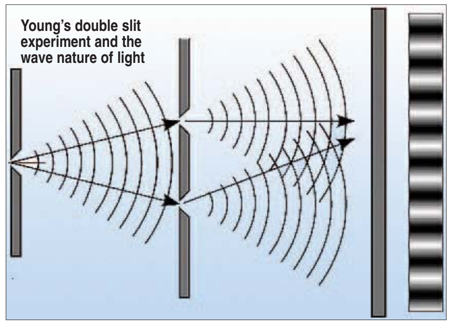
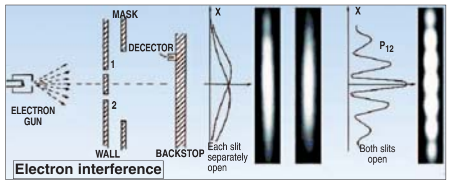
Thought experiment done for real

Richard Feynman's imaginary teaching example has been made to work in the lab, says
s ananthanarayanan





NOBEL laureate Richard P Feynman is the legendary physics expositor who created more committed physicists, professional or amateur perhaps, than his great contribution to physics itself. He is renowned for his maverick, informal but direct teaching methods and is celebrated for the third volume, *Feynman Lectures on Physics*, the record of the undergraduate course that he taught at the Massachusetts Institute of Technology in the 1960s. A celebrated "thought experiment" he used to introduce quantum mechanics, an experiment so called because it could happen only in the mind, has been practically carried out, report Roger Bach, Damian Pope, Sy-Hwang Liou and Herman Batelaan at the University of Nebraska-Lincoln, USA, and at Waterloo, Ontario, Canada, in *The New Journal of Physics*.

Light was first conceived as consisting of a shower of particles, or *corpuscles*, as early scientists, including Sir Isaac Newton, called them. Later studies showed this was not true and at the scale of very small distances "light did not throw sharp shadows" but behaved like a wave. A celebrated experiment with light waves was to pass a beam through a pair of slits, set close together, and on to a screen at some distance. Light that came straight along the centre-line travelled the same distance from either slit and shone brightly on the screen. But at distances off the centre, the light wave from one slit could be a half wavelength further off than light from the other slit, and the "crest" of one wave would clash with the "trough" of the other, to use an analogy of waves in water, and there would be a dark band. A little further away, the path difference would be a whole wavelength and the waves again would create a bright image. And in this way, there would be a pattern of *fringes* on the screen, rather than a single bright line. It was this experiment, among other evidence, that established light as consisting of waves, later shown to be electromagnetic waves.

And then, in the early 20th century, while studying the way a warm object radiated heat at different frequencies, it became necessary again to correct course, as light, for all its qualities of a wave, was found to consist of *lumps*, or *quanta*, which is to say *particles* called *photons*. That energy was carried by light only in discrete packets, the higher the energy of the packet, the higher the frequency, was soon firmly established and proved by the *photo-electric effect*, where the electrical effects of light packets were found to depend on their frequency.

In the meantime, another conjecture was that where waves could show particle behaviour, particles should act like waves, too, the greater their momentum, the greater the frequency of the wave. This was also experimentally realised in experiments showing that a stream of electrons, which were quintessential particles, could form patterns when scattered, just like X-rays passing through a piece of crystal. These were ways of nature's behaviour that were non-intuitive and with no analogy in experience.

The concept of energy states in finite steps that transitions between which led to the emission of light of given frequencies were successful in explaining the structure of the atom and much behaviour of matter at the very small scale. An elegant mathematical system, based on established classical laws of motion and incorporating the particle properties of waves and vice-versa, was developed and became incredibly successful in working with matter at the atomic and subatomic level. The concept of the exact location or exact energy of a particle had to be given up, for a certain fuzziness of position and inherent uncertainty of all measurement. A state of a system was seen as endowed with simultaneous potential for all possible values of its parameters, some values being more probable, in the event of measurement, the probability changing when the dimensions of the system were large, into the certainty that we find in the familiar world. But at the elementary level, it was an unreal, particle-wave sceptre that throws the dice that decides the outcome of interactions.

