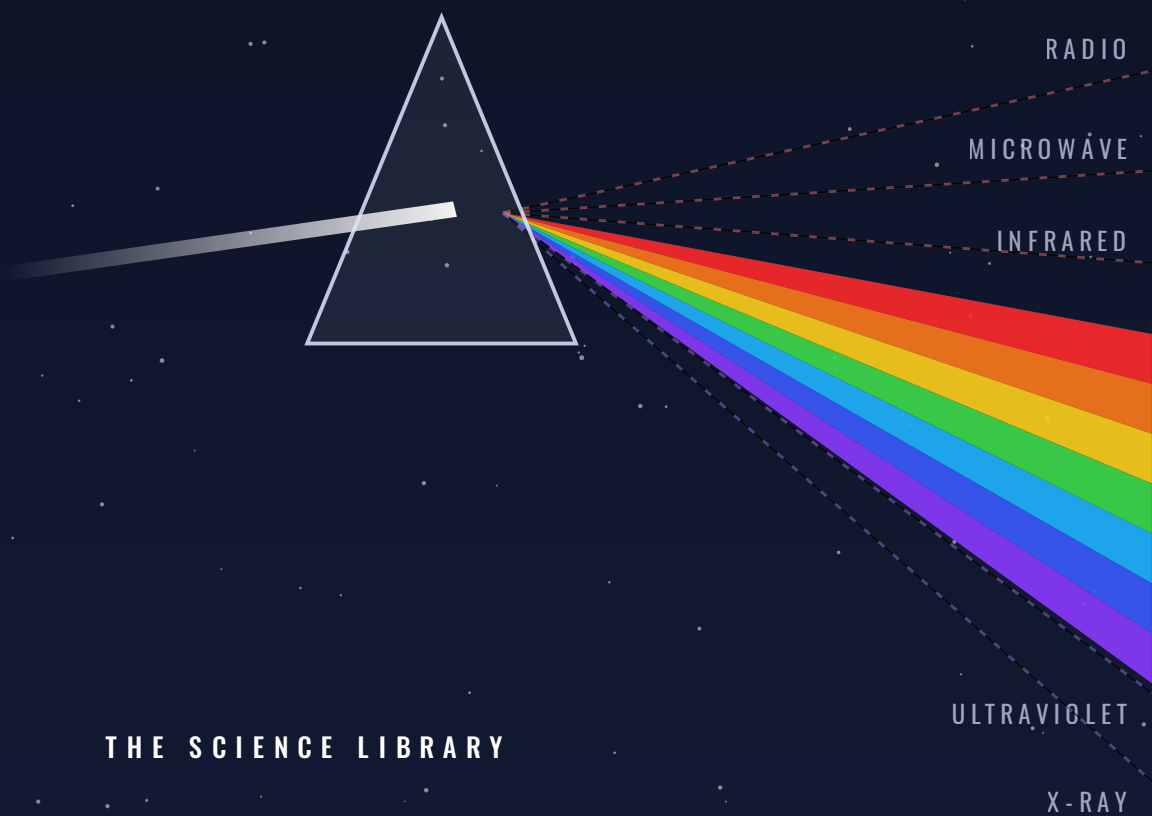


DISCOVERY STORIES · VOLUME I

THE INVISIBLE WORLD

*20 Discoveries That Revealed Light, Electricity and
the Waves We Cannot See*



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The Invisible World

20 Discoveries That Revealed Light, Electricity and the Waves We Cannot See
Discovery Stories · Volume I

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This book is a work of popular history, intended for general education and enjoyment. Names, dates and figures have been checked against standard histories of science; where accounts disagree or a story is uncertain, the text says so. The diagrams are simplified illustrations drawn for this book. The "Try it" activities are classic classroom demonstrations, provided for interest; carry them out at your own risk, follow the safety notes, and supervise children.

Corrections are welcome and will be made in future editions.

First edition, 2026.

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Before You Begin

THE WORLD WE CANNOT SEE

Almost everything that makes modern life work is invisible.

The signal that carries your phone call is invisible. So is the Wi-Fi in your home, the heat radiating from your own body, the X-ray that shows a broken bone and the pulses of laser light carrying this sentence, if you bought this book online, through glass fibers under the ocean. The electricity in the walls is invisible. So is the electron, which makes all of it run.

