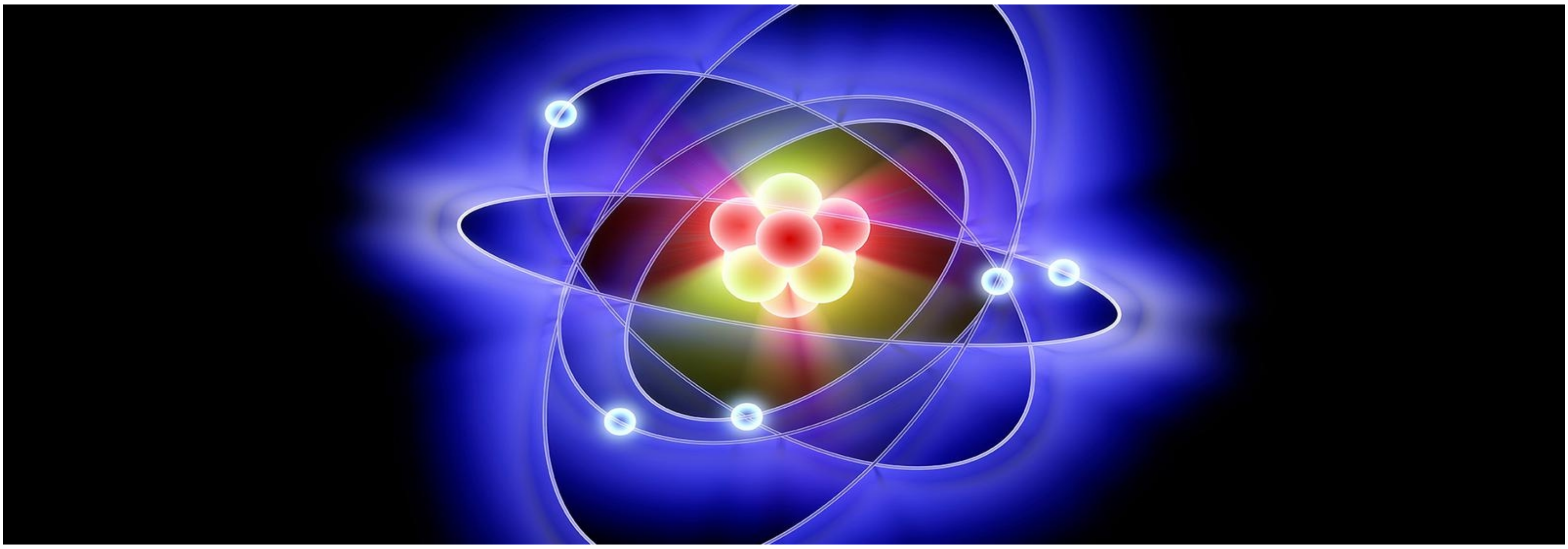

The Big Questions

It's all around us and allows us to see the world. But most of us would struggle to explain what light actually is

Presented by
Colin Barras

Light is what allows us to understand the world we live in. Our language reflects this: after groping in the dark, we see the light and understanding dawns.

Yet light is one of those things that we don't tend to understand. If you were to zoom in on a ray of light, what would you see? Sure, light travels incredibly fast, but what is it that's doing the travelling? Many of us would struggle to explain.

It doesn't have to be that way. Light certainly has puzzled the greatest minds for centuries, but landmark discoveries made over the last 150 years have robbed light of its mystery. We actually know, more or less, what it is.

Not only do today's physicists understand the nature of light, they are learning to control it with ever-greater precision – which means light could soon be put to work in surprising new ways. That is part of the reason why the United Nations designated 2015 as the **International Year of Light**.

What is that bright stuff coming through the trees? (Credit: Valentyn Volkov/Alamy)

There are all sorts of ways to describe light. But it might help to begin with this: **light is a form of radiation**.