Feynman lectures

To introduce the fascinating but unfamiliar world of how systems actually worked, before they averaged out to the familiar laws of motion, Feynman created his classic example of the two-slit experiment conducted with electrons in place of light. When conducted with ordinary light, a pair of slits a millimetre apart can create fringes that can be made out with a microscope at a distance of about a metre. But the effective wavelength of particles with the mass of electrons is so many thousands of times smaller than that of light, so that Feynam's experiment would need slits placed really close together, as also a detector at a very fine scale to make out any fringes. Feynman, hence, made it clear that the experiment he proposed was in the mind only and was meant to explain the way matter behaved, as learnt during the first half of the 20th century.

The experiment was first to shine ordinary light on the pair of slits and observe what happened when either slit was open and again when both were open. When any one slit was open, light shone on the screen intensely when directly before the slit, and falling off, in a bell shaped curve, as one moved away. Normally, hence, when both slits were open, the illumination should have been the addition of the effect of the slits by themselves. But as we know, this does not happen because of the wave nature of light and the effect is called *interference*.

Now, Feynman proposes the experiment using not light but a beam of electrons. Again, with only one of the two slits open, the distribution at the screen is like in the case of light. But when we consider the case with both slits open, we are now dealing with electrons, each of which is separate particle and would move only through one or the other of the two slits. In fact, if the source of electrons is made feeble enough, we can ensure that only one electron reaches the screen at any time, and as that electron has come through one of the two slits, the result of all the electrons should be no different from just the addition of the effect of each slit by itself. And yet, this is not what happens, the result is a pattern of fringes, just like in the case of light!

Feynman proposes that we could check up what was happening by keeping a watch on each electron to trace what slit it passed through. Now if the distribution of electrons reaching the screen is plotted, with the path of each electron identified, again the pattern is like the sum of the patterns of each slit by itself, there is no interference pattern. But stop watching the electrons, and the fringes reappear!

There is no intuitive explanation for what is going on. It would appear that the effect of each electron on the screen is the sum of the *probabilities* of the electron going through either slit. This is in keeping with the idea of the uncertainty of the location of the electron, at the scale of the experiment. When working with probabilities, with both slits open, there is interference outside the centre-line and hence the pattern of fringes. But when there is a measurement of which path the electron took, which limits the uncertainty of position, there is only one path and the interference of the probability of the other path vanishes. But stop making measurements and interference comes back.

This imaginary experiment demonstrates many mysterious aspects of the very small world. The quantum computer, for instance, uses components that can be in a large number of states at the same time. For example, the spin, up or down, of a pair of particles can be, both up, both down or up and down. Two such pairs can interact in 3x3=9 ways. A quantum computer would act in a manner analogous to the slits in the experiment when the electrons are not watched — and would evaluate all possibilities simultaneously. But such a computer is a delicate system and the slightest disturbance would throw each system into one of its possible states and only one combination would be evaluated. This would amount to the electron being "watched", typically by shining a light and a photon getting scattered by the electron.

Two slit in practice

The achievement of the Canada-USA scientists is to use modern technology to actually demonstrate Feynman's thought experiment. They used a 100-nanometre thin sheet of silicon nitride coated with a two-nanometre layer of gold. With a precise focused beam of ionised atoms, they cut slits that were 62 nanometres wide and 272 nanometres, or 272 millionths of a millimetre apart. The mask, used to block either of the slits, was a huge 4.5 thousandths of a millimetre wide and the arrangement was mounted on a sliding frame to perform the experiment. The image was magnified using a lens that consisted of electric fields and the detector was a state-of-the-art, *charge coupled device* camera.

The results of the experiment, when the mask was used and when it wasn't, were just as Feynman described. Not that there was any doubt, but here was modern nano-fabrication techniques giving shape to an image of unparalleled simplicity and technical rigour, that looks at electron diffraction "which has in it the heart of quantum mechanics" (to quote RP Feynman), with the insight that could come from none other than the master!