Two hundred and fifty years ago, nobody knew that any of these things existed. Light was thought to be a stream of particles, or a mysterious instant influence. Electricity was a parlor trick done with rubbed glass. Magnetism was a separate force entirely. The idea that light, electricity and magnetism were all aspects of one thing, and that the visible rainbow is only a tiny slice of a vast spectrum of invisible waves, would have sounded like fantasy.

This book tells the story of how that changed, through twenty discoveries.

HOW THE STORIES WORK

Each chapter is a discovery story. It begins with a moment: a thermometer that warmed in the dark, a frog's leg that twitched, a needle that moved when it shouldn't, a screen that glowed across a darkened room. Then it goes back to explain why that moment mattered, what everyone believed beforehand, who doubted it and how the doubts were settled.

Each chapter ends with the chain: the line of cause and effect running from that first small observation to something in your life today. Science rarely moves in one leap. It moves in steps, each of which looked minor at the time.

You can read the chapters in any order. Each one stands on its own. But they are arranged roughly in the order the discoveries happened, and in four parts that build on each other:

Part One, Light, follows the long argument about what light is, and the discovery that the rainbow extends far beyond what our eyes can see.

Part Two, Electricity and Magnetism, follows the taming of electricity, from sparks and shocks to batteries, motors and generators.

Part Three, The Unseen Waves, shows how light, electricity and magnetism turned out to be one thing, and how that led to radio, X-rays and the electron.

Part Four, The Quantum of Light and the Modern World, follows the discovery that light comes in packets, and the inventions that grew from it: the microwave, the transistor, the laser and the fiber-optic cable.

A NOTE ON ACCURACY

The history of science is full of good stories that are not quite true. Where a famous anecdote is uncertain or disputed, such as Franklin's kite, Faraday's remark about taxing electricity, or the exact wording of a scientist's reaction, this book says so. Dates, names and numbers have been checked against standard histories of science. Where historians disagree, the book tells you that, too.

Numbers are given in metric units, as scientists use them, with everyday comparisons where they help.

WHERE THESE STORIES COME FROM

Many of the chapters in this volume grew out of episodes of Science Retold, a channel that tells the stories behind great scientific discoveries. Some cover subjects the channel has explored on screen, retold here in more depth. Others are new, written for this book. If you enjoy them, there is more in Volume II, *Inside the Atom*, and Volume III, *Cold, Heat and Strange Matter*.

Before You Try the Experiments

Eleven chapters in this book end with a “Try it” box: a simple activity that lets you see a piece of the discovery for yourself.

These are not new experiments. They are classic demonstrations that have been used for generations in classrooms, science museums and educational programs, chosen because they are simple and low-risk. None of them uses household electricity, high voltage, chemicals more dangerous than lemon juice, or anything that needs special equipment.

Even so, please use common sense:

- Children should only try these with an adult.
- Never look at the Sun, directly or through a prism, lens, CD or anything else.
- Read the safety line in each box before you start.
- Strong magnets, small batteries and balloons should be kept away from young children, who can swallow them.
- If anything gets hot, smells of burning or doesn't behave as described, stop.

Results can vary with the weather, the equipment and a little luck. Herschel repeated his thermometer readings many times, and Millikan discarded plenty of oil drops. If something doesn't work the first time, try again.

PART ONE

Light

What is light, and how far does the rainbow really go?

1. The Speed of Light
2. Light Is a Wave
3. Infrared
4. Ultraviolet
5. The Dark Lines in Sunlight

The Speed of Light

A MOON THAT RAN LATE

In the 1670s, an astronomer at the Paris Observatory noticed that one of Jupiter's moons was not keeping time.

The moon was Io, the innermost of the four large moons Galileo had discovered in 1610. Io circles Jupiter once every 42 and a half hours, and on every orbit it passes into Jupiter's shadow and disappears. Those disappearances are about as regular as anything in the sky. In the seventeenth century, that regularity was valuable. If you could predict exactly when Io would vanish, as seen from Paris, then a navigator anywhere on Earth who watched the same event and noted his own local time could work out how far east or west of Paris he was. Jupiter's moons were, in principle, a clock that every ship at sea could read.

The work of making that clock usable fell to the observatory's director, the Italian-born Giovanni Domenico Cassini, and to a young Danish astronomer named Ole Rømer, who had arrived in Paris in 1672. Their job was to time the eclipses as precisely as possible and build tables that would predict them years ahead.

The trouble was that the eclipses would not stay on the timetable.

