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Speed limit: how the search for an absolute frame of reference in the Universe led to Einstein's equation $E=mc^2$ — a history of measurements of the speed of light

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Abstract

This article describes one of the greatest intellectual adventures in the history of mankind — the history of measurements of the speed of light and their interpretation (Spence 2019). This led to Einstein's theory of relativity in 1905 and its most important consequence, the idea that matter is a form of energy. His equation $E=mc^2$ describes the energy release in the nuclear reactions which power our sun, the stars, nuclear weapons and nuclear power stations. The article is about the extraordinarily improbable connection between the search for an absolute frame of reference in the Universe (the Aether, against which to measure the speed of light), and Einstein's most famous equation.

Introduction

In 1900, the field of physics was in turmoil. Despite the triumphs of Newton's laws of mechanics, despite Maxwell's great equations leading to the discovery of radio and Boltzmann's work on the foundations of statistical mechanics, Lord Kelvin's talk[1] at the Royal Institution in London on Friday, April 27th 1900, was titled "Nineteenth-century clouds over the dynamical theory of heat and light." In it, he cited the recent failed attempts by Michelson and Morley to detect the Aether, and the black-body radiation problem as the two great unsolved problem of physics. The Aether was a ghostly invisible vortex foam believed to fill all space and to provide an absolute stationary reference frame, through which the Earth was speeding along at about 70,000 mph around the Sun, creating an "Aether wind" on Earth. Maxwell had successfully used this concept of the Aether to derive his equations, with light travelling at a fixed speed with respect to the Aether frame of reference. If we consider waves running along a river in which there is a current, it was understood that the waves "pick up" the speed of the current. But Michelson in 1887 could find no effect of the passing Aether wind on his very accurate measurements of the speed of light, no matter in which direction he measured it, with headwind or tailwind. This could not be reconciled with Maxwell's work, which treated the Aether as a fixed frame of reference. Only Einstein was to clarify all of this in one of his great papers of 1905, by introducing his theory of relativity, and later that year the mass–energy equation which it predicted.

The solution of the first problem identified by Kelvin led to Einstein's relativity in 1905; the solution of the second led to the birth of quantum mechanics. By this time the ageing Kelvin had become very opinionated. Like Max Planck, he had worked on the problem of the energy balance between light emitters and absorbers in black-body

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[1] Kelvin (1901).

radiation. He was well known not to be a good listener, unlike the great physicists Rayleigh and Stokes. J.J. Thomson, the discoverer of the electron in 1897, said of him, in this regard, that "he was a counter-example to the idea that a good emitter is a good absorber."

Author's Note: In view of the technical sophistication of many of the ideas, the difficulty of seeing things through the eyes of a mediæval philosopher and mystic such as Kepler, for example, and the subtlety of historical context (our view of the past depends on the present) I've tried to emphasize the underlying concepts and personalities instead, and to explain them in clear simple language, perhaps to the point of oversimplification. Much fuller historical detail, context, interpretation and mathematical analysis can be found in the extensive list of references, particularly in the texts by Whittaker (1910),[2] Darrigol (2000),[3] Hunt (1994),[4]Weinberg (2015)[5] and Filonovich (1986),[6] and other professional historians of science. The books by Richard Holmes (2008), Richard Rhodes (1986), and Malcolm Longair (2003)[7] are particularly recommended.

The speed of light before Rømer

Two great questions have perplexed scientists from the time of the ancient Greeks: how can light reach us from the distant stars across the vastness of empty space — what medium supports the light waves or particles in a vacuum? — and at what speed does it travel — is it instantaneous, as most believed, or does it take time, as the Greek philosopher Acragas (BC 490–435) believed, so that when we look at the stars we are looking back in time? In addition to his great book *Elements* on geometry, Euclid had also written a book on *Optics* (Burton 1945), in which he suggested that vision was based on rays ("visual fire") shooting out from the eye at the things we look at, and in this way was able to explain changes in perspective. (In fact the eye receives light from the sun reflected from objects). Euclid avoids trying to explain why we cannot see at night. Galileo, in a book published in 1638, speculates on the speed of light, proposing experiments using people on mountain tops signalling to each other with shuttered lanterns to measure the speed of light. Since that speed is about 186,000 miles per second, this could never have worked, but it was actually tried experimentally in 1667 by the Florentine Academy.

