# 50 quantum physics ideas

## you really need to know

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# Introduction

The story of quantum physics has as many twists and turns as it has strange phenomena. A stream of vivid characters – from Albert Einstein to Richard Feynman – have puzzled over the interiors of atoms and the nature of forces over the past century. But physics has trumped even their wild imaginations.

The quantum world runs according to the physics of the very small. But subatomic goings-on are hardly clockwork, and are often baffling. Elementary particles pop in and out of existence and once-familiar substances like light seem impossible to pin down, behaving like waves on one day and a stream of bullets the next.

The more we have learned, the stranger the quantum universe has become. Information can be 'entangled' between particles, raising the possibility that everything is connected by invisible threads. Quantum messages are transmitted and received instantaneously, breaking a taboo that no signal can exceed light speed.

Quantum physics is not intuitive – the subatomic world behaves quite differently from the classical world that we are familiar with. The best way to understand it is to follow the path of its development, and to grapple with the same puzzles that the pioneers of the theory wrestled with.

The first chapters summarize how the field emerged at the dawn of the twentieth century, when physicists were starting to dissect the atom and comprehend the nature of light. Max Planck introduced the term 'quanta', arguing that energy came in small packets rather than a continuum. The idea was applied to the structure of the atom, where electrons orbited a compact nucleus in shells.

Out of that work grew quantum mechanics, with all its paradoxes. As particle physics gathered pace, quantum field theories and the standard model emerged to explain it. Finally the book explores some of the implications – for quantum cosmology and concepts of reality – and highlights recent technological developments, such as quantum ‘dots’ and quantum computing.

# 01 Energy conservation

**Energy powers movement and change. It is a shape shifter that takes many forms, from heat given off in burning wood to the speed gained by water flowing downhill. It may swap from one type to another. But energy is never created or destroyed. It is always conserved overall.**

The idea of energy as the cause of transformations was familiar to the ancient Greeks – *energeia* means activity in Greek. We know that its magnitude scales with the force we apply and the distance by which an object subjected to it shifts. But energy is still a slippery concept for scientists. It was in investigating the nature of energy that the ideas of quantum physics originated.

When we push a supermarket trolley, it rolls along because we are giving it energy. The trolley is being powered by the chemicals combusted in our bodies, transmitted by the force of our muscles. When we throw a ball we also convert chemical energy into motion. The Sun's heat comes from nuclear fusion, where atomic nuclei are crushed together, and give out energy in the process.

Energy appears in many guises: from speeding bullets to lightning strikes. But its origin can always be traced back to another kind. Gunpowder created the bang of the gun. Molecular motions stirred up the static electricity in a cloud that was released in the vast spark. When energy changes from one type to another it makes matter move or change.

Because it simply changes form, energy is never created or destroyed. It is conserved: the total amount of energy in the universe, or any completely isolated system, stays the same.

**‘It is just a strange fact that we can calculate some number and when we finish watching nature go through**

**her tricks and calculate the number again, it is the same.’**

Richard Feynman, *The Feynman Lectures on Physics* **(1961)**

**Conservation** In ancient Greece, Aristotle was the first to realize that energy seemed to be conserved, although he had no means of proving it. It took centuries for early scientists (then known as natural philosophers) to understand the different forms of energy individually, and then to link them together.

Galileo Galilei experimented in the early 17th century with a swinging pendulum. He noticed that there was a balance between how fast the bob moved in the centre of its swing and how high it climbed at the end. The higher the bob was released, the faster it swung in between, rising to around the same height at the end. Over the full cycle, energy was being exchanged from ‘gravitational potential’ (associated with height above the ground) to ‘kinetic’ (speed) energy.

The 17th-century mathematician Gottfried Leibniz referred to energy as ‘vis viva’, or life force. The physicist polymath Thomas Young introduced the word energy in the sense we use now in the early 19th century. But exactly what energy is has remained elusive.