When Earth, in its own orbit around the Sun, was moving away from Jupiter, Io's eclipses arrived later and later than predicted. When Earth swung around and approached Jupiter

again, they arrived early. The errors were not random. They grew and shrank in step with the distance between the two planets. Across the whole cycle, the difference added up to many minutes.

Rømer's explanation was simple, and for its time it was radical. Io was not running late. The news of Io's disappearance was. The light carrying the image of the eclipse had to cross the space between Jupiter and Earth, and when that space was larger, the light took longer to arrive.

That meant light took time to travel. It had a speed.

WHAT EVERYONE ALREADY KNEW

To see why this was a hard sell, you have to know what educated people believed about light in 1676.

Most of them believed that light did not travel at all, at least not in the sense that a ball or a sound travels. It was simply there, instantly, from source to eye. Aristotle had argued this. René Descartes, the most influential natural philosopher of the century, had built light into his whole system of physics as a pressure transmitted instantaneously through a medium, and he reportedly said that if light were shown to take time to travel, his philosophy would be overturned.

There had been attempts to test it. Galileo described an experiment in which two people stood on distant hills with covered lanterns. The first would uncover his lantern; the second, on seeing the light, would uncover his; the first would time how long it took to see the reply. Galileo reported that over short distances he could not detect any delay. That was a fair result. Over a few kilometers, light takes a few millionths of a second, far less than any human reaction. The experiment could not distinguish "infinite" from "very fast".

Rømer's method could, because it used a distance no laboratory could match: the width of Earth's orbit.

In September 1676, Rømer reportedly predicted to the Academy of Sciences that an eclipse of Io expected in November would come about ten minutes late. When it did, the prediction made an impression. Rømer's reasoning was published in December 1676 in the Academy's journal. His figures implied that light needed about 22 minutes to cross the full diameter of Earth's orbit.

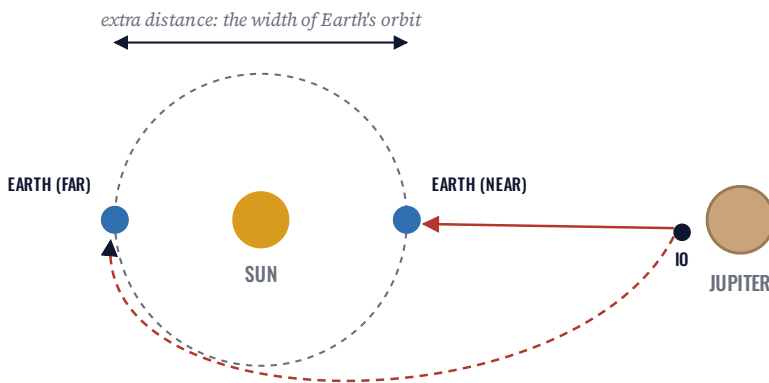


Figure 1. Rømer's reasoning. When Earth is on the far side of its orbit, light from Io must cross the extra width of the orbit, so each eclipse is seen later. Rømer's data implied about 22 minutes for that crossing; the true figure is about 16 minutes 40 seconds. (Not to scale.)

A REJECTED IDEA THAT WOULD NOT GO AWAY

Cassini did not accept it.

His objections were not foolish. Cassini pointed out that if light were really the cause, the same delays should show up in the eclipses of Jupiter's other moons, and the data for those moons were too messy to confirm it. He suspected that the

irregularities came from something about Io's orbit that had not yet been understood. And the observations were hard. Timing the moment a tiny point of light vanishes, through a seventeenth-century telescope, with seventeenth-century clocks, left plenty of room for error.

Others took Rømer seriously. The Dutch physicist Christiaan Huygens, who had his own theory of light as a wave spreading through a medium, combined Rømer's delay with the best available estimate of the distance from Earth to the Sun and published a figure for the speed of light in 1690: roughly 220,000 kilometers per second in modern units. In England, Isaac Newton accepted that light had a finite speed and estimated that sunlight reached Earth in about seven or eight minutes.

The number was too low. The modern value is close to 300,000 kilometers per second, and sunlight takes about 8 minutes and 20 seconds to reach us. Most of the error came not from Rømer's timing but from the distance to the Sun, which nobody knew well. But the central claim was right. Light took time.

What the idea needed was a second, completely independent piece of evidence. That evidence arrived about fifty years later, and it came from someone who was looking for something else entirely.

THE STAR THAT MOVED THE WRONG WAY

In 1725, the English astronomer James Bradley set out to measure the distance to a star.