Studies by Fermat and Descartes in 1637 of the phenomenon of refraction, the bending of light rays entering a new medium, were based on the concept of a refractive index, the ratio of the speed of light in vacuum to that in the medium, using Snell's

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[2] Whittaker is comprehensive, advanced and authoritative, with full mathematical analysis in modern notation. British emphasis, and later editions with important changes.

[3] A comprehensive, modern historical view, providing depth and insight. Equations in all four systems of units, and relationship between them.

[4] An excellent account of those who came after Maxwell (Lodge, FitzGerald, Heaviside, Hertz, Larmor) and their contributions as founders of modern classical electrodynamics.

[5] An excellent survey of the history of astronomy from the Greeks to the time of Newton, with simple mathematical derivations in appendices.

[6] An excellent short account of the topic of this article, with simple equations.

[7] A superb account of the history of fundamental theoretical concepts in physics, together with all equations in consistent modern form.

law.[8] This work, and that of Christiaan Huygens in his 1679 book *Traité de la Lumière* left the community of scientists divided for more than a century into two groups. There were those ("corpusculists") who believed that light was a stream of particles which sped up on entering a denser medium, and those ("undulationists"), like Huygens, who believed it was a wave which slowed down. The modern view is that light travels as a wave and arrives as a particle.

None of this answered the old question of what medium supports starlight in the vacuum of outer space, as air does for sound-waves. It was known that the speed of sound waves is given by the square root of the elastic modulus (Young's Modulus,[9] a measure of the stiffness of a material) divided by the square root of its density. For the enormous speed of light, one had to assume that the Aether (filling the vacuum of outer space) had a density similar to steel, but was also 3600 million times stiffer than steel. At the same time, it must not impede the motion of the planets, and it must be invisible, and permeate all forms of matter. Yet physicists clung to this notion of an Aether well into the twentieth century — it is fair to say that no physicist born before about 1900 (including Michelson himself, and even Lorentz, whom we will meet later in this essay) would say with certainty that it did not exist.

Ole Rømer

In 1676 the Danish scientist Ole Rømer was the first to make a reasonably accurate measurement which gave the speed of light, in one of the greatest experiments in the history of physics (Cohen 1940). But the story starts earlier, in 1598, when Ferdinand II, the King of Spain, established a prize for the determination of longitude. This is the distance, for example, which a ship might travel around the equator. By keeping the noon-day sun overhead (or the Pole Star in the same position at night) they could be sure they were sailing along the equator, that is, at constant latitude. Spain was losing many ships at sea due to poor navigation and piracy, and the military and commercial value of a reliable method of longitude determination was clear. Knowing that ships must stick to the equator to avoid getting lost, pirates could lie in wait anywhere along their path. In 1610, with his newly improved telescope, Galileo had discovered some of the moons of Jupiter, including Io. He realized that the eclipses of Io, as it disappeared behind Jupiter every 42.5 hours could be used as a universal clock (ticking every 42.5 hours) for mankind, since it could be seen from anywhere on Earth. So by using these eclipses to keep track of time at home in Spain while sailing around the world, and using the maximum height of the Sun each day to determine local noon, it would be possible to measure the time-difference between home and one's current location. This time difference, as we all know from international air travel, can tell us how far around the world we have travelled. A twelve-hour time difference takes us halfway around the planet.

Galileo's method was fine, and has been used on land for centuries since, but he did not win the prize because the ships rocked too much to allow accurate sightings of the eclipses of Io through a telescope. (Harrison's chronometer, with its torsion pendulum immune to the rocking of ships, did not appear until 1761.) In 1671, Cassini, the

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[8] On refraction. See https://en.wikipedia.org/wiki/Snell%27s_law [Ed.]