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So said Feynman

'THERE was a time when the newspapers said that only 12 men understood the theory of relativity. I do not believe there ever was such a time. There might have been a time when only one man did, because he was the only guy who caught on, before he wrote his paper. But after people read the paper, a lot of people understood the theory of relativity in some way or other, certainly more than 12. On the other hand, I think I can safely say that nobody understands quantum mechanics," said RP Feynman, in the course of his lecture on the double slit experiment.

Tempus fugit

tarun kumar maitra presents a spoof on the fine art of watchmaking

'DRAT! Another defective watch!" With a look of disgust, Tempus Fugit the watchmaker tossed the faulty timepiece into the wastebasket and grumbled to himself, "That's two out of the last three watches I've had to throw away. What kind of a watchmaker am I, anyway?"

"A good question, Fugit," came a voice from the doorway. Tempus looked up to see Caveat Emptor entering the shop. "Maybe I can help you with it if you'll tell me a bit about how you make your watches."

"Nobody asked for your help, Emptor," growled Tempus testily, wishing fervently he hadn't been caught thinking out loud.

"Ah, well, you'll get it just the same," continued Caveat, quite unperturbed. "Now tell me exactly how you make a watch and how long it takes you. I'd be especially interested in comparing your procedure with the way Pluribus Unum does it in his new shop down the street."

At the very mention of his competitor's name, Tempus groaned again. "Unum!" he blustered. "What does he know about the fine art of watchmaking?"

"A good deal, apparently — probably more than you do," replied Caveat. "But tell me exactly how you go about it. How many steps does it take you per watch, and how often do you make a mistake?"

"It takes exactly 100 operations to make a watch. Every step has to be done exactly right, or the watch won't work. It's tricky business, but I've got my error rate down to one per cent," said Tempus with at least a trace of pride in his voice. "I can make a watch from start to finish in exactly one hour, but I only make 36 watches each week because I always take Tuesday afternoons off to play darts."

"Well now, let's see," said Caveat, as he pulled out a pocket calculator. "That means, my good Mr Fugit, that you only make about 13 watches per week that actually work. All the rest you have to throw away just like the one you pitched out as I entered your shop."

"How did you know that, you busybody?" Tempus asked defensively, wondering how this know-it-all with his calculator had guessed his carefully kept secret.

"Elementary," returned Caveat gleefully. "Simple probability is all it takes. You told me that each watch requires 100 operations and that there's a 99 per cent chance that you'll get a given step right. That's 0.99 times itself 100 times, which comes out to 0.366. So only about 37 per cent of your watches will be put together right, and you can't even tell anything about a given watch until it's finished and you test it. Want to know how that compares with Unum's shop?"

Tempus was about to protest but his tormentor hurried on with scarcely a pause for breath. "He can manage 100 operations per hour too, and his error rate is exactly the same as yours. He's also off every Tuesday afternoon, but he gets about 27 watches made every week. That's twice your output, Fugit! No wonder he's got so many watches in his window and so many customers at his door. I've heard that he's even thinking of expanding his shop. Want to know how he does it?"

Tempus was too depressed to even attempt a protest. And besides, although he wouldn't like to admit it, he really was dying to know how Unum managed it.

"Subunit assembly, Fugit, that's the answer! Subunit assembly! Instead of making each watch from scratch in 100 separate steps, Unum assembles the components into 10 pieces, each requiring 10 steps." Caveat began pushing calculator buttons again. "Let's see, he performs 10 operations with a 99 per cent success rate for each, so I take 0.99 to the 10th power instead of the 100th. That's 0.904, which means that about 90 per cent of his subunits have no errors in them. So he spends about 33 hours each week making 330 subunits, throws the defective ones away, and still has about 300 to assemble into 30 watches during the last three hours on Friday afternoon. That takes 10 steps per watch, with the same error rate as before, so again he comes up with about 90 per cent success. He has to throw away about three of his finished watches and ends up with about 27 watches to show for his efforts. Meanwhile, you've been working just as hard and just as accurately, yet you only make half as many watches. What do you have to say to that, my dear Fugit?"

