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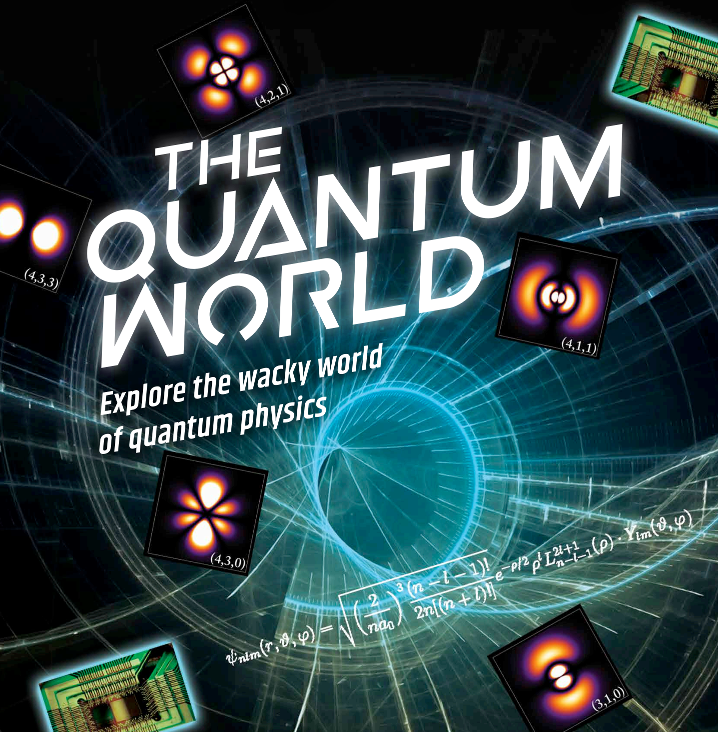
The Small Book of Big Thoughts



THE QUANTUM WORLD

Explore the wacky world of quantum physics digit

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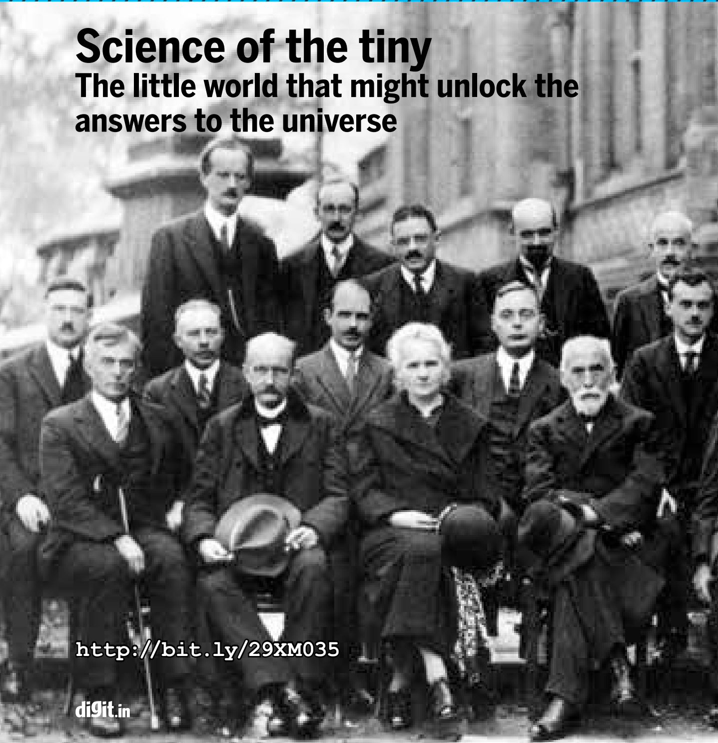
AUGUST 2016

Science of the tiny

The little world that might unlock the answers to the universe



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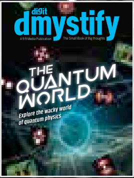

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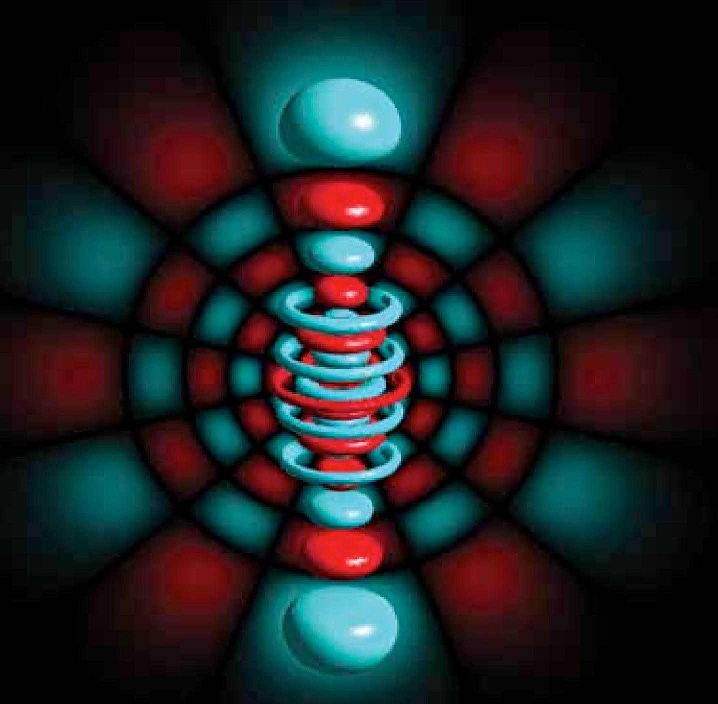


What the Hydrogen atom actually looks like

The twilight zone

A lot of people find the quantum world to be as wacky as an episode of the Twilight Zone. This is because just like the series, this area of physics is surprisingly unintuitive. If you expect something to happen, chances are, the opposite will happen in the really small world at the quantum level. Actually, chances are that nothing you could ever imagine will happen in the quantum world.

Add to that the fact that the most brilliant minds of our time say they don't really understand quantum mechanics, then what hope do we have of understanding it ourselves, or more importantly, how on earth can we hope to dmysitfy something we don't understand ourselves?

Let's find out. Although you may very well end up more confused about the quantum world than you were before you read this book, maybe that's not such a bad thing. The thing about the quantum world is that the more you know about it the more strange it all seems.

If somehow you end up understanding quantum mechanics after reading this book, do remember to give us a shout out at your Nobel acceptance speech. As always, write in with feedback to dmystify@digit.in and tell us what you think. ■

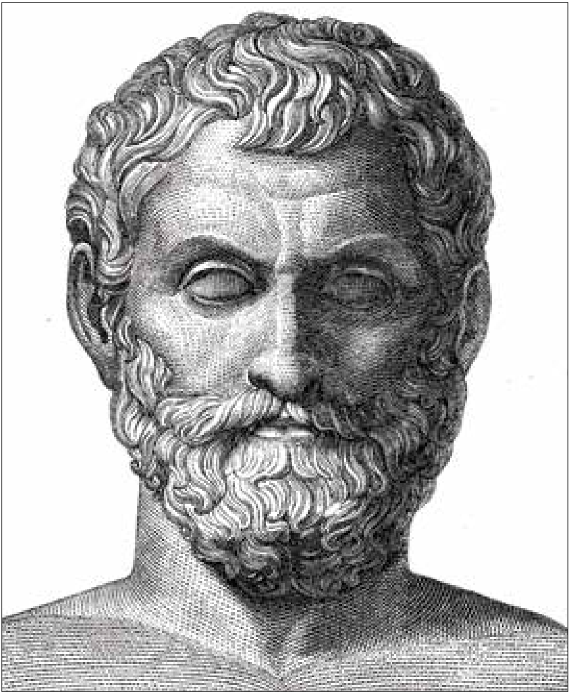
History of physics

Here's a quick trip down memory lane

All of science that preceded modern astronomy and quantum theory was essentially an attempt by mankind to explain what it saw with its own eyes. Most of human history – which is a mere blip in evolutionary time scales – elapsed with primitive attempts to explain things such as sunrise and sunset, eclipses, weather, seasons, death, life, primitive biology, chemistry and physics. Most of the explanations involved superstitions and supernatural solutions, which gave birth to the gods – some of which have a hold over us even today. However, there were always people who were unsatisfied with the simple explanation: "The Gods did it". These first people were perhaps the first scientists, and they are just as responsible for the technological revolution as the modern humans who actually built it all. Isaac Newton, no less, said exactly that: "If I have seen further, it is by standing on the shoulders of Giants."