[9] See https://en.wikipedia.org/wiki/Young%27s_modulus [Ed.]

head of the Paris Observatory (still standing today) decided to test Galileo's method by measuring the longitude difference between Paris (longitude zero) and one of the few places whose longitude was known. This was Tycho Brahe's old observatory at Uraniborg (now a Brahe museum) on the island of Hven near Copenhagen. Cassini asked his colleague Professor Bartholin at Copenhagen to do this, and Bartholin took along his graduate student Ole Rømer, shown in **Figure 1**. Bartholin, a mathematician, later became famous for his discovery of birefringence. The group made many observations of Io at recorded times before Rømer took the observations back to Paris for analysis. They had found that the time difference between when the Sun was directly overhead in Paris and in Uraniborg was about forty-two minutes, due to the rotation of the Earth. If Uraniborg had been due west of Paris on the equator (it isn't), then the ratio of forty-two minutes to twenty-four hours should be equal to the distance between Paris and Uraniborg divided by the circumference of the Earth.

Figure 1. Ole Rømer. (From Google Images.)

But Rømer noticed that some of the Io eclipses were up to ten minutes late. He attributed this to the fact that light travels with a finite speed. This was a remarkably bold assumption at the time for a very young scientist. The situation is shown in **Figure 2**, in the original figure published by Rømer in 1676 in his paper, which eventually appeared in English in the *Philosophical Transactions of the Royal Society*. If the Earth were stationary at L (or moving near H), an observer on the Earth would measure a time interval of 42.5 hours between eclipses, the times at which Io (moving anticlockwise) first appears from behind Jupiter at D. But if the Earth moves from L to K while Io is performing its orbit, the measured time between eclipses will be longer by the time it takes light to travel from L to K to catch up with the Earth. The Earth moves at about 30 Km per second or 18.6 miles per second relative to the Sun, and so moves about 2.8 million miles between eclipses. On the other hand, if, six months later, the time between eclipses is measured while the Earth is moving toward G in an anticlockwise direction, light will have less distance to travel and this time will be shorter. This was Rømer's explanation for the variations in orbital periods of Io found among many observations at Uraniborg. His explanation gave the strongest evidence to date that light does not travel instantaneously, and if the diameter of the Earth's orbit around the Sun were known, and hence the Earth's speed, it could be used to estimate the speed of light with reasonable accuracy for the first time.

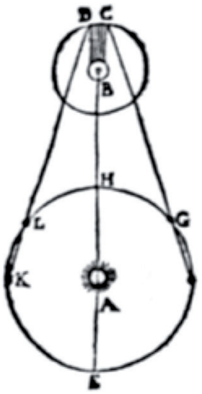

Figure 2. Rømer's original diagram (1676). The Sun at A, orbited by the Earth at K with Jupiter at B and its moon Io at C. (From Cohen 1942.)

Rømer made a prediction in September 1678 at an address to the Académie des Sciences in Paris that the November 9 eclipse of Io would be late by ten minutes. He added that he could further estimate that it would take light eleven minutes to travel from the Sun to Earth (the modern value is eight minutes and nineteen seconds). The confirmation of this prediction brought him immediate recognition and established his reputation as a scientist. The delay was important, since it would lead to errors in navigation. By using the best estimate then available for the distance between Earth and Sun (one Astronomical Unit, or AU), and knowing the Earth's period of a year, and hence its speed, one could then also estimate the speed of light. The best estimate of one AU, due to Cassini, had been obtained by the highly inaccurate method of parallax, and was rather fortuitously only in error by about 6%. In fact it was Christiaan Huygens who, in 1690, first used Rømer's time delay measurement to get a speed for light, which was within 15% of the modern value.

Newton (who met Rømer during his visit to England in 1679) duly took note of all this, and we can compare Newton's "action at a distance" theory of gravity, which assumed (incorrectly) that gravitational forces act instantaneously across the Universe, with his acceptance of a finite speed for light. Newton's ideas on gravity owed much to Robert Hooke. Since Kepler's laws (Love 2015), which provided a simple relationship between the period of a planet and the radius of its orbit, were well known at this time, the approximate radii of all the planetary orbits could be found from their known periods once that of one (the Earth) had been found.