Although it acts on vast bodies, from a star to even the whole universe, in its essence energy is a small-scale phenomenon. Chemical energy arises as atoms and molecules rearrange their structures during reactions. Light and other forms of electromagnetic energy are transmitted as waves, which interact with atoms. Heat reflects molecular vibrations. A compressed steel spring withholds elastic energy within its structure.

Energy is intimately tied to the nature of matter itself. Albert Einstein in 1905 revealed that mass and energy are equivalent. His famous $E = mc^2$ equation states that the energy ($E$) released by the destruction of a mass ($m$) is m times the speed of light ($c$) squared. Because light travels at 300 million metres per second (in empty space), crushing even a few atoms releases an enormous quantity of energy. Our Sun and nuclear power stations release energy in this way.

**Other rules** Properties linked to energy can also be conserved. Momentum is one. Linear momentum, the product of mass and velocity, is a measure of how hard it is to slow down a moving body. A heavy supermarket trolley has more momentum than an empty one, and is difficult to stop. Momentum has a direction as well as a size, and both aspects are conserved together. This is put to good effect in snooker – if you hit a stationary ball with a moving one, the final paths of both will sum to give the velocity and direction of the first moving ball.

Momentum is also conserved for rotating objects. For an object spinning about a point, angular momentum is defined as the product of the object's linear momentum and its distance from the point. Ice skaters conserve angular momentum when they spin. They whirl slowly when their arms and legs are outstretched; they speed up by pulling their limbs in to their body.

Another rule is that heat always spreads from hot to cold bodies. This is the second law of thermodynamics. Heat is a measure of atomic vibration, so atoms jiggle more and are more disordered within hot bodies than in cooler ones. Physicists call the amount of disorder, or randomness, 'entropy'. The second law states that entropy always increases, for any closed system with no external influences.

How do refrigerators work then? The answer is that they create heat as a byproduct – as you can feel if you put your hand near the back. Fridges don't bust the second law of thermodynamics but work with it, creating more entropy by warming the air than they extract for cooling. On average, taking both the fridge and air molecules into account, entropy increases.

Many inventors and physicists have tried to think of ways of confounding the second law, but none has succeeded. Schemes for perpetual-motion machines have been dreamt up, from a cup that drains and refills itself to a wheel that propels its own rotation by dropping weights along spokes. But when you look closely at their workings they all leak energy – to heat or noise, say.

The Scottish physicist James Clerk Maxwell in the 1860s devised a thought experiment that could create heat without a rise in entropy – although it has never been made to work without an external power source. Maxwell imagined two adjoining boxes of gas, both at the same temperature, linked by a small hole. If one side is warmed, the particles in that side move faster. Normally, a few of them would pass through the hole into the other side, gradually evening out the temperature.

But Maxwell imagined that the reverse could be possible – by some mechanism, which he pictured as a tiny demon or devil that sorted the molecules (known as 'Maxwell's demon'). If such a mechanism could be devised, it could shift fast molecules from the colder side into the hotter box, violating the second law of thermodynamics. No means of doing this has ever been discovered, so the second law prevails.

Ideas and rules about how to move and share energy around, coupled with increasing knowledge of atomic structure, led to the birth of quantum physics in the early 20th century.

## the condensed idea

## Shape-shifting energy

## timeline

| | |
|---|---|
| ***c.* 600 BC** | Thales of Miletus recognizes that materials change form |
| **AD 1638** | Galileo notes energy exchange in a pendulum |
| **1676** | Leibniz names energy *vis viva* |
| **1807** | Young names 'energy' |

| | |
|---|---|
| **1850** | Rudolf Clausius defines entropy and the second law |
| **1860** | Maxwell postulates his demon |
| **1901** | Max Planck describes energy ‘quanta’ |
| **1905** | Einstein shows that mass and energy are equivalent |

# 02 Planck’s law

**By solving the problem of why coals glow red and not blue, the German physicist Max Planck started a revolution that led to the birth of quantum physics. Seeking to describe both light and heat in his equations, he apportioned energy into small packets, or quanta, and in the process explained why so little ultraviolet light is given off by hot bodies.**

It’s winter and you’re cold. You imagine the cosy glow of a roaring fire – the red coals and the yellow flames. But why do coals glow red? Why does the tip of an iron poker placed within the fire also become red-hot?