Although many, many people would have had the same ideas, the first historical evidence we have of actual science is from Thales of Miletus, who in the 6th century BCE said that every observed phenomenon probably had a perfectly natural explanation. This is why he's known as the "Father of Science". Of course, the primitive knowledge of the time resulted in ideas that water was the element that made up most things, or other fanciful, but very wrong, theories. Still, it was this refusal to accept the "Gods" and mystical forces as the cause of everything that really kick started science. This tradition was later carried forward by famous Greek scientists such as Aristotle, Archimedes, Ptolemy, etc.

The Indians were no less gifted in the areas of scientific exploration. Obviously math was our strong point, with a fascination for numbers (especially large numbers) on display in the ancient vedas. As early as the sixth century, the Indians were talking about atoms and matter. Thought experiments were being used to marry philosophy and logic into science. Although there is no evidence to suggest that they knew about atomic structure, we can see how it could have been arrived at logically – you take something, a soft rock perhaps, and smash it into bits, then you take the smallest bit and smash it further, and pretty soon you're left with dust, but closer observation shows that even dust is a form of matter – like individual grains of sand. Thus, they arrived



Thales of Miletus is known as the father of all science!

logically at the theory that all larger matter is made up of small particles, and the smallest indivisible particle is not visible to us humans, and is called *Parmanu*. This is probably how logic and philosophy were used to arrive at surprisingly accurate answers in even ancient times. Of course we will never know for sure because of records being perishable.

The Chinese, Romans, and later Muslim scientists led the field of science after this. Ideas and learnings started flowing across the globe, which makes it very hard to really know who came up with what idea first. However, what's undeniable is that humanity as a whole started getting smarter, and more logical, very quickly. Science caught on, and was eventually brought under the control of various religions across the globe. It's hard to say whether this harmed or helped the cause of science. It was obviously helped because, as it is even today, religion is a very lucrative business, and thus scientists who worked for religious bodies back then were always well funded. This meant that science was able to progress quickly because experimentation was affordable. It could be bad as well because religion only funded the science that would give it the answers it wanted, and perhaps way too many smart people didn't follow their intuitions because it went against the teaching of their religions. We obviously don't have the space to go into detail on this subject, but we encourage all of you to read more about the history of science online.

A new era

There was an unprecedented leap forward in science about 500 years ago. Although many before, from many civilisations probably thought about the solar system, the accepted view was that everything revolved around the Earth – as god had intended. The first instance in more modern times (that we have undeniable records for) of someone suggesting a heliocentric system (sun at the middle) was Nicolaus Copernicus (1473-1543), the Polish astronomer. This, at the time was still blasphemy for religions, because religions thought of us as special creations of God. He published his book called On the Revolutions of the Celestial Spheres in 1543, just months before his death, in which he laid out his reasoning for why the Sun was at the centre, and we revolved around it.

This was a shot in the arm for science, because finally mankind had broken away from the idea that we were somehow special, or the centre of the universe, and allowed us to really search for our place in the universe.

Copernicus was lucky, however, because he died soon after his work became public knowledge. Galileo Galilei, the Italian mathematician and astronomer, wasn't as lucky. Galileo (1564-1642) championed Copernicus' heliocentric idea, but was shot down by the Roman Inquisition in 1615. He didn't give up however, and published a book called Dialogue Concerning the Two Chief World Systems, in

Copernicus was the first in written history to advocate a heliocentric view

1632, which again championed the idea (less forcefully, though). He was tried and sentenced to house arrest for the remainder of his life because of that book. His body was even refused burial near his father's grave because of his "heresy".

Galileo continued to write even under house arrest, and despite ill health. Some of his works from this period would receive high praise from Einstein later, and this is why many consider him to be the "Father of modern science".

Isaac Newton (1642-1727), needs no introduction to regular readers of this book. We've sung his praises so many times that we're just going to leave the mention of him here. You know what he did, you know why he is considered to be one of the greatest minds that ever lived...

Fast forward to James Clerk Maxwell (1831-1879), the Scottish mathematical physicist, who, in 1859 discovered that electric and magnetic fields propagated outwards at the speed of light from their source. This meant that light would be classified as electromagnetic radiation, and whether electric or magnetic, all forces and radiations were electromagnetic in nature.

Heinrich Rudolf Hertz (1857-1894) would then go on to prove Maxwell's theory by inventing the first radio device – the frequency unit is named after him (the Hz in GHz, MHz, KHz, etc). Hertz died early though (at just under 37 years old), and never considered his work to have any real practical value. Guglielmo Marconi (1874-1937) however, disagreed, and went on to built the first long distance radio transmission system, and the rest, as they say, is historic!

Modern physics

By the end of the 1800s, the physics of the mechanical world was pretty well established. Astronomy was picking up, we understood a lot about levers, pulleys, and were able to even understand invisible things such as radio waves. We had started widely accepting that there was more to the universe than meets the eye – or for that matter, could ever meet the eye, or be seen by any living thing.

Although it's not a widely held belief, we are of the opinion that radio changed everything. The idea that electromagnetic radiation could exist, and that light was merely a visible part of a huge spectrum of radiations, was in our opinion a huge change for humanity.

Not only did it forever end the belief that we were somehow special, but it also gave us the confidence to explore areas of physics that we wouldn't otherwise be able to perceive. It was also a big shot in the arm for mathematics, and the importance of mathematics in the world of physics.

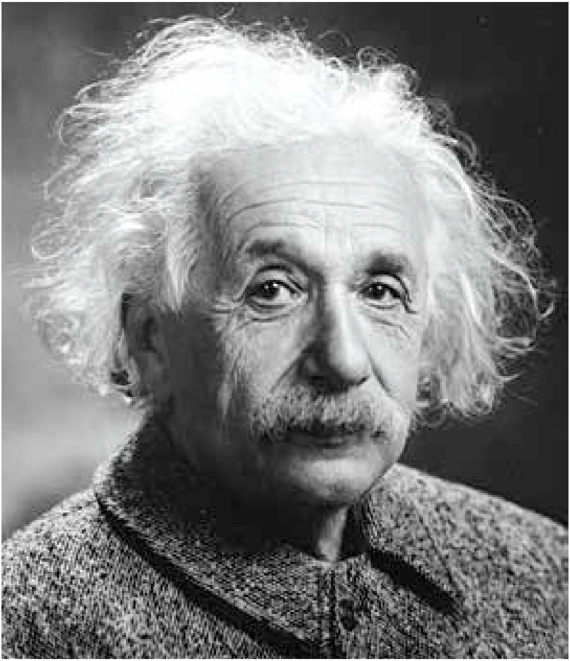
Wilhelm Röntgen (1845-1923) took the discoveries a step further by discovering X-Rays in 1895. Just a year later Henri Becquerel (1852-1908) found evidence of radioactivity. Marie Curie and her husband Pierre Curie would then go on to discover even more radioactive elements, which would shake the idea of the atom being the smallest possible form of matter. The discovery of the electron by JJ Thompson (1856-1940) in 1897 would end the 19th century on the cusp of the true great discoveries of modern science.

Albert Einstein

If you're paying attention, you will see that so far no scientist mentioned in this book has got a headline to themselves. Einstein is that exception because, well, when it comes to modern science, we believe no one person deserves a headline to themselves more than him.

