# The most beautiful experiment



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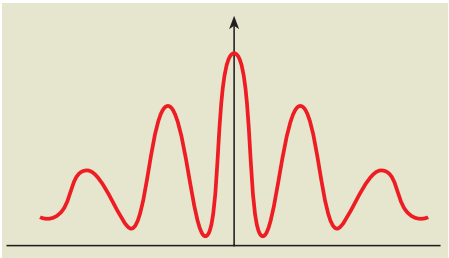
# The most beautiful experiment

The most beautiful experiment in physics, according to a poll of *Physics World* readers, is the interference of single electrons in a Young's double slit. **Robert P Crease** reports

When I asked readers earlier this year to submit candidates for the "most beautiful experiment in physics" (*Physics World* May p17), I was pleased to receive more than 200 replies. The responses covered a broad spectrum, ranging from actual experiments to thought experiments, and from proposed experiments to proofs, theorems and models. However, one experiment – the double-slit experiment with electrons – was cited more often than any other, receiving a total of 20 votes.

Others in the top 10 included Galileo's experiments with falling bodies, Millikan's oil-drop experiment and Newton's separation of sunlight with a prism. Young's original double-slit interference experiment with light also appeared in the list (see box).



Simply beautiful – the spatial intensity distribution of electrons that have interfered in a Young's double-slit experiment.

## Aspects of beauty

Readers offered a variety of reasons for their selections. One was the transformative power of the experiment – its ability to change thinking and behaviour. "You'll never think the same way about light," commented one reader who proposed a photoelectric-effect experiment.

A fan of Millikan's oil-drop experiment, meanwhile, observed that repeating the experiment can leave no-one in doubt that electrical charge is quantized and that modern physics is real, observable and true. "When I did the experiment in a junior physics lab many years ago," he said, "I literally sat staring at the spreadsheet, dumbfounded at how perfect and elegant the whole thing was. I redid the analysis just for the fun of seeing it come out again."

Experiments can transform our thinking and behaviour, no matter how prepared we may be for the result. Using phrases like "the only experiment I remember after so many years", readers described experiments they recalled from high school involving beach balls floating in air currents (illustrating the Bernoulli principle), ripple tanks (waves and interference), crushed metal cans (vacuum and air pressure), and skateboard antics (mass and inertia). A few mentioned the Apollo "feather-drop" experiment on the Moon – a recreation of Galileo's falling-bodies experiment – although they admitted that the location helped to make it unforgettable and possibly the "most watched experiment" of all time.

Readers also defined beautiful experiments in terms of "economy" – in other words how efficiently and dramatically the experiment made an important result stand out. Economy might refer to either the experimental equipment itself or how it presented a significant result, or to both. Someone recalled seeing the gyroscopic principle demonstrated via a bicycle wheel suspended from the ceiling with a rope tied to the axle nut, and observed that – without gyroscopic precession – "there would be no rockets, no global-positioning system (GPS), no advanced aircraft and no Segway [GPS-controlled one-man bikes] and, of course, no bicycles!".

Another cited a measurement of the time intervals between the drips of a simple tap to illustrate principles of chaos and nonlinear systems and to show how information is transmitted from small scales to large.

## Fair play

There were several people who mentioned economical *reductio ad absurdum* arguments. These included Stephen Hawking's proof that the universe has not existed forever – or, as one respondent commented, "it's true because if it were not, all things would be the same temperature". Others cited Olbers' paradox that the sky is not uniformly bright even though it contains – to all intents and purposes – an infinite number of stars. (The paradox is resolved by the fact that the universe is expanding, which means that distant light has not yet reached us.)

Still others cited the beauty of certain scientific instruments that used little beyond ingenuity to open up vast new domains for exploration. Examples that fell into this category included Charles Wilson's cloud chamber, the X-ray interferometer, the scanning tunnelling microscope and the Cosmotron at Brookhaven.