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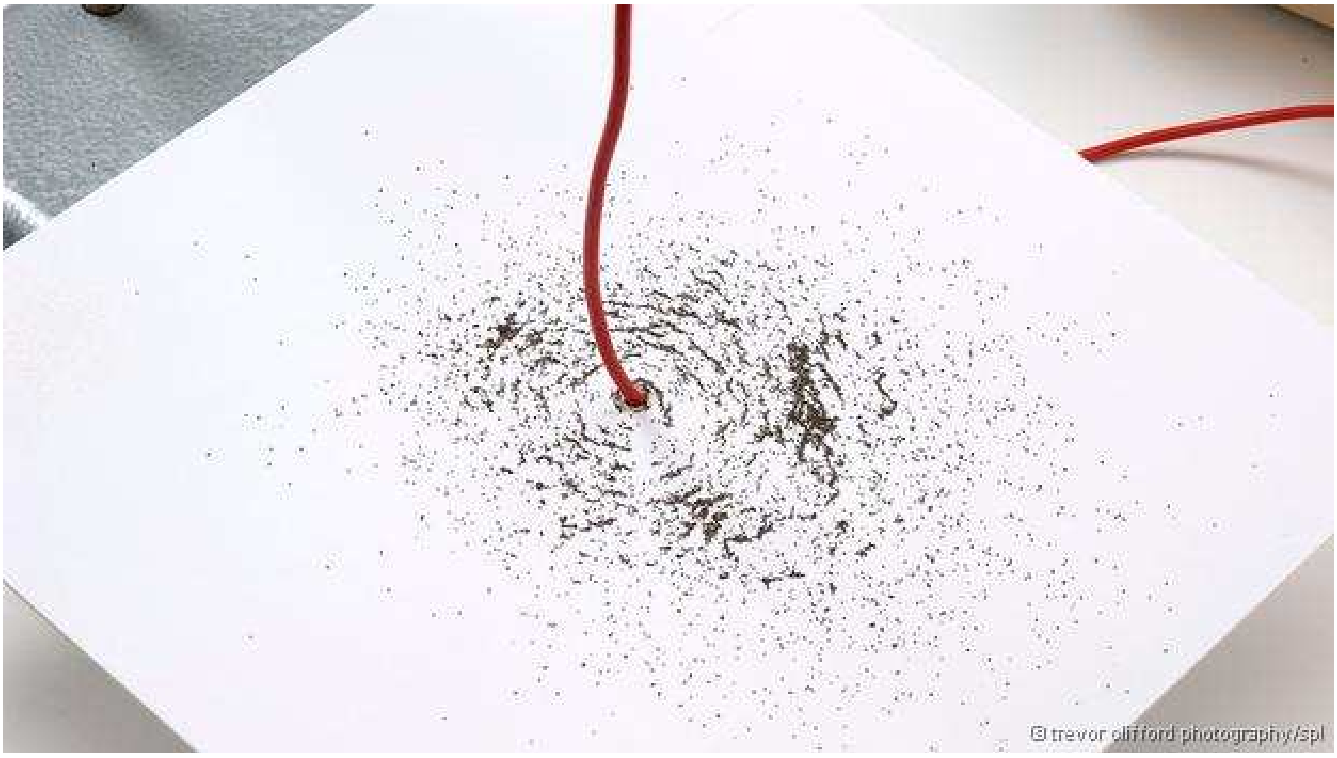
> *It wasn't until the late nineteenth century that scientists discovered the exact identity of light radiation*

This hopefully makes some sense. We all know that too much sunlight can trigger skin cancer. We also know that radiation exposure can raise the risk of developing some forms of cancer, so it's not hard to put the two together.

But not all forms of radiation are the same. It wasn't until the late nineteenth century that scientists discovered the exact identity of light radiation.

The strange thing is, this discovery didn't come from the study of light. Instead it emerged from decades of work into the nature of electricity and magnetism.



An electric current creates a magnetic field (Credit: Trevor Clifford Photography/SPL)

Electricity and magnetism seem like quite different things. But scientists like Hans Christian Oersted and Michael Faraday established that they are deeply entwined.

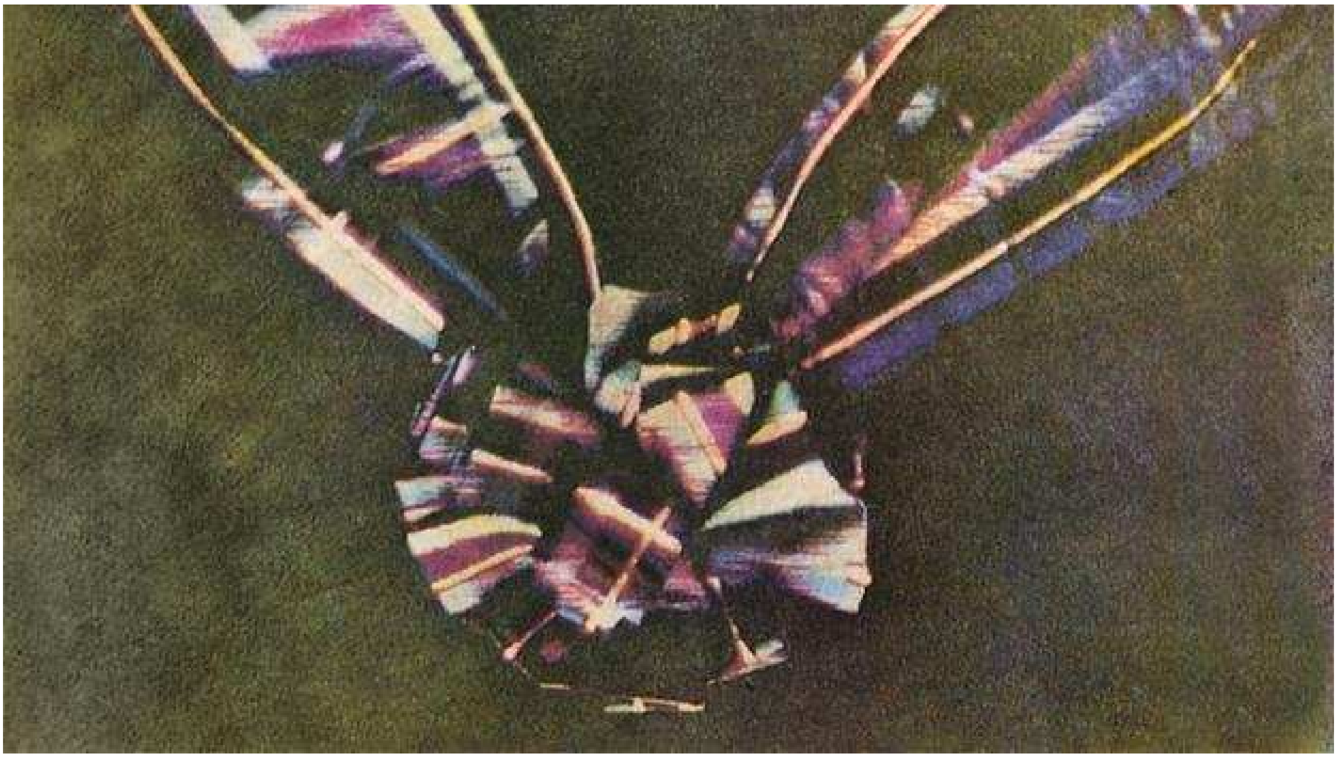
Oersted found that an electric current passing through a wire deflects the needle of a magnetic compass. Meanwhile, Faraday discovered that moving a magnet near a wire can generate an electric current in the wire.

