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Here They Are, Science's 10 Most Beautiful Experiments

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Whether they are blasting apart subatomic particles in accelerators, sequencing the genome or analyzing the wobble of a distant star, the experiments that grab the world's attention often cost millions of dollars to execute and produce torrents of data to be processed over months by supercomputers. Some research groups have grown to the size of small companies.

But ultimately science comes down to the individual mind grappling with something mysterious. When Robert P. Crease, a member of the philosophy department at the State University of New York at Stony Brook and the historian at Brookhaven National Laboratory, recently asked physicists to nominate the most beautiful experiment of all time, the 10 winners were largely solo performances, involving at most a few assistants. Most of the experiments - which are listed in this month's Physics World - took place on tabletops and none required more computational power than that of a slide rule or calculator.

What they have in common is that they epitomize the elusive quality scientists call beauty. This is beauty in the classical sense: the logical simplicity of the apparatus, like the logical simplicity of the analysis, seems as inevitable and pure as the lines of a Greek monument. Confusion and ambiguity are momentarily swept aside, and something new about nature becomes clear.

The list in Physics World was ranked according to popularity, first place going to an experiment that vividly demonstrated the quantum nature of the physical world. But science is a cumulative enterprise - that is part of its beauty. Rearranged chronologically and annotated below, the winners provide a bird's-eye view of more than 2,000 years of discovery.

Eratosthenes' measurement of the Earth's circumference

At noon on the summer solstice in the Egyptian town now called Aswan, the sun hovers straight overhead: objects cast no shadow and sunlight falls directly down a deep well. When he read this fact, Eratosthenes, the librarian at Alexandria in the third century B.C., realized he had the information he needed to estimate the circumference of the planet. On the same day and time, he measured shadows in Alexandria, finding that the solar rays there had a bit of a slant, deviating from the vertical by about seven degrees.

The rest was just geometry. Assuming the earth is spherical, its circumference spans 360 degrees. So if the two cities are seven degrees apart, that would constitute seven-360ths of the full circle - about one-fiftieth. Estimating from travel time that the towns were 5,000 "stadia" apart, Eratosthenes concluded that the earth must be 50 times that size - 250,000 stadia in girth. Scholars differ over the length of a Greek stadium, so it is impossible to know just how accurate he was. But by some reckonings, he was off by only about 5 percent. (Ranking: 7)

Galileo’s experiment on falling objects

In the late 1500’s, everyone knew that heavy objects fall faster than lighter ones. After all, Aristotle had said so. That an ancient Greek scholar still held such sway was a sign of how far science had declined during the dark ages.

Galileo Galilei, who held a chair in mathematics at the University of Pisa, was impudent enough to question the common knowledge. The story has become part of the folklore of science: he is reputed to have dropped two different weights from the town’s Leaning Tower showing that they landed at the same time. His challenges to Aristotle may have cost Galileo his job, but he had demonstrated the importance of taking nature, not human authority, as the final arbiter in matters of science. (Ranking: 2)

Galileo’s experiments with rolling balls down inclined planes

Galileo continued to refine his ideas about objects in motion. He took a board 12 cubits long and half a cubit wide (about 20 feet by 10 inches) and cut a groove, as straight and smooth as possible, down the center. He inclined the plane and rolled brass balls down it, timing their descent with a water clock - a large vessel that emptied through a thin tube into a glass. After each run he would weigh the water that had flowed out - his measurement of elapsed time - and compare it with the distance the ball had traveled.

Aristotle would have predicted that the velocity of a rolling ball was constant: double its time in transit and you would double the distance it traversed. Galileo was able to show that the distance is actually proportional to the square of the time: Double it and the ball would go four times as far. The reason is that it is being constantly accelerated by gravity. (Ranking: 8)

Newton’s decomposition of sunlight with a prism

Isaac Newton was born the year Galileo died. He graduated from Trinity College, Cambridge, in 1665, then holed up at home for a couple of years waiting out the plague. He had no trouble keeping himself occupied.

The common wisdom held that white light is the purest form (Aristotle again) and that colored light must therefore have been altered somehow. To test this hypothesis, Newton shined a beam of sunlight through a glass prism and showed that it decomposed into a spectrum cast on the wall. People already knew about rainbows, of course, but they were considered to be little more than pretty aberrations. Actually, Newton concluded, it was these colors - red, orange, yellow, green, blue, indigo, violet and the gradations in between - that were fundamental. What seemed simple on the surface, a beam of white light, was, if one looked deeper, beautifully complex. (Ranking: 4)

Cavendish’s torsion-bar experiment

Another of Newton’s contributions was his theory of gravity, which holds that the strength of attraction between two objects increases with the square of their masses and decreases with the square of the distance between them. But how strong is gravity in the first place?

In the late 1700’s an English scientist, Henry Cavendish, decided to find out. He took a six-foot wooden rod and attached small metal spheres to each end, like a dumbbell, then suspended it from a wire. Two 350-pound lead spheres placed nearby exerted just enough gravitational force to tug at the smaller balls, causing the dumbbell to move and the wire to twist. By mounting finely etched pieces of ivory on the end of each arm and in the sides of the case, he could measure the subtle displacement. To guard against the influence of air currents, the apparatus (called a torsion balance) was enclosed in a room and observed with telescopes mounted on each side.