Albert Einstein (1879–1955), was the first person to explain how space and time are relative to the observer. First, in 1905 he showed that the speed of light in a vacuum itself was constant, and though this made no difference to our relatively slow moving worlds, it did make a difference to things moving at appreciable fractions of the speed of light. He also theorised that nothing could move faster than the speed of light in inertial reference frames (a frame of reference where no external force is felt).

His later mass-energy equivalence equation – e=mc2 *(read more about it in our dmystify of the same title)* – would show that matter and energy are essentially just different forms of each other, and can be converted from one to the other.



Einstein didn't much like the fact that Quantum Mechanics forced you to accept uncertainty

Einstein also established the now accepted fact that time is also relative, and could be thought of as a dimension itself. Thus, giving birth to the idea of spacetime. His later theory of General Relativity went on to replace Newton's own theory of gravitation, and we now know that spacetime itself curves around bodies of large masses, and that's what explains the orbits of things around one another. What was a very important result of this theory, however, was that light should also obey these laws, and thus light could also be considered a particle that gravity could act on.

Although Einstein's theories explained away a lot of the discrepancies between science theory and experimentation, it still couldn't answer a few problems, especially problems regarding the world of tiny particles and radiation. Thus was born the study of quantum mechanics. ■

Quantum mechanics

How we arrived at the science of the very, very, small

Although it's hard to really pinpoint where the science of the really small really got started, because of all the mentions of it in early philosophy, however, we will stick to actual scientific history for this chapter.

In 1900, Max Planck (1858-1947), the famous German theoretical physicist, explained black body radiation by suggesting that electromagnetic energy was radiated in specific units that could be calculated by using the equation $E=hv$. Here, E is the unit of energy radiated, h is the Planck constant, and v is the frequency of the radiation that is being measured.

In 1905, Albert Einstein would then take this one step further and explain how light itself would also have to consist of quantum particles, which we now call photons. This explained an experiment done by Heinrich Hertz in 1887, which showed that shining lights of particular wavelengths on to the surface of certain metals could, in fact, cause electrons to be freed up. This was known as the photoelectric effect, and Einstein explained it perfectly by suggesting that light was also made up of unit quantities of particles.

Perhaps we've arrived at it a bit late in the book, and maybe should have explained it in the introduction itself, but we believe this this is the point at which you will realise why this field of physics is called "Quantum" Physics, or "Quantum" Mechanics, or why this book is titled the "Quantum" World. Obviously, the word quantum is used to specify the smallest possible unit of something, and that "something" could effectively be "anything" – matter or radiation / energy.

What Einstein gave birth to, with his quanta of light theory, was a debate that would last for decades about whether light was a particle or a wave. This is because experiments were done that showed it as both. More on that later, however.

Understanding the atom

The biggest problem with the theory of the atom at the time was that scientists assumed that it consisted of positive and negative charged particles – the protons and the electrons. However, much like magnets, positive and negative charged particles obviously attract one another. If this was the case, scientists were wondering why the electrons didn't just spiral in and eventually merge with the protons in a flash of massive energy.

It wasn't until 1913 when Niels Bohr (1885-1962) theorised that electrons were located around the nucleus of an atom in stable orbits that we finally got an understanding of how the atom was structured. Of course this isn't how we consider the atom to be these days, and the Bohr model is considered outdated now, but the principles on which he made his model up are still right.

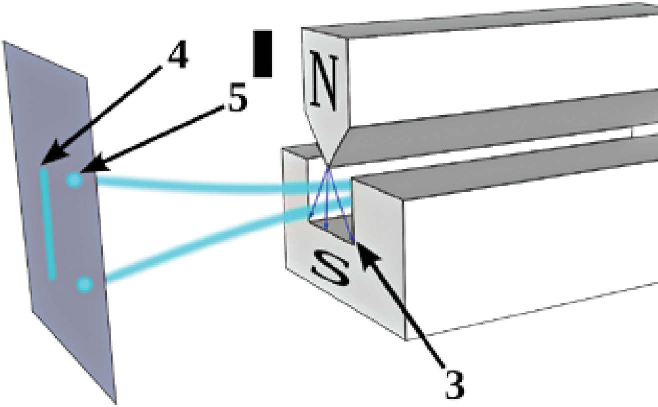
In case you didn't take Chemistry in high school, the Bohr model basically said that electrons rotate around the nucleus in stable states or orbits, and can jump from one orbit to another, but always either emit or absorb electromagnetic radiation when they do so. This energy is one quanta of energy (E=hv, from Max Planck).

Bohr himself knew that his model wasn't correct (it only worked for Hydrogen) and he would be the first to admit it. He called on the physics world to try and find a new way of explaining the atomic structure, and the elements. It took over a decade, but eventually we started on our way to understanding the quantum world.

Spin

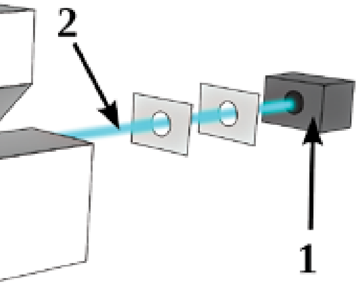
We've spoken about this many times before in previous dmystify's and have received some feedback suggesting that maybe we should have explained this concept. This is that explanation; a short and sweet one.

The simplest way to explain this is for you to first know a little bit about magnetism. Now, if you were to create a magnetic field,



Stream of silver atoms (1) | Concentrated stream (2) | Uneven magnetic field (3) | Expected pattern (4) | Observed pattern (5)

say, by fixing the south and north poles of two powerful magnets in such a way they face one another (but don't touch). Thus, you have a case where the north face of one magnet is separated by a small distance from the south face of another (they're pulling towards one another). It's important to note that the strength of the magnets has to differ here, so that, say, the bottom magnet is slightly stronger.



Now, shoot a bunch of dipoles through this gap. A dipole is basically a small magnet that has only north and south magnetic poles – like a regular magnet, but minimal space between the poles. When you allow the dipoles to hit a screen on the other end, you will see that depending on the orientation of the dipole, they are deviated off centre. Only when the dipole is oriented in such a way so as to negate the effects of the magnetic field, does it pass through without being deviated. Thus, on the screen, you get a vertical line, ranging from the top where a dipole was deviated by repulsion from the field – in our example, since the bottom magnet is stronger, it would repel a suitably oriented dipole slightly more than the weaker top magnet. The bottom most part of the vertical line would be dipoles that were attracted more by the stronger lower magnet, and the line would be filled in by all the other orientations of dipoles that would cause them to be either repulsed or attracted by the magnetic field to varying levels.

Now, when doing this same experiment, with, say, silver atoms, researchers expected the same results of a vertical line. However, what they noticed was that the screen recorded two horizontal lines – one at the top that corresponded to max repulsion, and one at the bottom that was indicative of max attraction. This meant that somehow, all the atoms that were sent through that magnetic field were somehow all oriented in only one of two orientations. This is how we learnt that atoms and subatomic particles such as electrons might have north-south or south-north orientations, but they have only those two configurations and no other ones. Since this was very unlike dipoles, we called this property spin.

This was pretty much exactly the nature of the experiment that was run in 1922 by Otto Stern and Walther Gerlach. They used silver atoms, and shot them through a non-uniform magnetic field, and found those two horizontal bars on the screen that we mentioned earlier.

Another result that was arrived at from this experiment was that there was no pattern of which atoms had which spin, it was purely probability based.

Understanding the atom

As we've mentioned, until the 1920s the science world imagined the atom to be much like the solar system – a nucleus in the centre and electrons revolving around it at different radii lengths from the centre.

When experiments were done by noting the radiation emitted by atoms, specifically Hydrogen gas that was excited by adding energy, it was found that when viewed through a prism, instead of broad bands of light that were overlapping (what happens when we use a prism to split sunlight into its seven constituent colours), there were just very precise lines of colours, and only a few colours. This experiment supported Bohr's model of the atom, because it was showing that light was emitted in very specific quanta from the atom, and not white light across all frequencies and wavelengths (colours) like we get from sunlight.