> *Maxwell showed that electric and magnetic fields travel in the manner of waves*

Mathematicians of the day set about using these observations to create a theory describing this strange new phenomenon, which they called "electromagnetism". But it wasn't until James Clerk Maxwell looked at the problem that a complete picture emerged.

Maxwell's contribution to science is huge. Albert Einstein, who was inspired by Maxwell, said that **he changed the world forever**. Among many other things, his calculations helped explain what light is.

Maxwell showed that electric and magnetic fields travel in the manner of waves, and that those waves move essentially at the speed of light. This allowed Maxwell to predict that light itself was carried by electromagnetic waves – which means **light is a form of electromagnetic radiation**.



The first durable colour photograph, taken by James Clerk Maxwell in 1861

In the late 1880s, a few years after Maxwell's death, German physicist Heinrich Hertz became the first to formally demonstrate that Maxwell's theoretical concept of the electromagnetic wave was correct.

> *In 1861 he unveiled the first durable colour photograph*

"I am convinced that if Maxwell and Hertz had lived into the Nobel prize era, they would have surely shared one," says Graham Hall of the University of Aberdeen in the UK – **where Maxwell worked in the late 1850s**.

Maxwell holds a place in the annals of light science for another, more practical reason. In 1861 he unveiled the first durable colour photograph, produced using a three-colour filter system that still forms the basis of many forms of colour photography today.

Still, the idea that light is a form of electromagnetic radiation may not mean too much. But this idea helps to explain something that we all understand: **light is a spectrum of colours**.

We are taught that a rainbow contains seven bands of colour (Credit: Dennis Frates/Alamy)

This is an **observation that goes back to the work of Isaac Newton**. We see this colour spectrum in all its glory whenever a rainbow hangs in the sky – and those colours relate directly to Maxwell's concept of electromagnetic waves.

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Many animals can actually see ultraviolet, and so

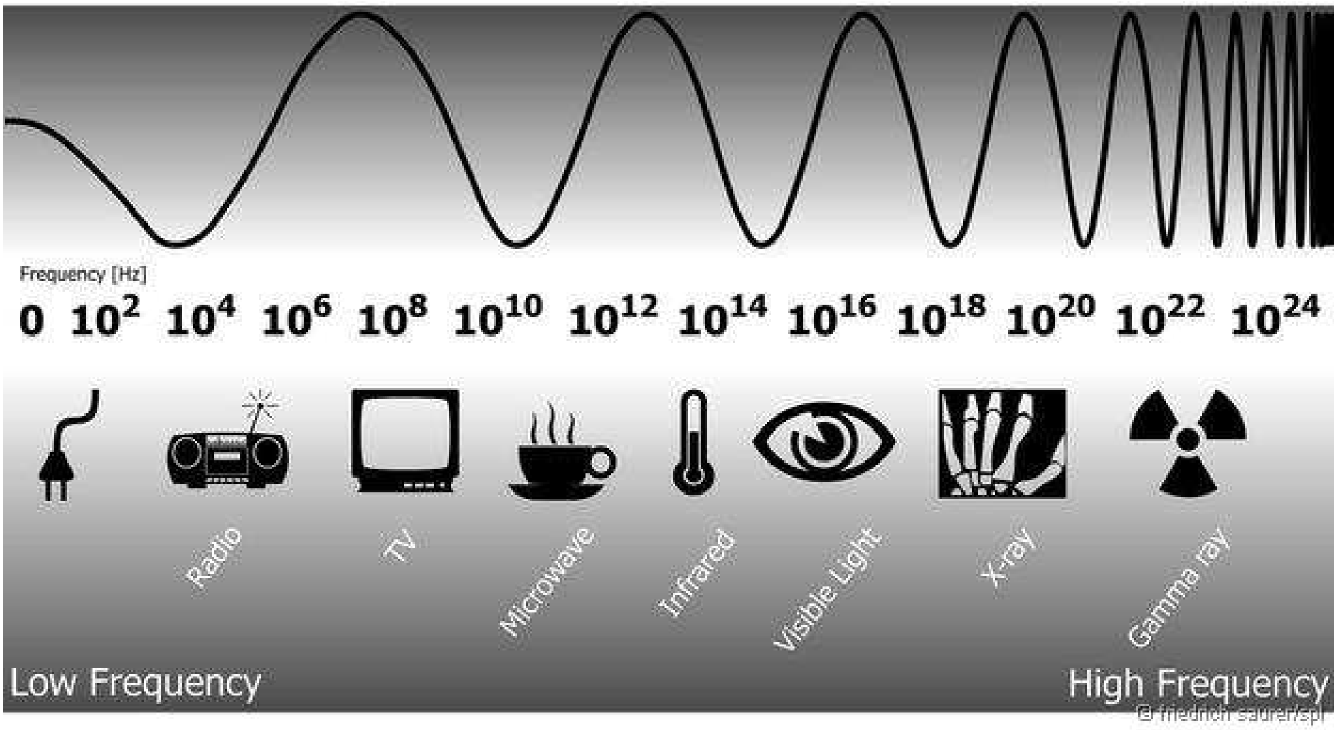
The red light along one edge of the rainbow is electromagnetic radiation with a wavelength of about 620 to 750 nanometres; the violet light along the opposite edge is radiation with a wavelength of 380 to 450nm.

