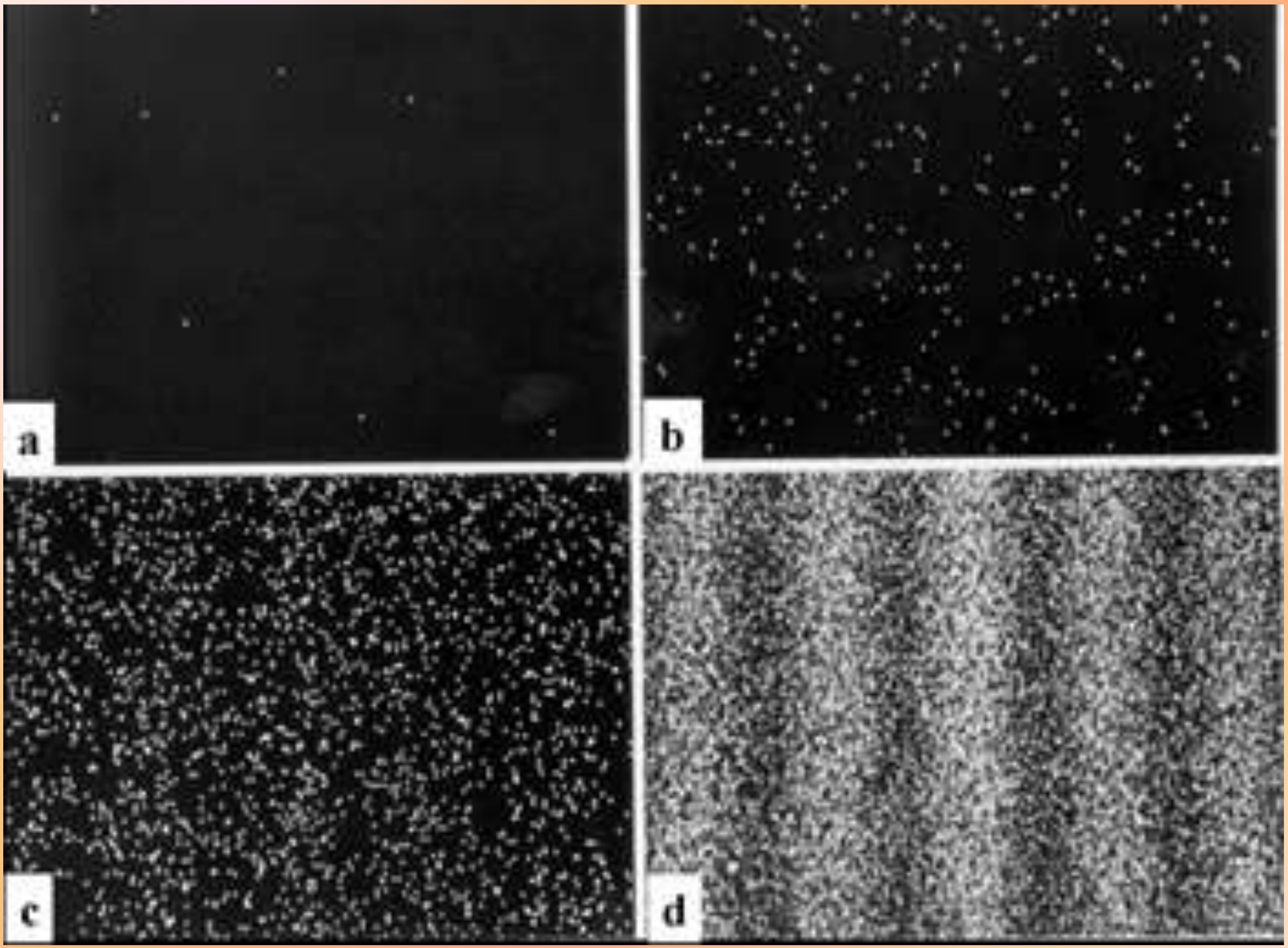
What this meant was that a single electron was passing through both slits and interfering with itself!