His target was Gamma Draconis, a fairly bright star in the constellation Draco that happens to pass almost directly overhead in London. Bradley and his colleague Samuel Molyneux mounted a long telescope vertically at Molyneux's house in Kew, pointing straight up, so that they could measure

tiny changes in the star's position without the distortions caused by looking through a thick slice of atmosphere near the horizon.

The goal was stellar parallax. If Earth really orbits the Sun, then a nearby star should appear to shift back and forth slightly over a year, the way a finger held in front of your face shifts against the background when you look at it with one eye and then the other. Parallax had never been detected, and detecting it would be direct proof of Earth's motion.

Bradley did see the star move. Over the year it traced out a small ellipse in the sky, about 40 seconds of arc across, which is roughly the width of a coin seen from a hundred meters away. But the motion was wrong. Parallax should make the star's shift greatest when Earth was at the far sides of its orbit relative to the star. Bradley's shift was greatest three months out of step with that, at the points where Earth was moving fastest toward or away from the star's direction.

The pattern did not match position. It matched velocity.

The explanation reportedly came to him on a boat on the River Thames, when he noticed that the little flag at the top of the mast changed direction every time the boat changed course, even though the wind had not changed. What the flag showed was the combination of the wind's motion and the boat's motion.

Starlight works the same way. Picture walking through rain that falls straight down. If you stand still, you hold your umbrella straight up. If you walk forward, the rain seems to come at you at an angle, and you tilt the umbrella forward to stay dry. A telescope on a moving Earth has to be tilted very slightly in the direction of Earth's motion to catch the light of a star, and as Earth's direction changes through the year, the tilt changes too. The star appears to trace a small circle or ellipse.

Bradley called the effect the aberration of light, and he announced it in 1729. The size of the effect depends on just one

ratio: Earth's orbital speed divided by the speed of light. Since Earth's orbital speed could be worked out from the size of its orbit, the aberration gave a new way to calculate the speed of light. Bradley's result was that light from the Sun reaches Earth in about 8 minutes and 12 seconds. That is within a couple of percent of the modern value.

Two completely different phenomena, the timing of Io and the tilt of starlight, now pointed to the same conclusion. Light was fast, but it was not infinitely fast. After Bradley, few serious astronomers doubted it.

Bradley never found the parallax he was looking for. Stellar parallax was first measured in 1838, by Friedrich Bessel. But in failing, Bradley had produced the first precise measurement of the speed of light, and also the first direct evidence that Earth moves through space.

BRINGING LIGHT DOWN TO EARTH

Both of these measurements shared a weakness. They depended on astronomical distances that were themselves uncertain. If you got the size of Earth's orbit wrong, you got the speed of light wrong. The next step was to measure light's speed over a distance you could survey on the ground, with apparatus you could build and inspect.

The difficulty was the timescale. Light crosses a kilometer in about 3.3 millionths of a second. No clock in the eighteenth or early nineteenth century could time that. The answer, when it came, was not a better clock but a cleverer machine.

In 1849, the French physicist Hippolyte Fizeau set up a light source and a rapidly spinning toothed wheel at his parents' house in Suresnes, west of Paris. Light shone out through a gap between two teeth, traveled about 8.6 kilometers to a mirror on the hill of Montmartre, bounced back, and returned to the wheel.

Here is the trick. If the wheel is turning slowly, the returning light passes back through the same gap it left through, and the observer sees it. Speed the wheel up, and there comes a point where, in the time the light takes for its 17-kilometer round trip, the wheel has turned just far enough for a tooth to move into the gap. The returning light is blocked, and the observer sees darkness. Spin faster still, and the light gets through the next gap.

Fizeau's wheel had 720 teeth. By noting the rotation rate at which the light first disappeared, and knowing the distance, he could calculate the travel time without ever measuring a millionth of a second directly. His result was about 313,000 kilometers per second, a few percent high, but obtained entirely on the ground.

A year later, his rival Léon Foucault improved the method by replacing the toothed wheel with a rapidly rotating mirror. Light bounced off the spinning mirror to a distant fixed mirror and back. In the brief moment the light was away, the spinning mirror turned through a tiny angle, so the returning beam was deflected slightly. Measuring that deflection gave the travel time. By 1862, Foucault had a value of about 298,000 kilometers per second, much closer to the truth.

THE EXPERIMENT THAT SETTLED AN OLDER ARGUMENT

Foucault's rotating mirror did something else, and in some ways it mattered more than the number.