But there is far more to electromagnetic radiation *can some people*

than these visible colours. Light with wavelengths slightly longer than the red light we see is called infrared. Light with wavelengths slightly shorter than violet is called ultraviolet.

Many animals can actually see ultraviolet, and so can some people, says **Eleftherios Goulielmakis** of the Max Planck Institute of Quantum Optics in Garching, Germany. In some circumstances **even infrared is visible to humans**. Perhaps this is why it's not uncommon to see both ultraviolet and infrared described as forms of light.

Curiously, though, go to even longer – or shorter – electromagnetic wavelengths and we stop using the word "light".



The electromagnetic spectrum is far more than just light (Credit: Friedrich Saurer/SPL)

Beyond ultraviolet, electromagnetic wavelengths can go shorter than 100nm. This is the realm of X-rays and gamma rays. You won't often hear X-rays described as a form of light.

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"A scientist wouldn't say 'I'm shining X-ray light on the target'. They would say 'I'm using X-rays'," *There is no real physical difference between radio waves and visible light*

says Goulielmakis.

Meanwhile, go beyond infrared and electromagnetic wavelength stretches to 1cm and even up to thousands of kilometres. These electromagnetic waves are given familiar names like microwaves and radio waves. It may seem strange to think of the radio waves used in broadcasting as light.

"There is no real physical difference between radio waves and visible light from the point of view of physics," says Goulielmakis. "You would describe them with exactly the same sort of equations and mathematics." It's only our everyday language that treats them as different.

So we have another definition of light. It is the very narrow range of electromagnetic radiation that our eyes can actually see. In other words, **light is a subjective label that we only use because our senses are limited**.

For more evidence of just how subjective our concept of light is, think back to the rainbow.

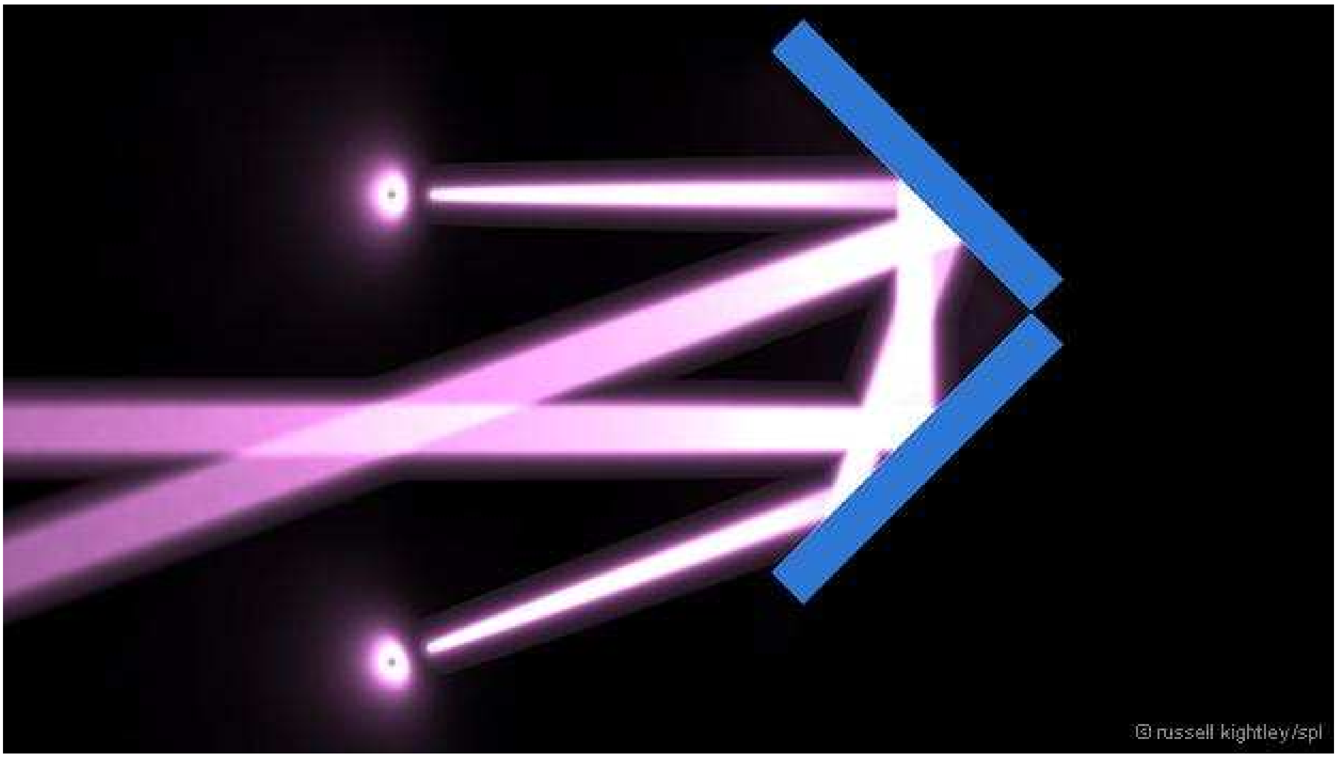
Rainbows show us every kind of visible light (Credit: Adam Burton/Alamy)

Most people learn that the spectrum of light contains seven main colours: red, orange, yellow, green, blue, indigo and violet. We are even given handy mnemonics and songs to remember them.

Look at a strong rainbow and you can probably convince yourself that all seven colours are on show. However, Newton himself struggled to see them all.