The same was found to happen with photons.

The results were interpreted like this.

An electron (or photon or any other particle) does not have a definite location until it is observed. Until then, it has a probability distribution of being in various positions.
This probability distribution at any particular time is in fact given by Schrodinger's wave equation.

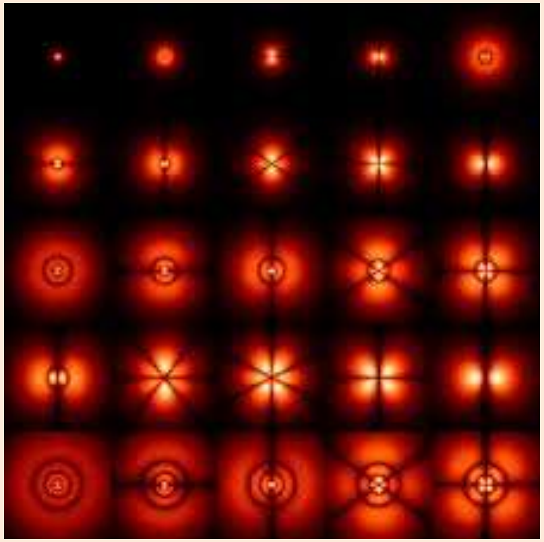
So the electron in the slit experiment went through both slits with equal probability. It's path only became definite when it hit the photographic plate and was observed.


a
b
c
d

Imagine a photon leaving a glowing hydrogen cloud in space.

Until it hits something, it does not have a particular position. One year after it leaves, it is spread out over a spherical shell one light year in radius. Only when it hits something, does it then have a history of having followed a particular path through space.

In modern chemistry, electron orbitals are seen as probability distributions. For each point in space, this probability distribution gives the probability that, if the electron's position were measured, it would be at that point.



Note that this is not just a case of us not knowing where the electron is. It is a case of the electron not having a definite location, but rather being a probability cloud.

It should be stated that, even today, physicists are not all agreed on the interpretation of some aspects of quantum mechanics.

For instance, the position of a particle is fixed when it is observed. But who has to observe it? Does it have to be a human? a physicist? a camera? an affected atom? a cat?

Speaking of cats . . .

In 1926, Schrodinger published a thought experiment involving a cat. He did this to point out the problems with some interpretations of quantum mechanics.

In his thought experiment, a cat is placed in a box along with a flask of poison gas, a hammer set up to break the flask, an unstable atomic nucleus that may or may not decay and a sensor which will detect the decay, connected to a device which will cause the hammer to fall on the flask if it does decay.

In his paper, he said that, until someone opened the lid of the box to see it the cat was dead, the cat was in a probability distribution of two states – alive and dead.

It was only when the box was opened that the probability function collapsed to a single value – either dead or alive. Before then it was both dead and alive at the same time.


WANTED
DEAD & ALIVE
SCHRODINGER'S CAT


First, her new hoomin had called her Pandora.
Now he was messing about
with acid and uranium
and some thingumajig with a switch.
She started to wonder
whether life in the pound
had really been THAT bad, after all...

Even when we make a measurement on an electron or other particle, not everything we can measure is definite.

Werner Heisenberg showed in 1927 that if we know the position of a particle very precisely, then we cannot know its momentum precisely – and vice versa.

$$\sigma_x \sigma_p \geq \frac{\hbar}{2},$$

This is Heisenberg's Uncertainty Principle.

"Be patient, a few more strokes and I'll soon have the momentum going."

Note that it is not just that we cannot measure these quantities accurately.
It's that they do not have well defined values.

Another pair of quantities connected by the uncertainty principle is time and energy.

If time is defined precisely, then energy is not defined precisely.

$$\Delta E \Delta t \approx \frac{h}{2\pi}$$

A consequence of this is that energy can be created from nothing as long as it doesn't last very long.

Because of the equivalence of mass and energy, this means that matter can be created from nothing as long as it disappears again very quickly – in about 10^{-35} seconds.