Burning coals reach hundreds of degrees Celsius. Volcanic lava is hotter, approaching 1,000°C. Molten lava glows more fiercely and can appear orange or yellow, as does molten steel at the same temperature. Tungsten light-bulb filaments are even hotter. With temperatures of thousands of degrees Celsius, similar to the surface of a star, they shine white.

**Black-body radiation** Bodies give off light at progressively higher frequencies as they are heated. Especially for dark materials such as coal and iron – which are efficient at absorbing and giving off heat – the spread of frequencies radiated at a particular temperature has a similar form, known as ‘black-body radiation’.

Most light energy radiates around one ‘peak’ frequency, which scales with temperature from red towards blue. Energy also leaks out to either side, rising in strength towards the peak at low frequencies, and declining above it. The result is an asymmetric ‘hill’-shaped spectrum, known as a ‘black-body curve’.

### Colour temperature

The colour of a star gives away its temperature. The Sun, at 6,000 kelvins, appears yellow, while the cooler surface of the red giant Betelgeuse (in the constellation Orion) has a temperature of half that. The scorching surface of Sirius, the brightest star in the sky, which shines blue-white, reaches 30,000 kelvins.

A glowing coal might put out most of its light in the orange range, but it also gives off a little low-frequency red and some higher-frequency yellow, but barely any blue. Hotter molten steel shifts this pattern up in frequency, to emit mostly yellow light, with some orange-red and a touch of green.

**The ultraviolet catastrophe** By the late 19th century, physicists knew of black-body radiation and had measured its frequency pattern. But they could not explain it. Different theories could describe part of the behaviour but not all of it. Wilhelm Wien concocted an equation that predicted the rapid dimming at blue frequencies. Meanwhile, Lord Rayleigh and James Jeans explained the rising red spectrum. But neither formula could describe both ends.

Rayleigh and Jeans’s rising spectrum solution was particularly problematic. Without a means of curtailing its growth, their theory predicted an infinite release of energy at ultraviolet and shorter wavelengths. This problem was known as the ‘ultraviolet catastrophe’.

The solution came from the German physicist Max Planck, who was trying to unify the physics of heat and light at the time. Planck liked to think mathematically and to tackle physics problems from scratch, starting from the basics. Fascinated by the fundamental laws of physics, notably the second law of thermodynamics and Maxwell’s equations of electromagnetism, he set about proving how they were linked.

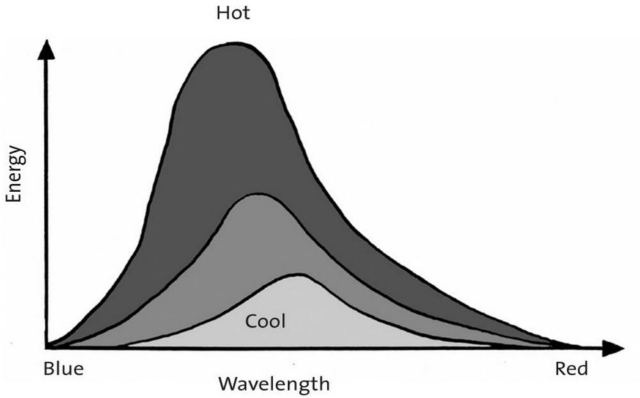
### Max Planck (1858–1947)

At school in Munich, Germany, Max Planck's first love was music. When he asked a musician where he should go to study it he was told he'd better do something else if he had to ask that question. He turned to physics, but his professor complained that physics was a complete science: nothing more could be learned. Fortunately, Planck ignored him and went on to develop the concept of quanta. Planck endured the deaths of his wife and two sons killed in the world wars. Remaining in Germany, he was able to rebuild physics research there in the aftermath. Today, Germany's prestigious Max Planck research institutes are named after him.