A final aspect of beauty that was often cited by readers might be called "deep play". This is the sense that we are actively engaged with something outside ourselves that is responding to us – rather than watching a game of our own construction or watching nature from a detached distance. Readers found beauty in small-scale play with simple things like balls, waves, sounds and coins – allowing order in apparently random and contradictory events to show itself. Other readers found beauty in much larger play – such as Roemer's observations of Jupiter's moon Io to determine the speed of light or Eddington's measurement of the bending of starlight. These astronomical observations turn the entire solar system – and even the galaxy and beyond – into a vast playing field for experiment.

## Slashdot discussion

My original article was also mentioned on Slashdot.org, an extremely active website. Although Slashdot bills itself as "news for nerds", its audience evidently includes a large number of science-history aficionados. A discussion with more than 500 comments ensued, many dissecting the merits of particular experiments. Here too the double-slit electron-interference experiment topped the list. One participant remarked that this and other experiments illustrating quantum-mechanical principles "even seem to reveal something about ourselves", noting that "philosophers and cranks are attracted to the results like moths".

Other Slashdot participants proposed many of the same experiments as *Physics World* readers – and often for similar reasons. However, they also came up with an imaginative variety of examples of deep play. These included fun things like putting discarded CDs into microwave ovens, firing potatoes using lengths of pipe and cans of hairspray, and synchronizing coloured lasers to the music of Pink Floyd.

One of the contributors described watching small plastic bags circulating in wind pockets, commenting that "sometimes there's so much beauty in the world, I just can't take it". Another mentioned the fact that a hunter firing at a falling monkey always hits the monkey no matter how far away it is, even though it drops just as the hunter fires. One person even cited sitting outside a hospital to hear the Doppler effect, with the comment: "Anytime an ambulance passes me, I'm amazed."

One Slashdot participant described a method of producing a fractal using a coin, marker and tape measure, claiming to have nearly cried the first time they saw it. Another described an impromptu game that he and classmates had invented at the end of a lab class, in which a liquid-nitro-

gen-filled styrofoam cup with holes in the bottom can be made to glide pleasingly around the floor when kicked about as the gas leaks out.

### The beauty of the double-slit experiment

The double-slit experiment exemplifies the wave–particle duality of light, as well as quantum physics itself. It demonstrates that light interferes with itself in passing through a pair of slits. It also shows that even single electrons – proceeding one by one – interfere. Richard Feynman is said to have remarked that it contains everything you need to know about quantum mechanics.

The double-slit experiment with electrons possesses all of the aspects of beauty most frequently mentioned by readers – although, unlike all of the other experiments in the top 10, it does not have anyone's name attached to it. It is transformative, being able to convince even the most die-hard sceptics of the truth of quantum mechanics. "Before seeing it," one respondent wrote, "I didn't believe a single word of 'modern' physics." It is economical: the equipment is readily obtained and the concepts are readily understandable, despite its revolutionary result. It is also deep play: the experiment stages a performance that does not occur in nature, but unfolds only in a special situation set up by human beings. In doing so, it dramatically reveals – before our very eyes – something more than was put into it.

"I saw it during an optics course at Edinburgh University," wrote respondent Alison Campbell, an astronomer at St Andrews University. "The prof didn't tell us what was going to happen, and the impact was tremendous. I cannot remember the experimental details any more – I just remember the distribution of points that I suddenly saw were arranged in a diffraction pattern. Seeing the two-slit experiment is like watching a total solar eclipse for the first time: a primitive thrill passes through you and the little hairs on your arms stand up. You think this particle–wave thing is really true and the foundations of your knowledge shift and sway."

### Beauty and the experimental process

I was a little disturbed, however, by the ease with which many people seemed to think that the experiments that they were proposing had been conceived, or could be carried out and understood. This seemed a function, in part, of the way that these experiments are often taught. Demonstrations can vastly simplify the experimental process through the use of modern equipment constructed with the "right answer" in view. Textbooks and Web simulations – which exist for most of the experiments on the top 10 list – can involve far greater simplifications. That is true even when, as in the case of some Millikan oil-drop simulations, "dirty" drops that cannot be fitted to the right result are deliberately included along with clean ones in an attempt to promote verisimilitude.