The only problem with Bohr's model was that it had no explanation for why this happened, or for that matter, why some lines of light emitted were brighter than the others (indicating that more light corresponding to that particular frequency was emitted). This is why it was relatively quickly that the Bohr model was found to be wrong, but the assumption that he based his model on – that electrons were quantised, and that's why sharp lines of colours were appearing – was in fact pretty accurate.

In 1924, Louis de Broglie (1892-1987) in his PhD paper, made a prediction that all matter in fact, can act as both waves and particles. This wave-particle duality is the very basis of quantum mechanics. For us, however, de Broglie's biggest contribution to the cause of science was to call for cross-border collaboration. He was the first

De Broglie called for scientific collaboration across borders way before CERN was even dreamed of

scientist of repute to advocate this idea, and the idea spread, eventually resulting in the setting up of CERN (Conseil Européen pour la Recherche Nucléaire, which translates to European organisation for nuclear research). So many of the most cutting-edge discoveries being made even today come from CERN, and we can only hope that mankind can learn to work even more closely together than it does today for the noble cause of science.

De Broglie was eventually proven to be right, as experiments (the double slit experiment, which we will explain later) proved the wave-particle duality of electrons (this duality of photons had already been shown before). It was not just for electrons and photons that experiments were done, but also for atoms and molecules, thus proving the duality of matter. It was finally proven that neither particle physics nor wave functions could be used individually to accurately describe how matter behaved at the quantum scale. Thus, a whole new branch of physics was indeed birthed. ■

Wacky and spooky

Forget all you know about the world around you if you you want even limited understanding of the quantum world

It's true. Almost everything you know about classical physics that you're taught in school has to be forgotten in order to be able to understand the quantum world. Nothing in your everyday life ever just disappears, and re-appears somewhere else in an instant. Nothing exists as one of many states at the same time.

For example, it's your birthday, and a loved one has bought you a surprise gift. This gift is in a box that's wrapped, and it's opaque, so you can't make out what's inside. Let's say the box is rather big. Say a it's a large box that's about 2 feet across on all sides. All you know is that what's inside the box can fit inside an 8 cubic feet volume. You are told that inside this box is one of the things you love! Think about all of the things you love that could fit into that volume. What if we told you that all of those things you love were inside that box. They were flitting in and out of existence, and only at the point when you open the box would one of those many things pop into reality and be there for you to find when you opened the lid.

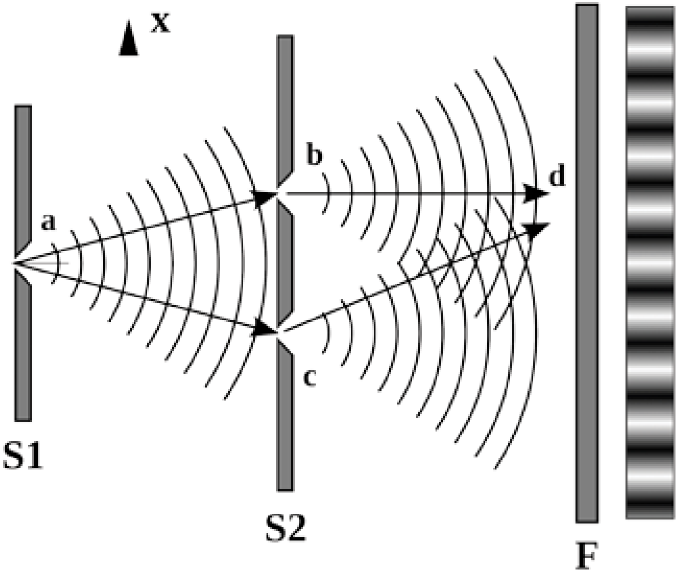
Now, we know that in the actual world, your loved one bought you one specific gift and got it wrapped up. However, what if she or he only gave a store clerk a list of things you love and told them to put one of them in the box, wrap it up, and not tell them what was inside. That way, even your loved one doesn't know what's inside. Would you believe then that all of the possibilities existed inside that box until you opened it?

In the macro world that we live in, this obviously isn't the case, however, in the quantum world, the very act of observation forces one of the multiple outcomes to happen. The outcomes happen in a probabilistic way. More on this later. For now, let's get to the experiments that were run that led us to believe all we've said above.

Double-slit experiment

This is the first experiment that we need to understand in order to be able to begin to understand the quantum world.

Basically, you shine a light at a screen. Then, you insert a card in front of the screen so that light cannot get through to the screen. Now, you cut one vertical slit just to the right of the centre of the card. Light travels through the slit and falls on the screen. Since the card is blocking all but that tiny slit, you'd expect to see just that slit



The famous interference (double slit) experiment by Thomas Young of light. Like the opposite of a shadow – perhaps bigger, or smaller, but a vertical line of light. What actually happens is that there's a band of many vertical lines all bunched together.

So now you cut another slit to the left of centre of the card, parallel to the first slit, and the same size and width. Now you shine the light, and you see a band of vertical lines of light again, but this time more pronounced dark areas. This is puzzling if you look at light as particles. They are after all photons that are being shot at the card...

Now, take a large rectangular bowl. Fill it with water, and insert a barricade that cuts off one half of the bowl from the other. Let's assume the barricade first has one gap right of centre. You drop something into one end of the bowl and the ripples move outwards in a circle. At the gap, more ripples are formed, and the gap becomes the centre from which the ripples spread out in the other half of the bowl. Now, do the same as the light experiment and repeat the experiment with two gaps in the barricade this time. If you notice the ripples as they hit the opposite end of the bowl, you will see that the two waves of ripples from the two gaps meet and appear to amplify at some points, and cancel out at some points. When two waves interfere, this is exactly what happens. If you were to take the deviations from the normal water level (peaks and troughs) as brightly lit parts, and points where the waves cancel each other out as dark parts, you would end up with exactly the same picture as the double slit experiment with light. This is how it was proved that light is in fact propagated as a wave.

This same experiment was repeated for electrons, and the same result was achieved. Thus, particles at the quantum level behave like waves, not particles – at least as far as this experiment goes.

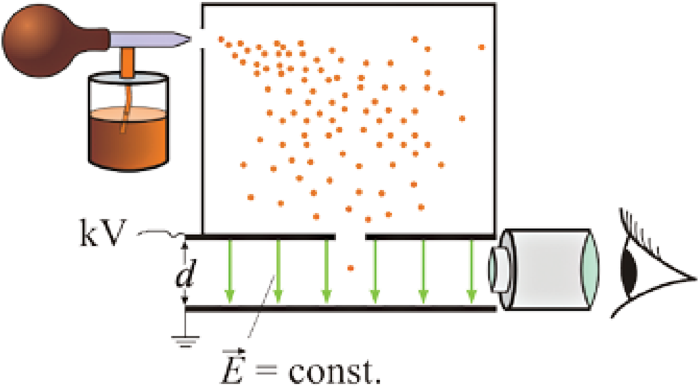
The first such double slit experiment was done in 1801 by Thomas Young (1773-1829), an English physician – much, much before anyone had even thought about quantum theory.

Oil drop

In 1909 Robert Millikan (and Harvey Fletcher) conducted the experiment that is now known as the oil drop experiment. This experiment was done to try and arrive at the charge of a single electron. It was ingenious, because they were able to calculate it pretty accurately using a pretty primitive setup.

How this experiment worked was basically first choosing the right type of oil, creating a fine mist of it, and inserting it into a chamber, and calculating the oil drop's terminal velocity, and timing it to find out how long it took to fall to the bottom from a fixed point of reference.

Remember, we are talking miniscule oil drops here, which have to be looked at under a microscope just to be seen. Also, remember that it was not like you could just extract one electron from an atom and measure the charge.