Tempus managed a weary response. "Just one question, Emptor, and I'll probably hate myself for asking. But do you happen to know what Unum does on Tuesday afternoons?"

"I'm glad you asked," replied Caveat as he slipped his calculator back into his pocket and headed for the door. "But I don't think you'll be able to interest him in darts — he spends every Tuesday afternoon giving watchmaking lessons."

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Much older than previously thought

steve connor delves into the portents of a map of the 'old light' in the universe

WHAT you see is a picture of the most accurate and detailed map of the oldest light in the universe. The radiation originally formed about 380,000 years after the Big Bang, when all matter was created some 13.82 billion years ago. Scientists call this radiation "the cosmic microwave background" because it pervades all corners of space – providing a universal backdrop – due to the fact that it was formed so soon after the event that led to an ever-expanding universe.

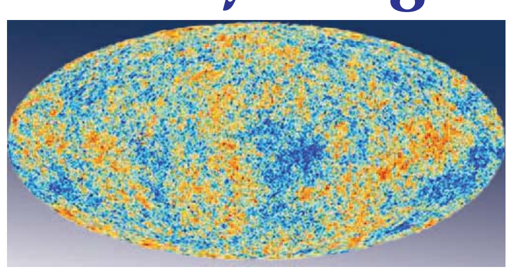
The image is the culmination of nearly 16 months of work on data gathered by the European Space Agency's Planck space telescope, a satellite launched in 2009 that has been collecting the very slight temperature fluctuations in what has become known as the relic radiation of the Big Bang.

Scientists said the data indicates that the universe is expanding at a slightly slower rate than previously believed, making it somewhat older than the 13.7 billion years formerly given for the age of the universe.

Differences in the colours of the map represent tiny variations in the temperature of the microwave background radiation, an extremely cold remnant of the Big Bang set at about 2.7° above absolute zero (-273°Celsius).

These temperature variations correspond to regions of slightly different densities in the very earliest stages of the universe when everything was a smooth soup of subatomic particles. These ripples represent the initial clumping together of matter to form the "seeds" of future stars and galaxies. "This is the best ever baby picture of the universe. It represents the moment when it was very young," said Mark Ashdown, a Planck scientist at the University of Cambridge.

At this early point in time, the universe was filled with a hot, dense soup of protons, electrons and photons that were interacting at temperatures of about 2,700° Celsius. When the protons and electrons joined together to form hydrogen atoms, light was set free. This light



became stretched out to microwave wavelengths as the universe went through a rapid phase of expansion. The fluctuations in temperature and density of this microwave radiation reflect what happened within the first fractions of second after the Big Bang.

"The sizes of these tiny ripples hold the key to what happened in that first trillionth of a trillionth of a second. Planck has given us striking new evidence that indicates they were created during the incredibly fast expansion just after the Big Bang," said Joanna Dunkley of Oxford University.

Scientists have peeled away the layers of light and radiation that separates us from this relic of the Big Bang, revealing a picture of an early universe that conforms remarkably well to the standard model of cosmology. "Since the release of Planck's first all-sky map image in 2010, we have been carefully extracting and analysing all the foreground emissions that lie between us and the Universe's first light, revealing the cosmic background in the greatest detail yet," said George Efstanthiou of Cambridge University.

Although the measurements made by Planck match the theoretical predictions of what the universe should look like, there are some important differences, such as a notable asymmetry between the opposite hemispheres of the sky and a "cold spot" that extends over a much larger patch of the sky than expected. "The fact that Planck has made such a significant detection of these anomalies erases any doubts about their reality; it can no longer be said that they are artefacts of the measurements. They are real and we have to look for a credible explanation," said Paolo Natoli of Ferrara University in Italy.

Jan Tauber, Planck's project scientist based in the Netherlands, added, "On the one hand we have a simple model that fits our observations extremely well, but on the other hand we see some strange features which force us to rethink some of our basic assumptions."

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