Rømer, a Protestant in Catholic France, eventually had to leave Paris due to prejudice against his religion. He became Professor of Mathematics at Copenhagen University and Astronomer Royal. There were many notable achievements in his later career, including his appointment as Chief Justice of the Supreme Court of Copenhagen, Mayor of Copenhagen, and his reform of the tax system. In science he invented the epicycloid gear shape for reducing gear friction, and devised the modern two-point "Fahrenheit" temperature scale, essentially inventing the thermometer. He was unlucky in that practically all of his observations were destroyed in a fire at his observatory in 1728, but some were rescued by his devoted assistant Peder Horrebow, as vividly described in his book (still in print, in Latin (Horrebow 1735)). Rømer also sent observations to friends, which have survived, and maintained a "commonplace book" for notes, entitled *Adversaria*, which he kept by his window at the library of the University of Copenhagen. Remarkably, this book was discovered, still there, early in the last century, and has since been published. A modest and generous man, he died in 1710. **Figure 3** shows him at work in his observatory.

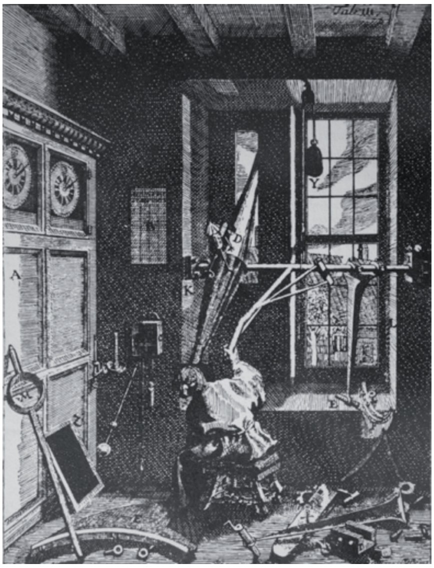

Figure 3. Rømer's transit telescope. Note pendulum clock and counterweights. (From Horrebow 1735.)

Measuring the cosmos

Rømer had measured a time delay, and to convert this to the speed of light he needed accurate distance measurements. The Greek astronomer Eratosthenes (BC 276–194) had used measurements of the length of the shadow of a stick at the same time in two cities to give an estimate of the size of the Earth within 15% of the correct value. The Greek's estimate of the Sun–Earth distance (actually about 93,000,000 miles), although based on sound trigonometric principles (such as the right-angle triangle which occurs at half-moon) were at least twenty times too small, since they had no method for measuring angles accurately (Weinberg 2015). Astronomers became obsessed with determining the path and predicting the motions of the planets, and measuring the distances to the Sun, planets and stars. For a simple mathematical description of the methods used by early astronomers such as Ptolemy, Copernicus and Kepler (the first to show that planets moved in an elliptical orbit), see Hoyle (1973). The parallax method for measuring distances is shown in **Figure 4**. But for the nearest star, this angle is equivalent to observing a one-inch diameter disk at a distance of 4.2 miles. A telescope was clearly needed. It was not until 1838 that Bessel provided an accurate measurement to a nearby star using parallax.

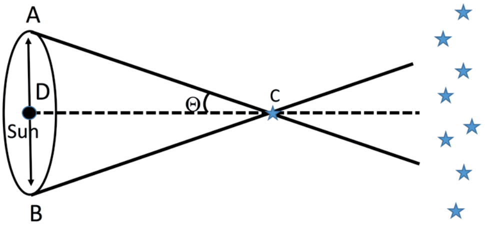

Figure 4. The principle of parallax used to measure stellar distances from Earth. The Earth orbits the Sun around the circle AB with diameter D. A planet is shown at C against a background of fixed stars at right. A different group of background stars will be seen behind the planet if we observe first from A, then six months later from B. This allows angle Θ to be measured. If the baseline AB is known, the distance DC can be found by trigonometry. The diameter of the Earth can also be used as a baseline.