**Quanta** Planck faithfully manipulated his equations, without worrying about what those steps might mean in real life. To make the mathematics easier to work with, he devised a clever trick. Part of the problem was that electromagnetism is described in terms of waves. Temperature on the other hand is a statistical phenomenon, with heat energy shared out among many atoms or molecules. So Planck decided to treat electromagnetism in the same way as thermodynamics. In place of atoms, he envisaged electromagnetic fields as being carried by tiny oscillators. Each one could take a certain amount of the electromagnetic energy, which was shared out among many of these elementary entities.

Planck scaled the energy of each oscillator with frequency, such that $E = h\nu$, where $E$ is energy, $\nu$, is light frequency, and $h$ is a constant factor now known as Planck's constant. These units of energy were called 'quanta', from the Latin for 'how much'.

In Planck's equations, quanta of high-frequency radiation have correspondingly high energies. Because the total amount of energy available is capped, there couldn’t be many high-energy quanta in the system. It’s a bit like economics. If you have $99 in your wallet, it’s likely that there are more bills of smaller denominations than large ones. You could have nine dollar bills, four or more ten-dollar bills but only one 50-dollar bill, if you’re lucky. Similarly, high-energy quanta are rare.



Black body curves

Planck worked out the most likely energy range for a set of electromagnetic quanta. On average, most of the energy was midway – explaining the peaked shape of the black-body spectrum. Planck published his law in 1901. It was received with great acclaim as it neatly solved the troublesome ‘ultraviolet catastrophe’ problem.

Planck’s concept of quanta was entirely theoretical – the oscillators weren’t necessarily real but were a useful mathematical construction to match the physics of waves and heat. But coming at the beginning of the 20th century, a time when our understanding of light and the atomic world was advancing rapidly, Planck's idea had implications beyond anything he imagined. It became the root of quantum theory.

**Planck's legacy in space** The most accurately known black-body spectrum comes from space. A faint microwave glow with a precise temperature of 2.73 K emanates from all directions in the sky. Its origin is in the very early universe, a hundred thousand years after the Big Bang when the first hydrogen atoms formed. Heat energy from that time has since cooled as the universe has expanded, and now peaks in the microwave part of the spectrum, following a black-body law. This cosmic microwave background radiation was detected in the 1960s but mapped in detail in the 1990s by NASA's COBE (COsmic Background Explorer) satellite. Europe's latest microwave background mission is named after Planck.

> **'Scientific discovery and scientific knowledge have been achieved only by those who have gone in pursuit of them without any practical purpose whatsoever in view.'**
>
> **Max Planck, 1959**

## the condensed idea

### Energy economics

## timeline

| | |
|---|---|
| **1860** | Term 'black body' used by Kirchhoff |
| **1896** | Wien presents his law of high-frequency radiation |
| **1900** | Rayleigh presents his law of ultraviolet catastrophe |

| | |
|---|---|
| **1901** | Planck publishes law of black-body radiation |
| **1905** | Einstein identifies the photon and disproves ultraviolet catastrophe |
| **1918** | Max Planck receives Nobel Prize |
| **1994** | COBE team publishes black-body spectrum of cosmic microwave background (CMB) |
| **2009** | Planck spacecraft launched |

# 03 Electromagnetism

**Light is an electromagnetic wave. Extending beyond the familiar spectrum of visible light, electromagnetic disturbances range from radio to gamma rays. Now understood as one phenomenon that unites electricity and magnetism, electromagnetism is one of four fundamental forces. Its essence has been the stimulus for both relativity and quantum physics.**

We take light for granted, but there is a lot that we don’t understand about it. We see shadows and reflections – it doesn’t pass through or bounces off opaque or shiny materials. And we know it breaks up into the familiar rainbow spectrum when it passes through glass or raindrops. But what is light really?