In fact, researchers now suspect that he only divided the rainbow into seven colours because **the number seven was so significant in the ancient world**: for instance there are seven notes in a musical scale, and seven days in a week.

Maxwell's work on electromagnetism took us past all this, and showed that visible light was part of a larger spectrum of radiation. It also seemed to finally explain the nature of light.



Light bounces off mirrors in very precise ways (Credit: Russell Kightley/SPL)

For centuries, scientists had been trying to pin down the actual form that light takes at a fundamental scale as it travels from a light source to our eyes.

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> *Newton realised that rays of light obeyed very strict geometric rules*

Some thought that light travelled in the form of waves or ripples, either through air or a more nebulous "ether". Others thought this wave model was wrong and imagined light as a stream of tiny particles.

Newton preferred this second option, particularly after a series of experiments he performed using light and mirrors.

He realised that rays of light obeyed very strict geometric rules. Shine a ray against a mirror and it **bounced off in exactly the same way a ball would if it were thrown against the mirror**. Waves don't necessarily move in such predictable straight lines, he reasoned, so light must be carried by some form of tiny, weightless particles.

The trouble is, there was equally compelling evidence that light is a wave.

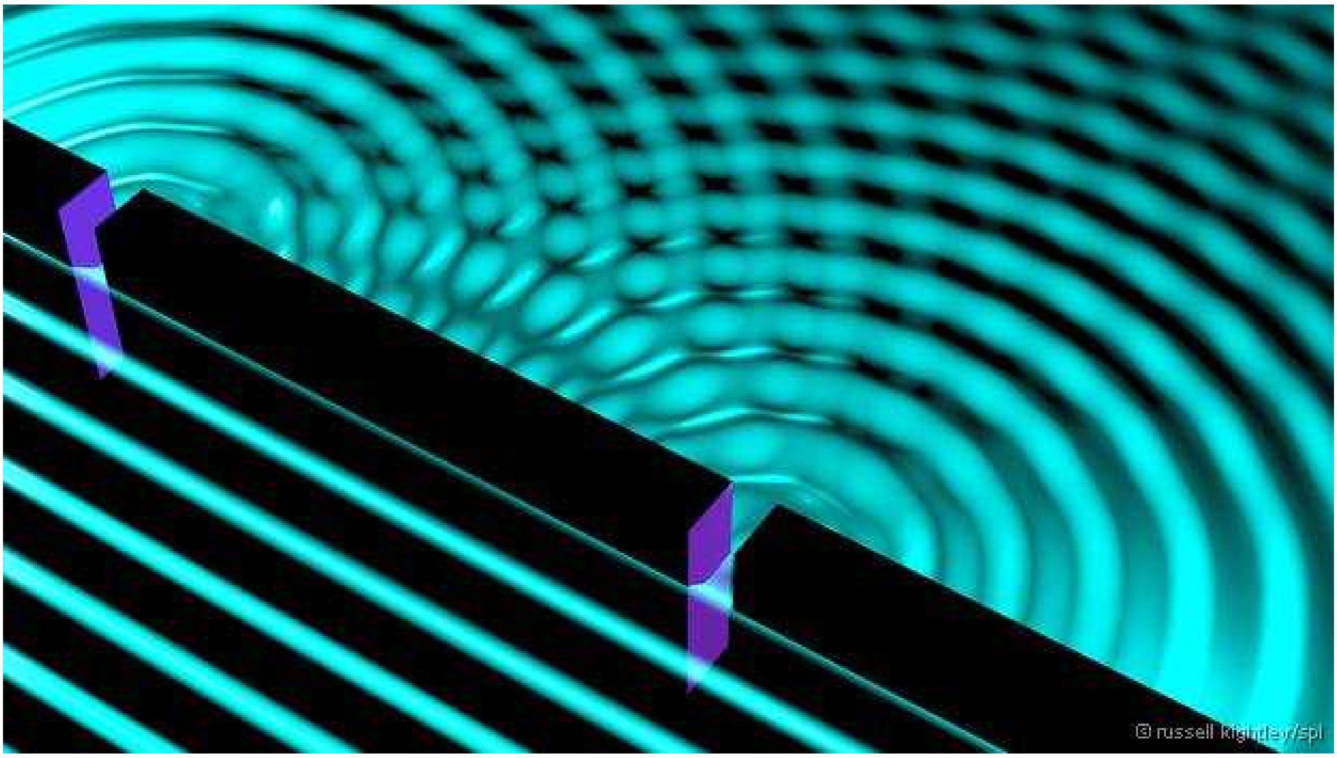
The double split experiment shows light is wave-like (Credit: Victor de Schwanberg/SPL)

One of the most famous demonstrations of this came in 1801. Thomas

Young's "double slit experiment" is the sort of experiment anyone can replicate at home.

Take a sheet of thick card and carefully make two thin vertical slits through it. Then get a "coherent" light source, which only produces light of a particular wavelength: a laser will do nicely. Now shine the light through the two slits onto another surface.

On that second surface, you might expect to see two bright vertical lines where some of the light has passed through the two slits. But when Young performed the experiment, he saw a sequence of light and dark lines rather like a bar code.



Coherent light (left) is distorted into ripples (right) (Credit: Russell Kightley/SPL)

When the light passes through the thin slits, it behaves in the same way that water waves do when they pass through a narrow opening: they diffract and spread out in the form of hemispherical ripples.

Where the "light ripples" from the two slits hit each other out of phase they cancel out, forming dark bars. Where the ripples hit each other in phase, they add together to made bright vertical lines.