Such occurrences are called quantum fluctuations.

It is believed that quantum fluctuations happen all the time and therefore that ‘empty’ space is full of particle-antiparticle pairs which are created and then annihilate one another.

The most common are electron-positron pairs because they contain little energy, but heavier pairs are present for correspondingly shorter times.

Because they are short-lived, these particles are called ‘virtual particles’.

This might seem very academic, but it does mean that empty space has energy and mass.

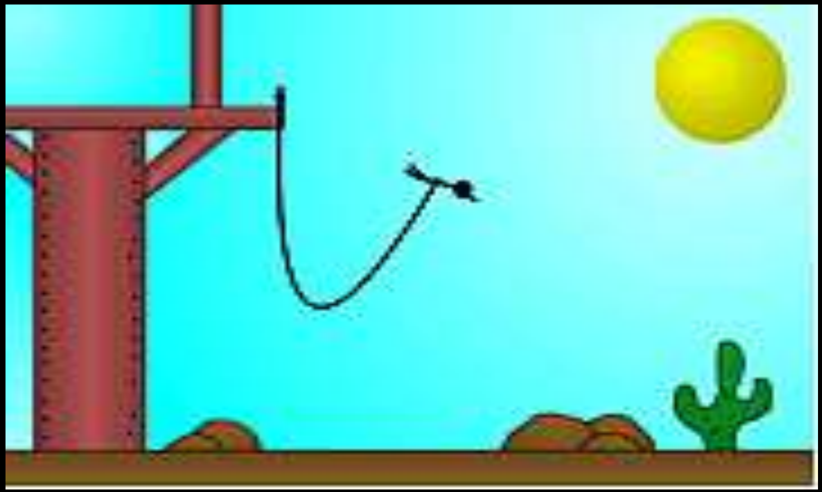
This vacuum energy may explain the dark energy which makes up about 73% of the mass-energy of the universe.

This vacuum energy has a negative pressure which opposes gravity and causes the universe to expand at an accelerating rate.

Woman using energy to vacuum (but not vacuum energy).

One problem is that the calculated density of vacuum energy (10^{113} J/m^3) is about 10^{122} times the inferred density of dark energy (10^{-9} J/m^3).

This is the biggest discrepancy between theory and observation in the history of science.



On the other hand, the uncertainty principle could explain the origin of the universe.

The product of energy and the time it exists for is limited by

$$\Delta E \Delta t \approx \frac{h}{2\pi}$$

Now if the total energy of the universe is zero, then the amount of time it can exist for is infinite.

But is the total energy of the universe zero?

Well, it seems that it might be.