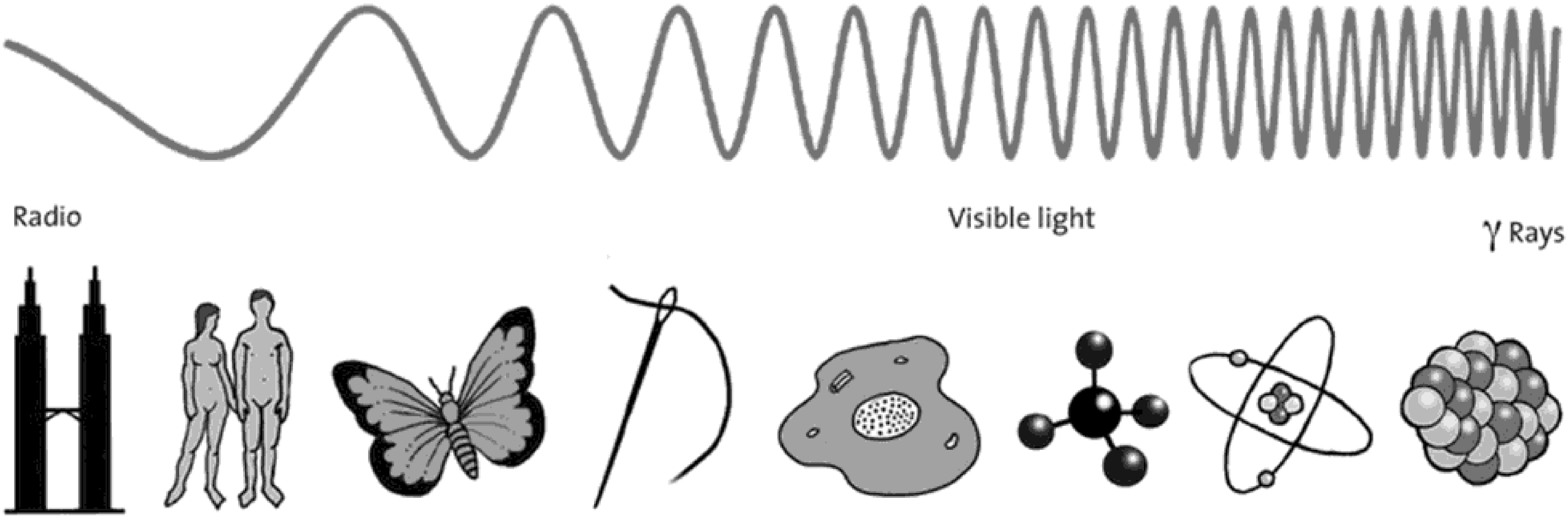
Many scientists have tried to answer that question. Isaac Newton showed in the 17th century that each hue of the rainbow – red, orange, yellow, green, blue, indigo, violet – is a fundamental ‘note’ of light. He mixed them together to produce intermediate shades, such as cyan, and recombined them all into white light, but he could not dissect the spectrum further with the equipment he had. Experimenting with his lenses and prisms, Newton found that light behaves like water waves – bending around obstacles and reinforcing or cancelling where waves overlap. He reasoned that light was made up, like water, of tiny particles, or ‘corpuscles’.

We now know that this is not strictly so. Light is an electromagnetic wave, made of oscillating electric and magnetic fields coupled together. But there is more to the tale. In the early 1900s Albert Einstein showed that there are situations where light does behave like a stream of particles, now called photons, which carry energy but have no mass. The nature of light remains a conundrum, and has been central to developments in relativity and quantum theory.

> **‘In order to understand the nature of things, men must begin by asking, not whether a thing is good or bad, noxious or beneficial, but of what kind it is?’**
>
> **James Clerk Maxwell, 1870**

**The spectrum** Each of light’s hues has a different wavelength, or spacing between adjacent wave crests. Blue light has a shorter wavelength than red; green lies in between. The frequency is the number of wave cycles (peaks or troughs) per second. When a beam of white light passes through a prism, the glass bends (refracts) each colour by a different angle, so that red bends least and blue most. As a result the colours spread out into a rainbow.