The Millikan Oil Drop Experiment

Inside the chamber, there was top plate and a bottom plate, and the top plate had a tiny hole in it. This would allow only a few drops of the oil to fall at any given time into the space between the plates. The atomiser would make tiny drops of oil, and spray them into the space above the top plate. Without any charge on the plates, they watched to see how soon the drop reached terminal velocity (point at which the drop is not accelerating due to gravity, because the friction of the air cancels out any further acceleration). If you know the density of the air inside the chamber (pretty standard at sea level), you can calculate the mass of the oil drop.

Next, they would select one of the many oil drops, and turn up the charge on the plates inside the chamber. Because of being atomised, some oil drops would lose some electrons and be positively charged. Since the top plate was negatively charged and the bottom positively charged, even a low charge would slow the oil drop's descent. A high charge would push the oil drop upwards, as the force of electricity acting on the drop would be greater than the force of gravity.

They would twiddle the dial to use enough electric charge to get the drop suspended in mid air. Now, at this point they would note down the amount of voltage required to suspend that drop, and because they knew that the forces were balanced, they were able to calculate the charge on the drop. This was repeated for many drops of varying sizes, and many data points were got.

After all the calculations were done, they found that the charges on the drops were all multiples of a certain number. So, for instance, they got numbers such as +16, +32, +48 etc, which made it obvious that all of the results were multiples of 16. The values are positive because the drops lost electrons, so in order to find the charge of an electron, just make positive into negative.

In their experiment, they found that charge to be -1.5924×10^{-19} coulombs. This is what they said was the charge of a single electron. Modern calculations, which are way more accurate and done with much more sophisticated methods and equipment have only improved that number by 1 per cent. The current scientifically accepted charge value of an electron is -1.602176565 x 10^{-19} coloumbs. This accuracy is why the oil drop experiment is considered one of the most inventive in science by many.

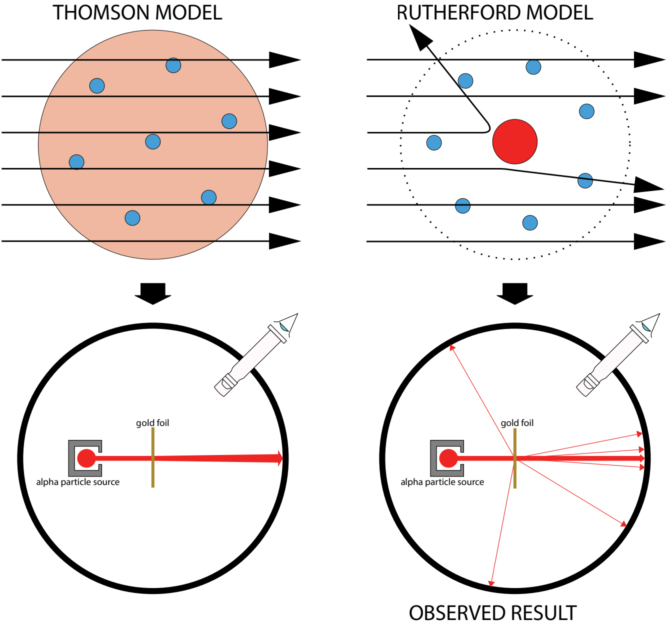
Rutherford's gold foil experiment

In 1911, Hans Geiger (1882-1945) and Ernest Marsden (1889-1970), working under the direction of Ernest Rutherford (1871-1937), did an experiment that showed the true form of the atom.

Before this, the accepted form of the atom was like a plum pudding. Imagine a pudding that's made up of the positively charged nucleus, with the pieces of plums inside the pudding being the electrons. Think of plum cake if the thought of a pudding confuses you.

So what they did was take a really thin foil of gold (only a few atoms thick). They surround the gold foil with a circular metal wall that flashes when hit with an alpha particle, and then through a small hole in the wall, they fire alpha particles at the gold foil. Alpha particles are basically a Helium atom with its electrons removed. It's made up of two protons and two neutrons, and thus is positively charged.

Obviously, thinking of the gold atoms as a plum cake, they expect alpha particles to rebound off the gold foil and go all over the place.



The Rutherford experiment to find the shape of the atom

To their surprise, almost all of the alpha particles just went straight through the foil as if it wasn't even there. Only a few, now and then, would either be diverted slightly, or rebound off the foil. By far, the majority of alpha particles just went straight through.

This led them to believe that the atomic structure was pretty much filled with empty spaces. The plum pudding model would obviously have to be thrown out. They then started thinking about what shapes could in fact produce the results they had observed, and thus they arrived at the model of the atom that we know and accept today. Thanks to them, we found out that the protons and neutrons were actually in the centre of the atom, were small, and the electrons orbited the nucleus.

Bosons

Satyendra Nath Bose (1894-1974) was an Indian physicist from Calcutta (now Kolkatta). He is the most famous Indian in the field of quantum mechanics, and he was self-taught in the field of quantum mechanics – because it was so new at that time that there were no "experts" to learn from in India.

He first appeared on the global scene when he sent a letter to Einstein, and attached a paper he had written titled Planck's Law and the Hypothesis of Light Quanta. Einstein translated the paper for him and published it under Bose's name in a leading German physics

Bose was India's greatest quantum physicist

journal in 1924. The paper was instrumental in understanding why some experiments were not agreeing with Pauli's Exclusion Principle, and although neither Einstein nor Bose knew it then, they would later collaborate and form a new field of quantum statistics which would be termed Bose-Einstein Statistics.

What Bose's paper did was explain how Bosons (named after Bose much later, and in Bose's time were just "particles that didn't follow Pauli's Exclusion Principle") would behave. This was to explain why, say, Photons didn't behave like electrons, and were indistinguishable from one another. In a Laser, for example, it's possible to get photons with the exact same quantum numbers, and thus they are identical – unlike electrons in an atom, which will always have unique quantum numbers.

Another result of this collaboration between Bose and Einstein was the Bose-Einstein Condensate. This is a state of matter that is obtained by super-cooling (almost to absolute 0 kelvin = -273.15 centigrade) a diluted gas made up of bosons. This would yield a state of matter best described as a superfluid. Although a theory at the time, this was later proved experimentally by many.

It is sad that Bose was never awarded with the Nobel prize in Physics, because he certainly deserved it. Many have got Nobel prizes after him by continuing along the line of work that he started, or which he and Einstein started together. Bose, however, was not as bothered by this as we are. He was just happy to be doing the science, and felt he got way more recognition than he ever expected. We suppose he was happy to live forever in history, as the particles he formulated a new field of statistics for were named after him – thanks to Paul Dirac. The newly discovered Higgs Boson, aka the God Particle, and the Graviton that we are so desperately searching for now are both Bosons, which were named after our very own Satyendra Nath Bose.

Exclusion principle

It was common knowledge in the 1920s that atoms with an even number of electrons were more stable (or more inert, in terms of chemical reactivity) than atoms with an odd number electrons. Austrian physicist

Wolfgang Pauli's exclusion principle is taught to all school kids

Wolfgang Pauli (1900-1958) decided to find out why this was so. In 1925 he published a groundbreaking paper that mathematically showed that no two electrons (later modified to include all fermions – subatomic particles named after Enrico Fermi) could have the exact same quantum state. A quantum state is derived by four numbers:

- The principle number (describing the electron shell that the electron in question was in)
- The azimuthal quantum number (the angular quantum number which is like describing which sun-shell the electron is in)
- Magnetic quantum number (which denotes the cloud within the sub-shell that the electron is in)

- The spin projection quantum number (which denotes the spin of the electron – +½ = spin up and -½ = spin down)

This paper went on to become Pauli's Exclusion Principle, which most of you science students would have already learnt about in school or early college.

New models of the atom

As we saw in the last chapter, Niels Bohr's model of the atom answered many questions, but it couldn't tackle the problem of the different intensities of different colours of light that are emitted when a gas is excited. This is a problem that Werner Heisenberg (1901-1976) was determined to solve. In 1925, at a very young age of 24, he published a paper that was considered a breakthrough for the time. It was a step in the right direction towards explaining the holes in Bohr's interpretation of the atom. He sent his paper to Max Born for review.