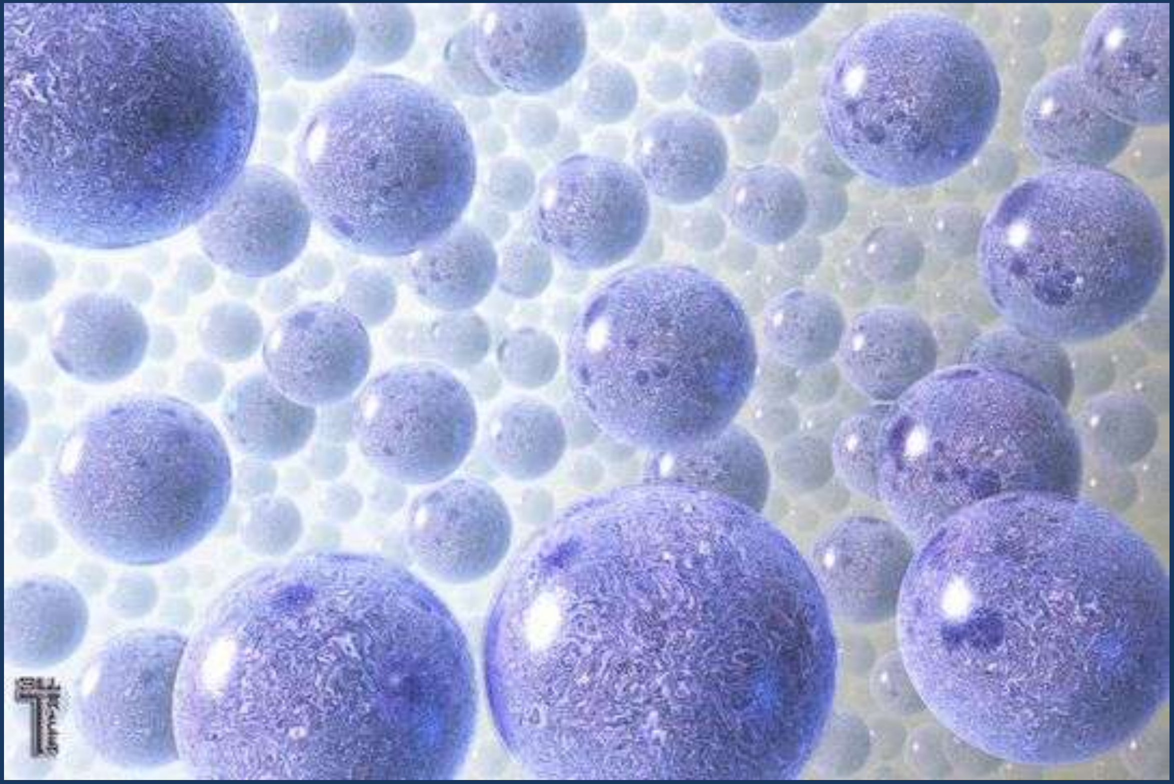
All matter has positive mass-energy. But there is also potential energy which is negative.

At the time of the big bang, the mass-energy would have been mc^2 and the gravitational potential energy would have been $-mc^2$. It seems that these two would have exactly cancelled out to make a universe with zero energy. As energy is conserved, it should still be zero now.

So the whole universe could be just a quantum fluctuation.

But where there was one quantum fluctuation, there were probably others.

The universe could well be just one of many – maybe an infinite number of universes – a multiverse.