But for the Earth–Sun distance (one AU), the most important improvement on Cassini's value came with the Transit of Venus expeditions during the eighteenth century (Wulf 2012). **Figure 5** (left-hand figure) shows an amateur astronomer's photograph taken in Melbourne of the 2012 transit, when Venus passed across a line drawn from the Earth to the Sun, so that its shadow is seen as a black dot crossing the Sun's bright disk. Using a lens (or a pin-hole) in the window facing the Sun, this image of the Sun can be projected onto an opposite wall in a dark room, and the motion of Venus traced out as it crosses the Sun over a period of hours, the time being noted. Jeremiah Horrocks, who died at the age of 22, did exactly that in 1639 from a house (still standing) near Preston in the UK, and from this observation obtained a value of the Earth–Sun distance of about 60 million miles (Aughton 2004). But predicting when these transits would occur, and the times and places on Earth from which they could be seen, was no easy task. Kepler (1571–1630) had made approximate predictions, and James Gregory in 1663 had shown how the Earth–Sun distance could be obtained from a similar transit of Mercury. The Venus transits occur in pairs eight years apart about once a century.

Figure 5. At left, amateur astronomer's photograph of the 2012 Transit of Venus. Taken in Melbourne Australia using 300 mm lens on June 6 2012 between 9.45 am and 10.45 am. Nikon D7000 camera with adjustable neutral density filter to attenuate the sun's light, fast shutter speed, small aperture. ISO 100. Venus (the black dot near the bottom) is shown crossing the sun's disk. At right, Venus (bright dot) is photographed near the Moon. (Author's copy.)

With the advent of Newton's theory of elliptical planetary orbits (consistent with Kepler's laws), more accurate predictions became possible, and it was Edmund Halley (1656–1742) who predicted the transits of 1761 and 1769, suggesting their use to determine the Astronomical Unit (AU). Halley, who died before it could be done, was a colleague of Newton, Hooke and Wren around the time of the founding of the Royal Society in London. The method proposed by Halley and Gregory is similar (but more complicated) than that shown in Figure 4, but now using the width of the Earth as a baseline. Observations of the transit from opposite sides of the Earth at the same moment will show Venus projected onto a different point on the Sun's disk in the shadow images. If many such observations are made across the Earth at known times, simple Euclidean geometry together with Kepler's laws will show that the distances between Earth and Sun (and to Venus) can then be found, given the diameter of the Earth, the latitude and longitude of the observations, and their local time. Telescopes and pendulum clocks were therefore the equipment taken by astronomers to all corners of the Earth in this first international scientific collaboration in 1761, organized by the Académie Française in Paris, resulting in tracings of the images of the transit drawn on paper. Many disasters attended this first attempt, from disease (dysentery), bad weather, war (between the French and British), piracy, inaccurate longitude determination, and perhaps a cloudy sky at the time of the transit, or a transit which occurred just before sunrise.

Much was learnt from these problems, and national rivalry became a spur to greater efforts for the second transit in 1769. The collaboration was organized by the Royal Society and strongly supported by George II, Catherine the Great, the Académie Française, Benjamin Franklin, and including James Cook. About 250 astronomers contributed from many nations at 130 locations. Points of observation included Baja California (in Mexico, south of Phoenix, Arizona) and Tahiti (by Cook), the selection depending partly on the need to use locations of known longitude and good transit visibility.