As soon as Max Born (1882-1970) read his paper he understood that a field of mathematics he had studied before, matrix theory, would be ideal to describe the fuzzy orbits of electrons that Heisenberg was proposing in his paper. Along with his colleague and ex-student Pascual Jordan (1902-1980), Born worked quickly to add on to Heisenberg's paper and they published a mere 60 days after Heisenberg. The three immediately started working together, and soon the field of matrix mechanics was born. They even published a paper together within a year after Heisenberg's original paper. Only Heisenberg would go on to win the Nobel prize, however, as Jordan went off to join the Nazi party, and since all Born's work was with Jordan, it was not considered.

Spin statistics

As is often the case in science, the people working on a problem don't always work together. This can result in two (or more) people ending up with the same results and theories despite working independently. This is exactly what happened with the work done on explaining the spin of (what would later be called) bosons and fermions.

Enrico Fermi (1901-1954) and Paul Dirac (1902-1984) both worked on explaining the spin of subatomic particles, and how it affected their interactions, and also the overall effect on a closed system. They treated the particles as waves, and used some pretty advanced math that we cannot understand to arrive at ways of differentiating between particles that have whole integer spins (Bosons) and those that have half-integer spins (Fermions).

Although working independently, they both correctly arrived at the math needed to explain this, and that field was later christened Fermi-Dirac statistics (Fermi published first, so his name comes first). Their work solved known problems, such as the

Enrico Fermi: "The architect of the nuclear age" mystery of why a heating element that was powered by a current seemed to use much less electrons to heat up than the amount of electrons supplied to it via the current. Until F-D statistics, it was thought that energy was transferred to all electrons inside the metal of the heating element equally, which should have resulted in all the electrons in the heating element giving out heat and that visible red glow that you see on a heating element. Thanks to F-D stats, we not only figured out that only a few electrons receive the energy from the current and are agitated and release heat and light, but also why.

That poor cat

We've mentioned particle duality before. It was always a pain for physicists, because almost all of the math was either done by either treating the subatomic stuff being calculated as waves or as particles. Take the electron for instance. When they were made to interact with other matter – smashed against a screen, or made to collide with other particles, they behaved like particles. However, as soon as they were left alone, they travelled as waves. This was proven definitively much later, in 1961, when the double-slit experiment was done using electrons instead of light (photons).

This is where Erwin Schrödinger (1887-1961) came in. In 1926, he sat down and formulated what he called the wave equation (now called the Schrödinger Equation), which was able to explain both wave and particle duality of subatomic particles. Again, the math is too complex for us to understand, let alone explain, but this equation is considered to be the very foundation on which quantum mechanics is built.

Schrödinger; a theoretical physicist and killer of cats

When he used this function to derive the electron states of Hydrogen atoms (the simplest atom) he got many different shapes of the Hydrogen atom. His equation was later used to get the shapes of even more atoms later, and we finally understood how electrons existed around the nucleus of an atom as probability waves.

In order to explain this "probability wave", and the ability of subatomic particles to have multiple quantum states at once, in 1935

Schrödinger's cat was born. Schrödinger's cat is a thought experiment that involves locking a cat in a box with a vial of poisonous gas. Assuming that the vial has exactly a 50% chance of breaking and killing the cat, Schrödinger said that the cat was both alive and dead, and that only by looking were you forcing nature to make a choice and either do nothing, or to kill the cat. A classic case of "curiosity killed the cat" – except it's our curiosity, and not the cat's. A total assumption we're making is that Schrödinger was a dog person, based on how willing he was to sacrifice his hypothetical cat.

Anyone who isn't insane will tell you that this is obviously silly. It's not the act of looking that causes the cat to be alive or dead, and the cat will be alive or dead whether we look or don't. However, the illustration of the totally ridiculous claim is exactly what Schrödinger wanted to achieve, in order to show how different the quantum world is from the one we're used to.

If the cat is an electron, or another subatomic particle, it actually does behave that way. And there are hundreds and thousands of experiments that have been done to try and disprove this, but all have ended up proving quantum theory correct.

The only real update to Schrödinger's equation was a correction of the interpretation. Whilst Schrödinger initially felt that the electron itself was becoming this, sort of, quantum foam, or like a quantum cloud which instantaneously recombined into a particle when we looked at it, it was Max Born who would raise the idea of this being a probability wave that the electron was travelling through. Thus, all those shapes that came out of Schrödinger's equation merely showed the areas where the electron would probably be found.

Heisenberg was very certain about his Uncertainty Principle

Uncertainty

In 1927 Werner Heisenberg released a paper that dealt with the precision of observing subatomic particles. Using complex mathematics he showed that the more precision with which you look to find out exactly where a particle (such as an electron) is the less you know about its momentum. And conversely, the more precise a measurement you make about its momentum, the less you know about it's position.

What's important to note here is that this isn't something that happens because our instruments are not good enough, or because of the observer effect – which states that the very act of observing a quantum particle changes it somehow. Heisenberg's uncertainty principle has now been proved to be the very nature of systems that have wave-like properties. Also, this is the case mathematically as well, so even just increasing levels of accuracy when calculating the position of something (without actually observing it), means that you get decreasing levels of momentum accuracy, even mathematically!

As you can tell, the 20s was where most of the action happened in quantum mechanics. What's more, if you've been paying attention to the dates of births that we've put into brackets after the first mention of each physicist's name, you might have noticed that many of them – Pauli, Heisenberg, Fermi, Bose, Dirac, Jordan, etc., were in their 20s, and Schrödinger was the old man at 36. All of this science was done by fresh young minds, and it must have been a very exciting time to be a young science researcher indeed!

Fast Forward

Catching up quickly to get to the end of the 20th century, some of the most notable events were as follows:

- 1930 - Paul Dirac publishes The Principles of Quantum Mechanics
- 1930 - Pauli suggests that there is an almost massless particle

called the “neutron” (which is later proven to be the neutrino, much later)

- 1931 - The first electron microscope is made by Ernst Ruska
- 1932 - James Chadwick experiments with alpha particles to produce radiation that others think are gamma rays, but actually turn out to be neutrons (as Fermi predicted, not Pauli’s neutrinos)
- 1933 - Fermi renames Pauli’s “neutron” to neutrino, so as to differentiate between the two
- Einstein-Podolsky-Rosen (EPR) write about quantum entanglement. Referring to the fact that particles can be entangled across large distances, Einstein famously called it “Spooky action at a distance”. This, he hoped, would be proof that quantum mechanics was in fact a flawed science and definitely more was needed.
- 1936 - Carl Anderson discovers muons – short lived leptons that have the same charge as an electron, but more mass.
- 1939 - Fermi and Leo Szilard discover the possibility of a chain reaction using Uranium that is bombarded with neutrons. (Precursor to the atomic bomb).
- 1942 - The first chain reaction is conducted under Fermi’s watch; it’s called the Chicago Pile-1
- 1945 - Under Robert Oppenheimer, the Manhattan project produces the first nuclear fission explosion

John Stewart Bell: The man who proved Einstein wrong!

- 1956 - The neutrino is finally experimentally discovered by Clyde Cowan and Frederick Reines.
- 1957 - Hugh Everett comes up with the many worlds hypothesis that assumes quantum superposition to conclude that every possibility of an outcome does happen in parallel universes.
- 1961 - Clauss Jönsson uses electrons to do the double-slit experiment and prove that electrons do indeed have both particle and wave properties.
- 1964 - Murray Gell-Mann and George Zweig both put forward the quark model for hadrons, and predict up, down, and strange quarks. Gell-Mann is credited with coining the term quark, which he found in James Joyce's book Finnegans Wake.
- 1964 - Amongst many others, Peter Higgs proposes a new quantum field that we now know as the Higgs Field. This Higgs Field imparts mass to all subatomic particles that interfere with it.
- 1964 - John Stewart Bell releases a paper that contains Bell's theory, which mathematically proves the Einstein-Podolsky-Rosen paradox to be false. Thus, quantum entanglement was actually possible!
- 1982 - Alain Aspect does an experiment that proves the quantum entanglement hypothesis. ■

Current and future theories

So how do theoretical physicists explain all this weirdness? And what's in store for us in the future?