For a century and a half, two theories of light had competed. Newton had favored the idea that light was a stream of tiny particles. Huygens, and later Thomas Young and Augustin Fresnel, argued that light was a wave. Each theory could explain why light bends when it passes from air into water, but they explained it in opposite ways. Newton's particle theory required

light to travel faster in water than in air. The wave theory required it to travel slower.

Nobody had been able to test this, because nobody could measure the speed of light in a tank of water. With a rotating mirror, the light path could be short enough to pass through a tube of water. In 1850, Foucault, and separately Fizeau working with the instrument maker Louis Breguet, compared the speed of light through water with its speed through air.

Light was slower in water. The particle theory, at least in the form Newton had left it, was wrong. The wave theory had passed a direct test.

LOOKING FOR THE WIND

If light was a wave, it raised an obvious question: a wave in what? Sound is a wave in air. Ripples are waves in water. Physicists assumed that light must be a wave in some invisible substance filling all of space, which they called the luminiferous ether.

If the ether existed, Earth was moving through it at around 30 kilometers per second on its way around the Sun. To an observer on Earth, that should feel like a wind blowing through the laboratory, and light traveling with the wind should go slightly faster than light traveling across it.

In 1887, at what is now Case Western Reserve University in Cleveland, Albert Michelson and Edward Morley built an instrument sensitive enough to detect that difference. Their interferometer split a beam of light in two, sent the halves along perpendicular arms, and recombined them. If one half took even slightly longer than the other, the recombined light would show a shift in its pattern of bright and dark bands. The whole apparatus floated on a pool of mercury so it could be turned smoothly in any direction.

They expected a clear shift. They found almost nothing, far less than the ether theory required. Light seemed to travel at the same speed in every direction, no matter how Earth was moving.

It was one of the most important failed experiments in the history of science. Physicists tried to rescue the ether. George FitzGerald and Hendrik Lorentz independently proposed that objects moving through the ether shrink slightly in the direction of motion, by exactly the amount needed to hide the effect. The equations worked, but the explanation felt contrived.

In 1905, Albert Einstein took a different approach. In his paper on special relativity, he simply took it as a starting principle that the speed of light in empty space is the same for every observer, however they are moving. From that single assumption, and the principle that the laws of physics are the same for everyone moving steadily, came everything else: that moving clocks run slow, that moving objects are shortened, and that mass and energy are related through the speed of light, in the famous equation $E = mc^2$. The ether was not hidden. It was unnecessary.

A NUMBER THAT BECAME A DEFINITION

Michelson spent much of his life measuring the speed of light ever more precisely. In the 1920s he used a rotating eight-sided mirror and a light path between Mount Wilson and Mount San Antonio in California, about 35 kilometers apart, with the baseline surveyed by the US Coast and Geodetic Survey with great accuracy. His 1926 result was 299,796 kilometers per second, within a few kilometers per second of the modern value.

Later methods, using radio waves, microwaves and lasers, pushed the precision so far that the measurement of light's speed became more accurate than the definition of the meter itself. So in 1983, the world's measurement authorities turned the

problem around. They defined the speed of light to be exactly 299,792,458 meters per second, and defined the meter as the distance light travels in a vacuum in $1/299,792,458$ of a second.

The speed of light is no longer measured. It is fixed by definition, and length is measured against it.

THE CHAIN

A satellite-based global positioning system depends on timing radio signals that travel at the speed of light; errors of a few billionths of a second would put you on the wrong street. The meter on every ruler is defined by that speed. Einstein built relativity on it. Michelson and Morley found that it did not change with Earth's motion. Foucault measured it in water and settled a century-old argument about the nature of light. Fizeau measured it with a spinning cogwheel and a mirror on a hill.

And before all of them, Bradley saw a star tilt the wrong way, and Rømer watched a small moon of Jupiter disappear a few minutes later than the tables said it should.

Rømer was not trying to measure the speed of light. He was trying to build a clock for sailors. He found a delay that would not go away, and he refused to explain it away.

KEY DATES

1676	Ole Rømer explains the late eclipses of Io: light takes time to travel
1729	James Bradley announces the aberration of starlight
1849	Hippolyte Fizeau measures light's speed with a toothed wheel
1850	Light is shown to travel slower in water than in air
1887	Michelson and Morley find no sign of the ether
1905	Einstein's special relativity makes light's speed the same for everyone
1926	Michelson measures 299,796 km/s between two California mountains
1983	The meter is defined by the speed of light