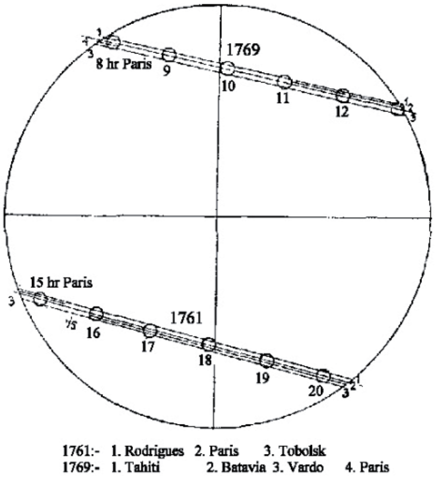

Figure 6. A summary of the observations of the 1761 and 1769 Transit of Venus observations across the sun's disk, as seen from different locations and times on earth. The Venus parallax angle (akin to angle Θ in Figure 4) is, for example, the angle between lines 1 and 3 measured down the page, based on the known angular diameter of the sun. The uppermost line across from the 1769 observations was observed from Tahiti, a lower one from Paris. (From European Southern Observatory web page, Transit of Venus.)

Figure 6 shows the published results, giving the tracks of Venus's shadow across the Sun for both expeditions. The final publication and analysis of all the results in *Philosophical Transactions* in 1771 gave a distance of 93,726,900 miles for the Earth–Sun distance, differing by less than one percent from the modern value. This was a great triumph for international collaboration and the science of the enlightenment: the President of the Royal Society, Joseph Banks, commented that "The science of two nations may be at peace, while their politics are at war."

We have detailed records of Cook's role in all this, as part of his voyage of exploration to Australia in *Endeavour*, with 94 men and 8,000 pounds of sauerkraut against scurvy (Beaglehole 1968). Cook was given written instructions to respect any native peoples, since "no European nation has any right to occupy any part of their country," and to explore the "unknown land of the South, Terra Australis Incognito." He chose the island of Tahiti at Point Venus, the name it has retained, on which to set up his telescopes and clocks in 1769, one of the few places in the Pacific ocean whose latitude and longitude were accurately known, as shown in **Figure 7**.

Figure 7. Cook's Endeavour at Fort Venus, Matavai Bay, Tahiti, for Transit of Venus observations in 1769. (Author's copy.)

As Cook wrote in his diary:

> This day prov'd as favourable to our purpose as we could wish, not a Clowd was to be seen the whole day and the Air was perfectly clear, so that we had every advantage we could desire in Observing the whole of the passage of the Planet Venus over the Suns disk: we very distinctly saw an Atmosphere or dusky shade round the body of the Planet which very much disturbed the times of the Contacts particularly the two internal ones. Dr. Solander observed as well as Mr. Green and my self, and we differ'd from one another in observing the times of the Contacts much more than could be expected. Mr Greens Telescope and mine were of the same Magnifying power but that of Dr Solander was greater than ours.

After many adventures (Holmes 2008), Cook returned to England and a hero's welcome, with his observations intact and a vast array of new botanical species collected by Banks. The First Fleet colonizing Australia arrived from Britain soon after at Botany Bay in 1788.

The movement of Venus across the Sun darkens the Sun very slightly. Detecting this darkening is one method which is now used in the search for new planets around stars (exoplanets). A dip in a star's brightness is sought as a planet crosses a line from the star to Earth. This is exactly what happens in a Venus transit under much better understood conditions, which can be used to accurately measure and calibrate the effect. Venus darkens our sun to 99.9% of its unobstructed value, showing how difficult is this search for exoplanets.

James Bradley — the aberration of starlight

James Bradley (1693–1762) is crucial to the history of lightspeed measurement because his entirely new astronomical method provided the first experimental evidence in support of Copernicus's theory that the Earth orbited the Sun, and because of the support it provided for Einstein's relativity. Bradley, in his 1729 publication,[10] provided irrefutable evidence for a finite speed for light, while also producing a measurement of the time for light to travel from Sun to Earth within 2% of the modern value (Stewart 1964). The story is told that he had his crucial idea while sailing on the Thames, comparing the direction of the wind with that of a weather vane on his boat when it turned. The vane, which one would think would always be lined up with the constant wind direction, regardless of the direction the boat was headed, seemed to turn with the boat, even when the wind direction was steady, which was hard to understand. For sailors, this relative velocity effect is familiar: the faster you go when windsurfing, the more the wind appears to swing around to come from a more forwardly direction. For Bradley, the wind was akin to light arriving from a distant star, the boat akin to the Earth. This observation explained to him how the apparent direction of starlight[11] could depend on the Earth's velocity across the stream of photons falling on Earth from an overhead star. His work gave much greater confidence and credibility to Rømer's earlier result, at a time when many still believed that light travelled instantaneously, or did not accept the Copernican idea that the Earth orbits the Sun.