Now that we've covered everything that's led us up to this point, it's time to look at what's been happening over the last one or two decades. Remember, it's not like we understand these things very well ourselves, so apologies beforehand to physicists everywhere just in case we screw up while trying to oversimplify everything.

Instead of giving you just the technical details or the trivia bits of what people are working on when it comes to quantum mechanics, we're going to break this chapter up into individual futuristic or science-fiction technologies, and then look at the work people are doing that very well might get us there.

Teleportation

"Beam me up Scotty!", says Captain Kirk in the original Star Trek series. Watching it at a time when even wireless communicators sounded like things from science fiction (yes, there was a time

Image Credit: CBS Photo Archive / Getty Images

Teleportation may never be this simple!

before mobile phones!), this writer had his mind blown the first time he saw someone on Star Trek teleport.

What made it an even bigger deal at the time was the fact that air travel wasn't as common as it is today, and most people watching that show had never been up in a plane. The idea of just turning into energy and then appearing somewhere else instantly was everyone's dream come true. Even today, 50 years (September 8, 1966) after the series first aired on American TV (and between 20 and 30 years after it aired in India), all of us would love to be able to teleport instead of travel through crowded airports.

Now if you thought teleportation is a pipe dream, think again, because quantum mechanics says it should, in theory, be possible. Because of quantum coupling and quantum entanglement – which we have already done experiments for and shown to be true – the idea is that we should be able to use containers of quantum-coupled subatomic particles that are separated over large distances, and make changes to one container and have those changes reflected in the second container.

This isn't theory anymore, it's already been done!

Back in 1998, a team led by Anton Zeilinger successfully achieved quantum teleportation. Many others, including Zeilinger's team have kept breaking the distance record since then, and the current holders are Zeilinger's team with a distance of 143 km. Based in the Canary

Islands off the west coast of Africa, the researchers have managed to send a qubit across.

Technically, this isn't transportation via teleportation, because a new version of the original is being created at the receiver's end, so in essence, a teleportation device would destroy this version of you and create a new you somewhere else, but then again, it might still be less painful and more desireable than enduring cramped seats with no space to put your legs, eating terrible food and breathing recycled air for hours on end!

Warp speed ahead!

Now we are certainly jumping way ahead of ourselves here, but who's to say 143 km can't become 143 light years away? Even imagining a much, much shorter trip to, say Mars, or Europa, or to our closest star systems (about 5 light years away) could potentially make quantum coupling and quantum entanglement the most important discoveries of all time!

Technically this is still quantum teleportation (which isn't teleportation at all), but when you do it instantaneously over very large distances, and faster than light can travel, then it appears that we might have found a loophole in Einstein's strict law that nothing can travel faster than the speed of light.

The problem? So far we haven't been able to create a system that doesn't have to first communicate and do a setup between the two points. Thus, if you setup a receiver station at a star 10 light years away, you're going to have to send equipment there at under light speed, you're going to have to communicate at under light speed, and finally, the quantum coupled "stuff" that's used to "teleport" things will have to be separated from one another and sent from point A to B at slower than light speed.

All this makes you wonder if quantum coupling and entanglement is even capable of propagating faster than light at all... though apparently, it is.

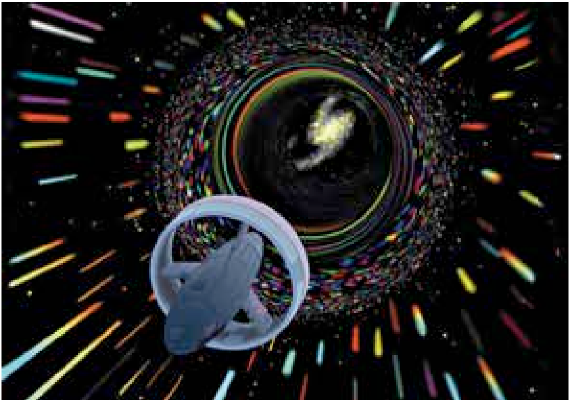
The results of an experiment conducted in China in 2013 are available here:

http://arxiv.org/pdf/1303.0614v1.pdf

The attempt was to try and find the speed of this "spooky action at a distance", and the researchers claim it was calculated to be over 100,000 times the speed of light!

However, is this even "communication"? Now that's where this all becomes tricky. Assume particle A and B are entangled, and separated by a distance that isn't important right now. Quantum mechanics says that both the particles are entangled to, say, have the same spin. Thus, you have a 1 or 0 available. Communication at faster than light could be achieved in the following way:

You send one particle on a robot ship at the speed of light (not faster) to a star 10 light years away. You have decided before hand



Faster than light travel using a wormhole

that if the ship finds rocky planets with water on them orbiting the star it should read it's particle and make it into a 1. Thus, when you read the particle back here on earth after 10 years, you know that if it's a 1, there is a planet worth investigating there. Now that message should have taken 10 years at the speed of light, but you got it instantaneously, so you have communicated faster than light.

This is where the error is made. Since neither particles (the one here on Earth and the one on the ship) have been read, we don't know whether they are 1s or 0s. Assuming we could read them without changing their state, we still can't "write" information to any of them, because doing so would break the entanglement. Although you can know (by reading your particle) whether the particle that's 10 light years away is a 1 or a 0, there is no way of knowing whether the particle is still entangled, and certainly no way of transmitting a message in the way we've detailed before. This is still debated though, and physicists are trying to find inventive ways in which to use quantum coupling / entanglement to communicate faster than light. We certainly hope they succeed.

Quantum computing

Would you like to have a computer that's smaller than your cell-phone but more powerful than all of the computers in the world put together? Would you rush to play your favourite game on it just to see how many FPS that baby can spit out? Join the club.

The major difference between a quantum computer and a regular computer is the way they process data. A regular computer, as we all know, uses bits. Data is written, stored and processed as either a 1 or a 0. Each transistor on a CPU can be either a 1 or a 0, and thus, if you take an example of a 4-bit data set, it's basically $2^4 = 16$ possible configurations of numbers:

```
0000 0001 0010 0011
0100 0101 0110 0111
1000 1001 1010 1011
1100 1101 1110 1111
```

A classical 4-bit computer can only have one of the above 16 values at a time.

With a quantum computer, using qubits (quantum bits), the number of values that you can represent with 4-qubits is all of the above 16 values at once. This only scales exponentially when you add on bits (or qubits for quantum computers).

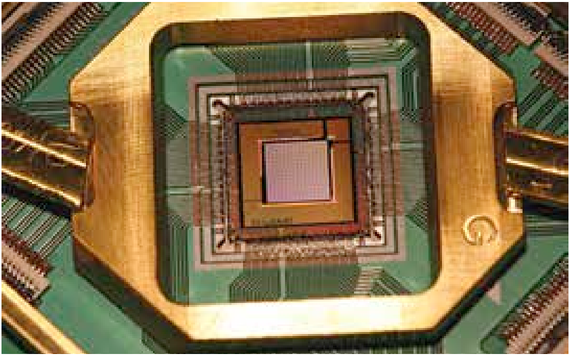


Image Credit: Courtesy of D-Wave Systems Inc.

The D-Wave quantum computer

When you add in the ability of quantum entanglement, which is basically the ability for qubits to be entangled with other qubits, you can see how all a processor would need to do would be read the first in the series of entangled qubits, and it would immediately know what the other values were. When you think of this as networking across large distances, you can see the promise that such a quantum network would have. Think very low bandwidth infrastructure transmitting data at the rate of a very fat pipe, or just exponentially increasing networking speeds.