The result was a remarkably accurate estimate of a parameter called the gravitational constant, and from that Cavendish was able to calculate the density and mass of the earth. Erastothenes had measured how far around the planet was. Cavendish had weighed it: 6.0 x 1024 kilograms, or about 13 trillion trillion pounds. (Ranking: 6)

Young’s light-interference experiment

Newton wasn’t always right. Through various arguments, he had moved the scientific mainstream toward the conviction that light consists exclusively of particles rather than waves. In 1803, Thomas Young, an English physician and physicist, put the idea to a test. He cut a hole in a window shutter, covered it with a thick piece of paper punctured with a tiny pinhole and used a mirror to divert the thin beam that came shining through. Then he took "a slip of a card, about one-thirtieth of an inch in breadth" and held it edgewise in the path of the beam, dividing it in two. The result was a shadow of alternating light and dark bands - a phenomenon that could be explained if the two beams were interacting like waves.

Bright bands appeared where two crests overlapped, reinforcing each other; dark bands marked where a crest lined up with a trough, neutralizing each other.

The demonstration was often repeated over the years using a card with two holes to divide the beam. These so-called double-slit experiments became the standard for determining wavelike motion - a fact that was to become especially important a century later when quantum theory began. (Ranking: 5)

Foucault’s pendulum

Last year when scientists mounted a pendulum above the South Pole and watched it swing, they were replicating a celebrated demonstration performed in Paris in 1851. Using a steel wire 220 feet long, the French scientist Jean-Bernard-Léon Foucault suspended a 62-pound iron ball from the dome of the Panthéon and set it in motion, rocking back and forth. To mark its progress he attached a stylus to the ball and placed a ring of damp sand on the floor below.

The audience watched in awe as the pendulum inexplicably appeared to rotate, leaving a slightly different trace with each swing. Actually it was the floor of the Panthéon that was slowly moving, and Foucault had shown, more convincingly than ever, that the earth revolves on its axis. At the latitude of Paris, the pendulum’s path would complete a full clockwise rotation every 30 hours; on the Southern Hemisphere it would rotate counterclockwise, and on the Equator it wouldn’t revolve at all. At the South Pole, as the modern-day scientists confirmed, the period of rotation is 24 hours. (Ranking: 10)

Millikan’s oil-drop experiment

Since ancient times, scientists had studied electricity - an intangible essence that came from the sky as lightning or could be produced simply by running a brush through your hair. In 1897 (in an experiment that could easily have made this list) the British physicist J. J. Thomson had established that electricity consisted of negatively charged particles - electrons. It was left to the American scientist Robert Millikan, in 1909, to measure their charge.

Using a perfume atomizer, he sprayed tiny drops of oil into a transparent chamber. At the top and bottom were metal plates hooked to a battery, making one positive and the other negative. Since each droplet picked up a slight charge of static electricity as it traveled through the air, the speed of its descent could be controlled by altering the voltage on the plates. (When this electrical force matched the force of gravity, a droplet - "like a brilliant star on a black background" - would hover in midair.)

Millikan observed one drop after another, varying the voltage and noting the effect. After many repetitions he concluded that charge could only assume certain fixed values. The smallest of these portions was none other than the charge of a single electron. (Ranking: 3)

Rutherford's discovery of the nucleus

When Ernest Rutherford was experimenting with radioactivity at the University of Manchester in 1911, atoms were generally believed to consist of large mushy blobs of positive electrical charge with electrons embedded inside - the "plum pudding" model. But when he and his assistants fired tiny positively charged projectiles, called alpha particles, at a thin foil of gold, they were surprised that a tiny percentage of them came bouncing back. It was as though bullets had ricocheted off Jell-O.

Rutherford calculated that actually atoms were not so mushy after all. Most of the mass must be concentrated in a tiny core, now called the nucleus, with the electrons hovering around it. With amendments from quantum theory, this image of the atom persists today. (Ranking: 9)

Young's double-slit experiment applied to the interference of single electrons

Neither Newton nor Young was quite right about the nature of light. Though it is not simply made of particles, neither can it be described purely as a wave. In the first five years of the 20th century, Max Planck and then Albert Einstein showed, respectively, that light is emitted and absorbed in packets - called photons. But other experiments continued to verify that light is also wavelike.

It took quantum theory, developed over the next few decades, to reconcile how both ideas could be true: photons and other subatomic particles - electrons, protons, and so forth - exhibit two complementary qualities; they are, as one physicist put it, "wavicles."

To explain the idea, to others and themselves, physicists often used a thought experiment, in which Young's double-slit demonstration is repeated with a beam of electrons instead of light. Obeying the laws of quantum mechanics, the stream of particles would split in two, and the smaller streams would interfere with each other, leaving the same kind of light- and dark-striped pattern as was cast by light. Particles would act like waves.

According to an accompanying article in Physics World, by the magazine's editor, Peter Rodgers, it wasn't until 1961 that someone (Claus Jönsson of Tübingen) carried out the experiment in the real world.

By that time no one was really surprised by the outcome, and the report, like most, was absorbed anonymously into science. (Ranking: 1)