But the colours don’t end there. Visible light is just one part of the electromagnetic spectrum, which stretches from radio waves with wavelengths spanning kilometres to gamma rays with wavelengths much smaller than an atom. Visible light’s wavelength is around a billionth of a metre, close to the sizes of many molecules. Beyond red light wavelengths of millionths of a metre is infrared light. At millimetre to centimetre wavelengths we find microwaves. Short of violet light lie ultraviolet, X- and gamma (γ) rays.



Electromagnetic waves range in wavelength from thousands of metres to billionths of a metre.

**Maxwell’s equations** Electromagnetic waves combine electricity and

# Colours of the rainbow

## timeline

| | |
|---|---|
| **1600** | William Gilbert investigates electricity and magnetism |
| **1672** | Newton explains the rainbow |
| **1752** | Benjamin Franklin conducts experiments on lightning |
| **1820** | Hans Oersted links electricity and magnetism |
| **1831** | Faraday discovers electromagnetic induction |
| **1873** | Maxwell publishes his four equations |
| **1905** | Einstein publishes his theory of special relativity |

# 04 Young’s fringes

**When a beam of light is split into two, the different trains can mix to either reinforce or cancel the signal. Like water waves, where crests meet the waves combine and bright bands appear; where peaks and troughs cancel there is darkness. This behaviour, called interference, proves that light acts like a wave.**

In 1801 the physicist Thomas Young shone a beam of sunlight through two very fine slits cut in a piece of card. The light spread out into its constituent colours. But it did not form one classic rainbow, nor even two. To his surprise, on the screen appeared a whole series of rainbow stripes. These are known today as Young’s fringes.

What was going on? Young closed off one of the slits. A single broad rainbow appeared, much as you’d expect from shining white light through a prism. The main rainbow was flanked by a few fainter flecks on either side. When he reopened the second slit, the pattern broke up once more into the array of vivid bands.

Young realized that light was behaving just like water waves. Using glass tanks filled with water, he had studied how waves pass around obstacles and through gaps. When a parallel series of waves goes through an opening, such as a harbour entrance in a sea wall, some of them go straight through. But the waves that graze the wall’s edge are deflected – or diffracted – into arcs, spreading wave energy to either side of the gap. This behaviour could explain the single-slit pattern. But what about the double-slit fringes?

Throwing a pebble into a lake generates rings of expanding ripples. Throw another stone close to the first, and the two sets of ripples overlap. Where two crests or two troughs meet, the waves combine and grow larger. When a crest and a trough meet, they cancel each other out. The result is a complex pattern of peaks and lows arranged around ‘spokes’ of flat water.

This effect is known as interference. What happens when the wave grows in size we call ‘constructive interference’; its diminution is ‘destructive interference’. The size of the wave at any point depends on the difference in the ‘phase’ of the two interfering waves, or the relative distance between the peaks of each. The same behaviour appears in all waves, including light.

By using a double slit, Young had made two trains of light – one from each – interfere. Their relative phases were dictated by their different paths through and beyond the card. Where the waves combined to reinforce one another, a bright stripe resulted. Where they cancelled, the background was dark.

### Thomas Young (1773–1829)

Born to a Quaker family in Somerset, England, in 1773, Thomas Young was the eldest of ten children. At school he excelled in languages and was familiar with more than a dozen, from Persian and Turkish to Greek and Latin. Young studied medicine in London and Edinburgh before gaining a doctorate in physics at Göttingen, Germany, in 1796. Back in England he received a large inheritance that made him independently wealthy. He practised medicine whilst performing science experiments and following an interest in Egyptology. As well as helping to decipher hieroglyphics by translating the passages carved on the Rosetta Stone, Young coined the term ‘energy’ and established the wave theory of light.

**Huygens’ principle** In the 17th century, the Dutch physicist Christiaan

**1905** Einstein shows light can behave as a particle