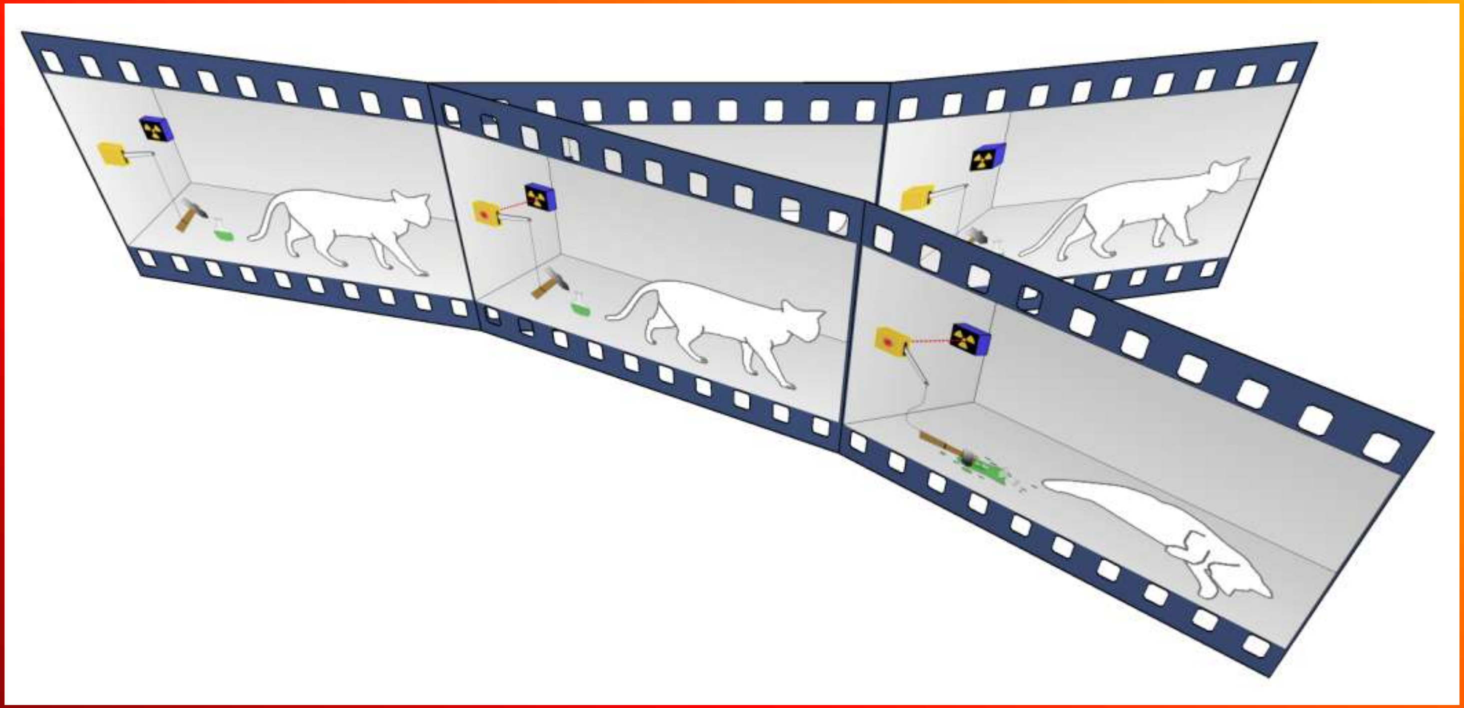


The many-worlds interpretation of quantum mechanics implies the existence of multiple universes in a different way.

There is something theoretically unsatisfying in the asymmetry that occurs when the probability distribution for an event collapses to a single outcome.

Why that one and not any of the others?

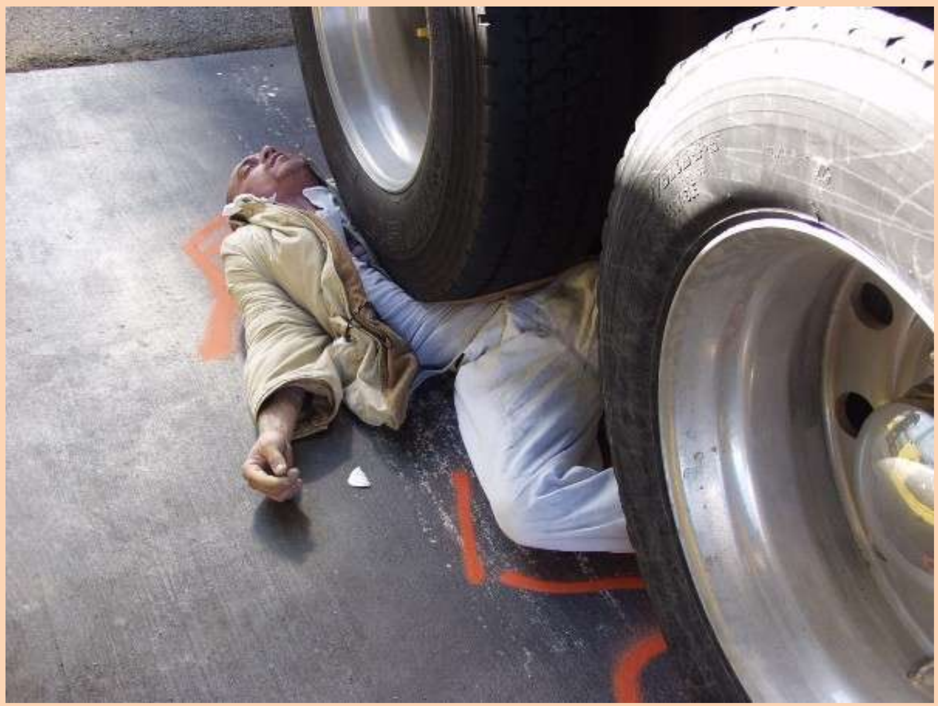
One theory is that all possible outcomes occur, but that the universe splits into a whole set of universes, one for each outcome. These new universes all have the same pasts, but will have different futures.