Young's experiment was compelling evidence of the wave model, and Maxwell's work put the idea on a solid mathematical footing. **Light is a wave**.

But then came the quantum revolution.

Lightbulbs rely on substances that emit electromagnetic radiation (Credit: 1997)

In the second half of the nineteenth century, physicists were trying to understand how and why some materials absorbed and emitted electromagnetic radiation better than others.

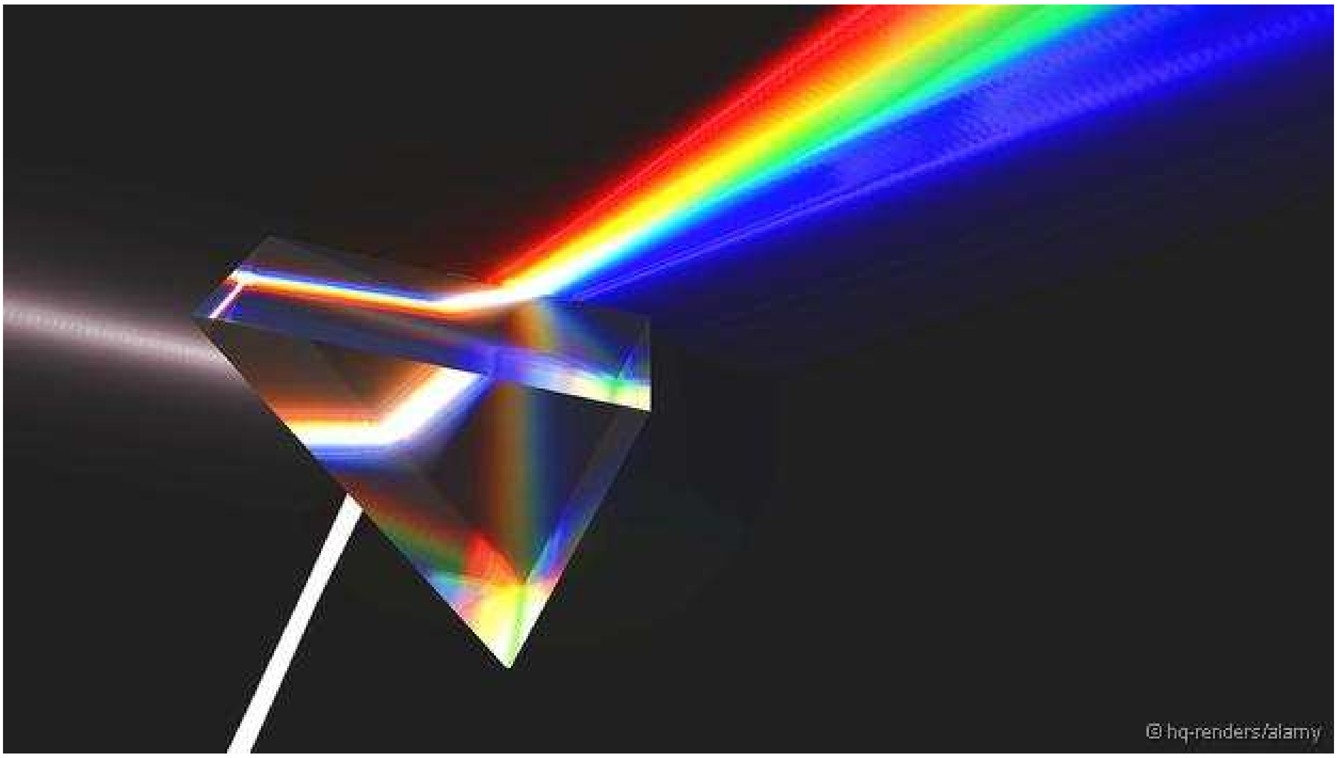
> *In 1900, Max Planck solved the problem*

That may sound a bit niche, but the electric light industry was emerging at the time, so materials that could emit light were a big thing.

By the end of the nineteenth century, **scientists had discovered that the amount of electromagnetic radiation released by an object changed depending on its temperature**, and they had measured these changes. But no one knew why it happened.

In 1900, Max Planck solved the problem. He discovered that the calculations could explain those changes, but only if he assumed that the electromagnetic radiation was held in tiny discrete packets. Planck called these "quanta", the plural of "quantum".

A few years later, Einstein used this idea to explain another puzzling experiment.



A prism splits white light into its constituent colours (Credit: HQ-Renders/Alamy)

Physicists had discovered that a chunk of metal becomes positively charged when it is bathed in visible or ultraviolet light. They called this the "**photoelectric effect**".

> *This doesn't make much sense if light is simply a wave*

The explanation was that atoms in the metal were losing negatively-charged electrons. Apparently, the light delivered enough energy to the metal to shake some of them loose.

But the detail of what the electrons were doing was odd. They could be made to carry more energy simply by changing the colour of light. In particular, the electrons released from a metal bathed in violet light carried more energy that electrons released by a metal bathed in red light.

This doesn't make much sense if light is simply a wave.

Sunlight through the clouds (Credit: imagestopshop/Alamy)

You usually change the amount of energy in a wave by making it taller – think of the destructive power of a tall tsunami – rather than by making the wave itself longer or shorter.

> *Each quantum packs a discrete energy punch*

By extension, the best way to increase the energy that light transfers to the electrons should be by making the light waves taller: that is, making the light brighter. Changing the wavelength, and thus the colour, shouldn't make as much of a difference.

Einstein realised that the photoelectric effect was easier to understand by thinking of light in terms of Planck's quanta.