The industry that will be hurt the most by quantum computing? Obviously the security industry. All of the public-key-private-key authentication methods that we have currently would be rendered useless if hackers got themselves a quantum computer – even a very basic one. It would take decades for traditional computers to compute your private key from your public key, because they have to do the operation sequentially – try one answer after the other. Quantum computers could do what traditional supercomputers do, but in a fraction of the time, because they can try many (or even all) the possibilities at once to see which one works and outputs a proper answer. Banks would be the first obvious target for anyone with a quantum computer and the will to use it...

Edward Snowden's leaks also showed that the US government was already funding research into quantum computers and quantum computing methods to try and bypass vulnerable security methods. Now we're not usually the type to wear tin foil hats in fear of big brother, but even we know that it's only a matter of time before there's just no privacy anymore anyway...

Without doubt, though, there are fields that needs quantum computing as soon as possible. DIsease research, and genome mapping are medical fields that are dying to get their hands on more computing powers. Research into cures for diseases such as AIDS or even Alzheimer's would greatly benefit from this, as would all genetic research.

Another field that would benefit from a quantum computer is, ironically, quantum mechanics. With so much math and so many possible outcomes, a quantum computer is actually ideal to help a quantum physicist search for answers. Though that very well might become a chicken and egg scenario.

Also, almost all advanced physics and chemistry could use more computing power. Cancer research, SETI, anything on folding@ home, you name it...

Quantum Cryptography

As we mentioned with quantum computers, the current system of security will be way too easy to crack. Thus, the need for a new system would arise in a world that has true quantum computers.

Well, you obviously need to fight quantum with quantum, and that's where quantum cryptography comes in.

Using the nature of quantum mechanics, where the very nature of reading a quantum key would forever alter it, you could (in theory) come up with pretty much unbreakable security. You could prevent copying of data very easily, because the act of copying would destroy the data itself. Reading might be easier, but then data could be encrypted with quantum keys.

The idea of quantum key distribution is that when communication is happening between A and B, even if a third party, C is listening in to the conversation, moving to a quantum key secured mode would immediately secure the conversation, and if C tried to read the key or access the conversation, the key itself would change, and thus A and B would immediately know that someone was listening in. This is how it would work in theory at least.

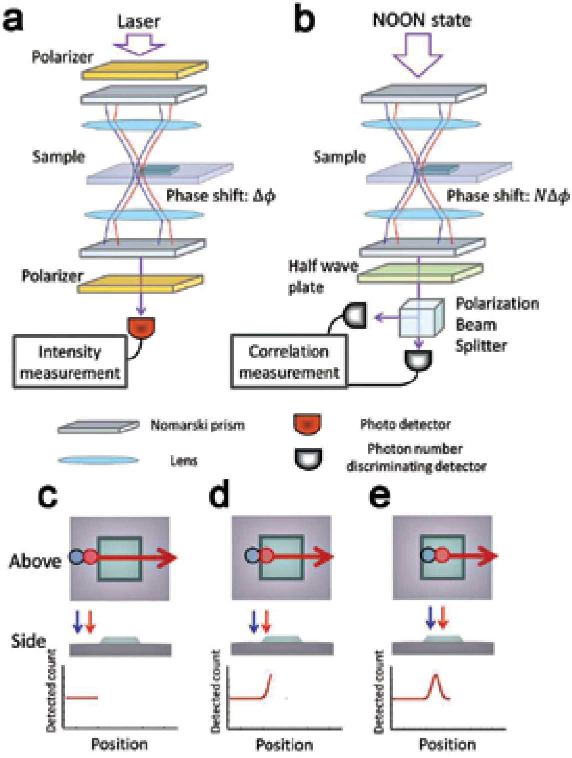
The brilliance of quantum key distribution is that it ensures secure conversations (data transfer, actual conversations, whatever), because there is no way for someone to eavesdrop without the conversing parties knowing, or the data itself being destroyed (and thus the conversing parties knowing when they get gibberish instead of the data they were expecting.). It's also foolproof against quantum computers, because there would be no "guessing" or cracking of codes involved. The encryption and key are secured by physical properties of quantum states, not software encryption.

This is all theory, obviously, because we are assuming that A and B would be able to identify one another, and that C wouldn't be able to impersonate either one. All this security is kind of useless if you left your quantum laptop lying on a park bench and it got stolen while you were distracted, for example.

Quantum Dots

A quantum dot is basically a very small particle that's made up of only very few atoms, or possibly is an artificial atom that contains electrons that are squeezed into a much tighter shell than in a regular atom. The advantage of this is obvious when you're thinking about solar power and efficiency. Imagine a photon entering a quantum dot – it's bound to interact with more than one of the tightly packed electrons. This would yield more energy per photon, and obviously increase the efficiency of solar panels made up of quantum dots.

That's not all, because of the way the electrons are packed tightly, it's possible to engineer them to react with light (photons) of different wavelengths. Thus, you could have a solar panel made up of many different kinds of quantum dots that would extract more energy across a broader spectrum of wavelengths. Either



How the entanglement-enhanced microscope works way, this ends up building way more efficient solar panels, and could solve the world's power problems.

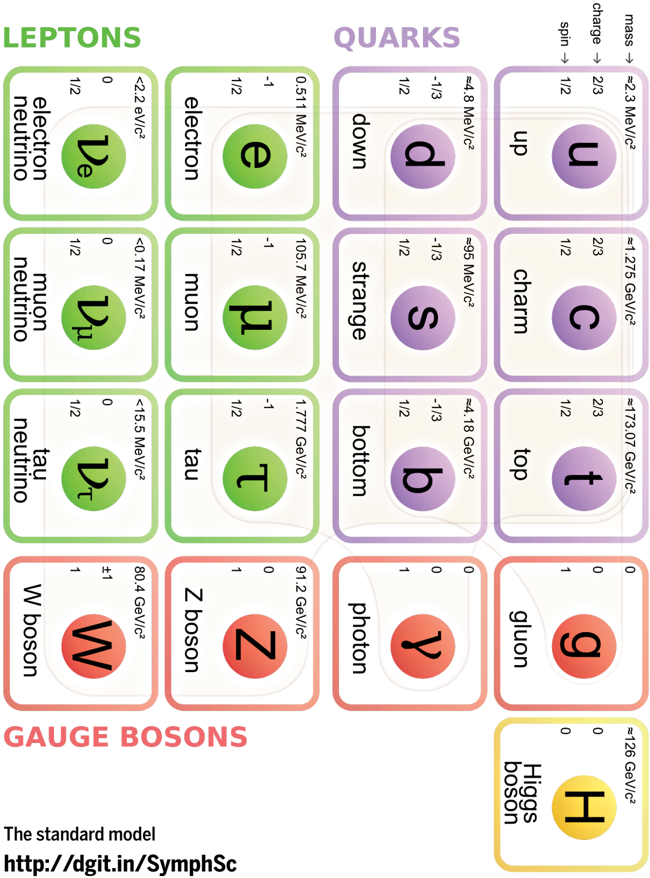
Microscopes

It's important to be able to see smaller and smaller things, and researchers in Japan built a quantum-entanglement-enhanced microscope. What this microscope does is fire two beams of entangled photons at the surface it's viewing, and then measures the patterns of interference of the photons when they bounce back off the surface. Because the photons are entangled, measuring one gives you information about the other.

The researchers in Japan were able to image an engraving that was a mere 17 nanometers higher than the background – which is a tremendous feat in itself!

The end!

As it stands, we already owe almost all the technology we already take for granted to the field of quantum mechanics, and it seems pretty obvious that our future is pretty entangled (pun intended) with the quantum world. Exciting times await, and if you're a student, we hope you can jump into the quantum world and achieve something so that our next book on quantum physics can feature you! ■



The standard model

http://dgit.in/SymphSc