These demonstrations and simulations, I think, diminish the experience of beauty in science by misrepresenting the experimental process. Even when a scientific experiment points to a simple fact or relationship – as Frederic Holmes writes in his book *Meselson, Stahl, and the Replication of DNA: A History of the Most Beautiful Experiment in Biology* – it usually has been extracted from a "matrix of complexity", and introduces new complexities into science. Despite its simplicity, he says, "the [Meselson–Stahl] experiment originated in complexity, was surrounded by complexity and directed the way toward the discovery of future complexities."

And it hardly needs saying that the various experiments demonstrating quantum-mechanical principles were not born simply, and have not made the world simpler. Demonstrations and simulations can misrepresent by encouraging the sense that a scientific experiment is just an illustration of an already formulated lesson – turning the experiment into a paint-by-numbers masterpiece, as it were – rather than a process by which a hitherto unknown truth becomes disclosed for the first time.

One Slashdot contributor touched on this after describing an experiment in which he measured the acceleration of gravity using a pin, a switch, a timer and a shuttlecock. "The most beautiful thing wasn't learning that gravity is 9.8 $ms^{-2}$," he wrote, "but in showing us that from a fairly simple set-up we could quantitatively measure something important in physics."

### The critical point

Beauty, Plato wrote, is not easy to define, but something that "slips through and evades us". For this reason, many logic-oriented philosophical approaches tend to divorce and even oppose truth and beauty. "The question of truth", wrote logician Gottlob Frege in one of his most influential works, "would cause us to abandon aesthetic delight for an attitude of scientific investigation."

I'm far more sympathetic to those philosophical traditions that view truth as involving, most fundamentally, the disclosure of something rather than accurate representation. These traditions allow us to see an intimate connection between scientific inquiry and beauty. At any given time, the scientific frontier is ambiguous and confusing, and requires the skilful planning and performing of experimental actions to sort out and bring clarity.

It is natural to call beautiful those that captivate and transform our thinking, that make the result stand out clearly and economically and not abstractly as a lesson but in a materially embodied way, and that reveal that we are actively engaging with something beyond us. To speak about beauty in science as belonging solely to the province of theory or equations is to misunderstand both beauty and science.

The quantum-mechanical world is likely to remain counterintuitive to human beings, no matter how well-versed or confident we are in the theory. The double-slit electron-interference experiment brings its reality before our eyes in a dramatic, economical and materially embodied way. It is therefore likely to remain in the pantheon of beautiful experiments for a long time to come.

● See "The double-slit experiment" on p15

## Top 10 beautiful experiments

The list below shows the top 10 most frequently mentioned experiments by readers of *Physics World*.

**1** Young's double-slit experiment applied to the interference of single electrons
**2** Galileo's experiment on falling bodies (1600s)
**3** Millikan's oil-drop experiment (1910s)
**4** Newton's decomposition of sunlight with a prism (1665–1666)
**5** Young's light-interference experiment (1801)
**6** Cavendish's torsion-bar experiment (1798)
**7** Eratosthenes' measurement of the Earth's circumference (3rd century BC)
**8** Galileo's experiments with rolling balls down inclined planes (1600s)
**9** Rutherford's discovery of the nucleus (1911)
**10** Foucault's pendulum (1851)

Others experiments that were cited included:

- Archimedes' experiment on hydrostatics
- Roemer's observations of the speed of light
- Joule's paddle-wheel heat experiments
- Reynolds's pipe flow experiment
- Mach & Salcher's acoustic shock wave
- Michelson–Morley measurement of the null effect of the ether
- Röntgen's detection of Maxwell's displacement current
- Oersted's discovery of electromagnetism
- The Braggs' X-ray diffraction of salt crystals
- Eddington's measurement of the bending of starlight
- Stern–Gerlach demonstration of space quantization
- Schrödinger's cat thought experiment
- Trinity test of nuclear chain reaction
- Wu *et al.*'s measurement of parity violation
- Goldhaber's study of neutrino helicity
- Feynman dipping an O-ring in water

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