At present we have no way of knowing if the many-worlds interpretation is correct, but it is the preferred option for many physicists.

It could be satisfying to know that if you missed out on winning the lotto, then in another universe somewhere, you are filthy rich.

On the other hand, if you narrowly missed getting run over, there's probably another universe in which you are squashed on the road.



Quantum theory seems in some ways very abstract and hypothetical.

However, there is sufficient evidence for it that almost all the world's physicists accept it as the way the universe is.

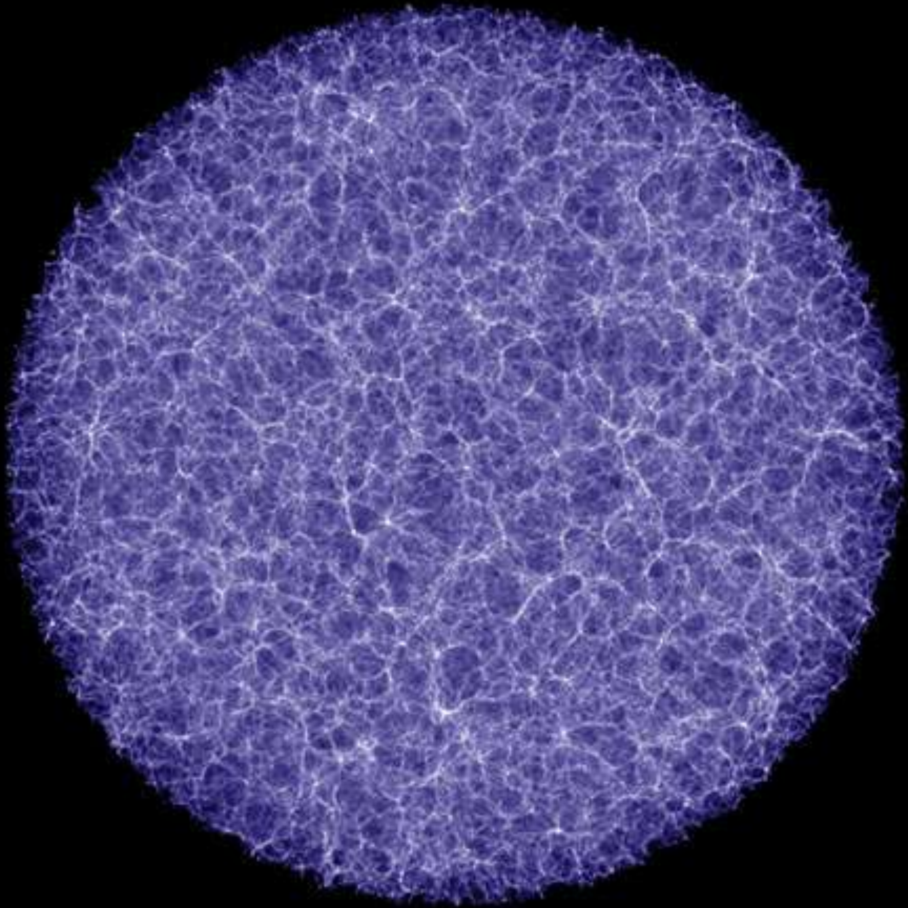
Of course, there are still many questions to be answered and details to be worked out.

There are many well-known phenomena whose explanation relies on quantum theory.
These include:
> lasers
> transistors
> electron microscopes
> magnetic resonance imaging
> superconductors
> superfluid helium
> even the common light switch
as well as many phenomena observed in stars.

Quantum ideas are also being used in the development of quantum computing.

We have in quantum mechanics quite a good theory of the interaction of subatomic particles through the strong, weak and electromagnetic forces.
We also have in relativity quite a good theory of the large scale structure of the universe and gravity.

Physicists are trying to unite these into a single 'Theory of Everything'
with one set of equations that explains the whole universe.



It may be a while coming.