He suggested that light is carried in tiny quantum packets. Each quantum packs a discrete energy punch that relates to the wavelength: the shorter the wavelength, the denser the energy punch. This would explain why violet light packets, with a relatively short wavelength, carried more energy than red light packets, with a relatively longer one.

It also explained why simply increasing the brightness of the light made less of an impact.

Light allows us to perceive the world around us (Credit: Image Source/Alamy)

A brighter light source delivers more light packets to the metal, but it doesn't change the amount of energy each light packet contains. Crudely speaking, a single violet light packet could transfer more energy to a single electron than any number of red light packets.

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The scientists decided that light behaved as

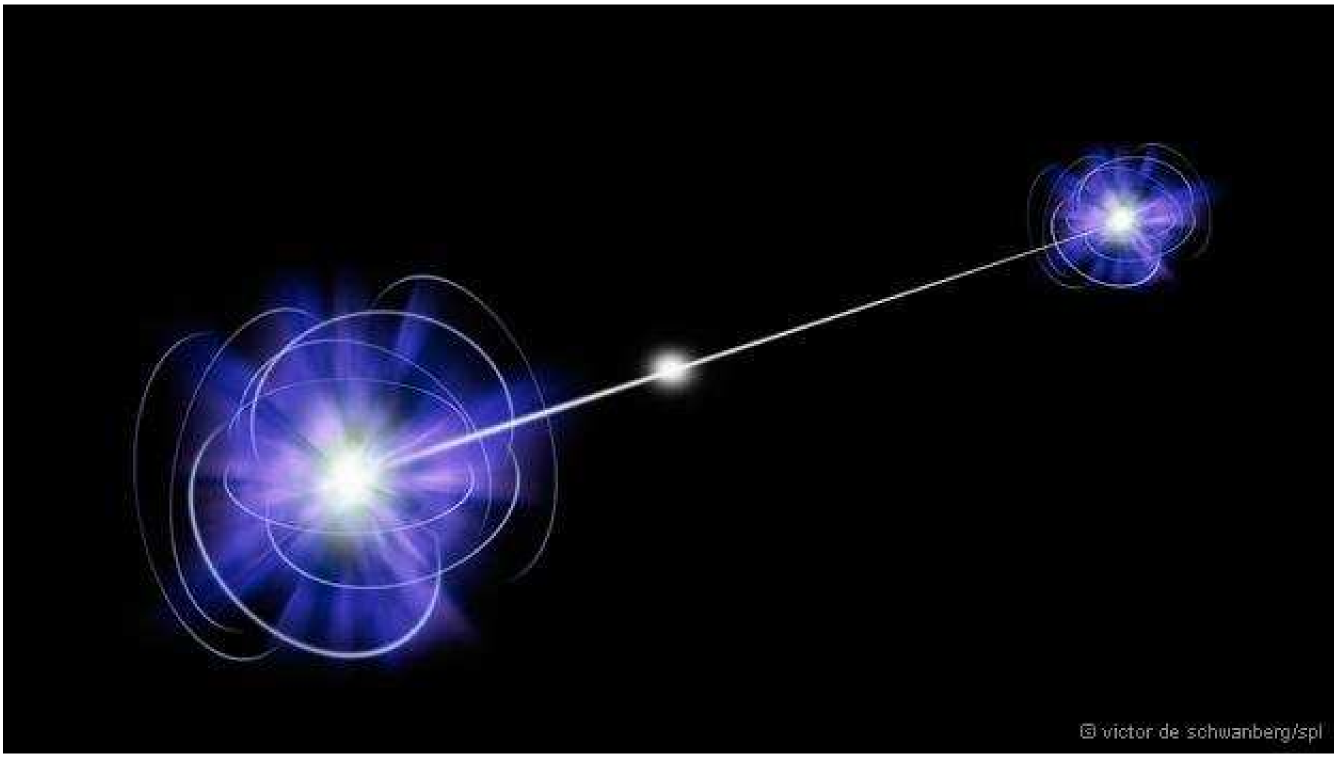
Einstein called these energy packets photons, and these are now recognised as a fundamental particle. Visible light is carried by photons, and so are all the other kinds of electromagnetic radiation like X-rays, microwaves and radio waves. In other words, **light is a particle**.

both a wave and a particle at the same time

At this point physicists decided to end the debate over whether light behaved as a wave or a particle. Both models were so convincing that neither could be rejected.

To the confusion of many non-physicists, the scientists decided that light behaved as both a wave and a particle at the same time. In other words, **light is a paradox**.

Physicists, though, have no problem with light's split identity. If anything, it makes light doubly useful. Today, building on the work of luminaries – literally "light-givers" – like Maxwell and Einstein, we are squeezing even more out of light.



Pairs of particles can become "entangled" (Credit: Victor de Schwanberg/SPL)

It turns out that the equations used to describe light-as-a-wave and light-as-a-particle work equally well, but in some circumstances one is easier to use than the other. So physicists switch between them, just as we use metres to describe our own height but switch to kilometres to describe a bicycle ride.

> *Entangled particles can be used to communicate information*

Some physicists are trying to use light to create encrypted channels of communication: **for money transfers, for instance**. For them, it makes sense to think of light as particles.

This is because of another strange quirk of quantum physics. Two fundamental particles, like a pair of photons, can be "entangled". This means they share properties no matter how far apart they are from one another, so they can be used to communicate information between two points on Earth.

Another feature of this entanglement is that the quantum state of the photons changes when they are read. That means if anyone tried to eavesdrop on a channel encrypted using the quantum properties of light, they would, in theory, immediately betray their presence.

Others, like Goulielmakis, are using light in electronics. For them it is far more useful to think of light as a series of waves that can be tamed and controlled.

Is that shaft of light made up of a wave, or tiny particles? (Credit: Nik Wheeler/Alamy)

Modern devices called "light field synthesisers" can corral light waves into perfect synchrony with each other. As a result, they create light pulses that are far more intense, short-lived and directed than the light from an ordinary bulb.

> *They literally took photos of light waves moving*

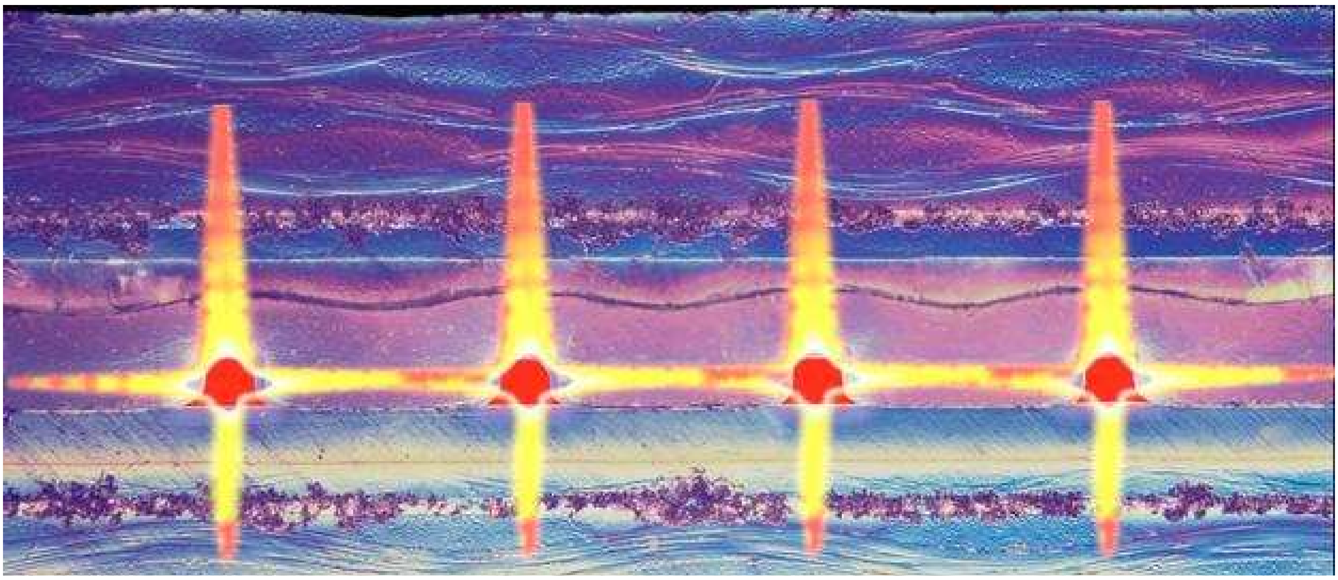
Over the last 15 years, these devices have been used to tame light to an extraordinary degree.

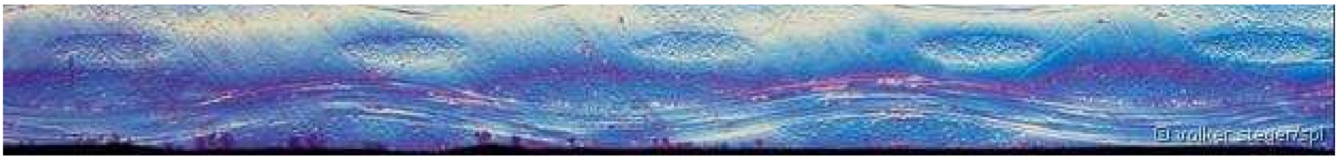
In 2004 Goulielmakis and his colleagues managed to produce incredibly short pulses of X-ray radiation. Each pulse lasted just 250 attoseconds, or 250 quintillionths of a second.

Using these tiny pulses like a camera flash, they managed to **capture images of individual waves of visible light**, which oscillate rather slower. They literally took photos of light waves moving.

"We've known since Maxwell that light is an oscillating electromagnetic field, but nobody dreamed we would be able to capture the light as it oscillates," says Goulielmakis.

Seeing those individual light waves is a first step towards controlling and sculpting them, he says, much as we already **sculpt much longer electromagnetic waves, like the radio waves that carry radio and television signals**.





Optical computers use light instead of electricity (Credit: Volker Steger/SPL)

A century ago, the photoelectric effect showed that visible light affects the electrons in a metal. Goulielmakis says it should be possible to precisely manipulate those electrons, using visible light waves that have been shaped to interact with the metals in a carefully defined way. "We can control the light, and through it we can control matter," he says.

> *Human eyes are photon detectors that use visible light to learn about the world around us*

That could revolutionise electronics, leading to new generations of optical computers that are smaller and faster than those we have today. "It's about setting electrons in motion in ways we want, creating electric currents inside solids using light, instead of conventional electronics."

So there is one more way light can be described: **light is a tool**.

That is nothing new. Life has been harnessing light ever since the first primitive organisms evolved light-sensitive tissues. Human eyes are photon detectors that use visible light to learn about the world around us.

Modern technology is simply taking this idea even further. In 2014, the Nobel Prize in Chemistry was awarded to **researchers who built a light microscope so powerful, it was thought to be physically impossible**. It turned out that, with a bit of persuasion, light would show us things we thought we would never see.