Bradley undertook his observations from his house near Kew in London, using a telescope mounted vertically against the internal side of a chimney, so that he could lie in comfort on a couch below it looking upward for observations over many years. He chose a star near the Pole Star and set out to measure parallax, hoping to support the theories of his near-contemporary Newton. But his star appeared to move in a small circle throughout the year, when he compared the direction of the axis of his telescope with that of a plumb bob, which gave the local vertical direction. (Any motion of the plumb bob was damped by immersing the bob in water).

These changes in the direction of the light from a star can also be understood from the way in which we must tilt an umbrella forward, when walking in the rain. The faster we walk, the more tilt is needed. Similarly, a

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[10] See https://royalsocietypublishing.org/doi/abs/10.1098/rstl.1727.0064

[11] Its *aberration*.

telescope will need to be pointed ahead of a star to see it, in the direction of the Earth's motion across the starlight. Equivalently, if the telescope is not tilted, the photons entering it will hit the sides of the telescope tube, as the Earth carries the tube forward, before they reach the observer's eye. Bradley could show that the tangent of this tilt angle is $\beta = v/c$, where v is the speed of the Earth, and c the velocity of light, as shown in Resnick (2018). This constant β became of crucial importance in Einstein's theory. His method therefore gave the speed of the Earth's motion around the Sun, given, for example, Huygens' value for the speed of light. Alternatively he could estimate the speed of light using, for example, Cassini's value for the Earth–Sun distance to obtain the speed of the Earth in orbit. His work was also important for the debate concerning the existence of the Aether, supposedly at rest in the Universe and supporting the propagation of light waves. One resolution to the paradoxes confronting physics in 1900 was the "complete Aether drag" idea that the Aether was fixed to the Earth, rotating with it, a most unlikely scenario. In that event, no tilt of Bradley's telescope would be needed, since the lightwaves are fixed to the Aether. Bradley's careful systematic work over many years was a major contribution to the development of quantitative methods in astronomy. He had shown that indeed "the Earth moves,"[12] supporting Copernicus, and in contradiction to the Church's teaching at the time of Galileo, even if Einstein was later to show that all motion is relative.

Terrestrial lightspeed measurements

To really pin down the speed of light, by 1800 it had become clear that what was needed was a terrestrial measurement of this speed. In 1833, Professor Charles Wheatstone at King's College London had the idea to measure the speed of electrical pulses (which travel at about the speed of light) running along a long wire, by use of a rotating mirror to image electrical sparks at either end (Keithley 1999). Wheatstone was an early developer of the printing telegraph, and he later consulted with Kelvin on the Atlantic telegraph. He started out making musical instruments[13] and studying acoustics. The "Wheatstone Bridge" for precision electrical measurements which he is mainly remembered for was actually invented by a colleague, Christy, but analyzed and promoted by Wheatstone. He was also responsible for using spectral analysis of electrical sparks to identify elements in the electrodes, the forerunner of spectroscopy. His rotating mirror apparatus remains in the basement museum of King's College. An electrical spark, viewed in a rotating mirror, caused an electrical pulse to travel over a quarter of a mile of wire on a drum, emerging to make another spark, viewed in the same mirror. During the time the pulse travelled down the wire, the mirror had rotated slightly, causing a displacement of the two images of the spark. By measuring this displacement, and knowing the speed of rotation of the mirror, he could calculate the time it took for the electrical pulse to travel a quarter of a mile, and hence the "speed of electricity." The mechanism, which I have studied, is a modified clockwork carriage clock. His 1834 publication gave the speed as 250,000 miles per second, somewhat larger than the speed of light.

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[12] Ed.: Galileo is said to have murmured, "E pur si muove" — and it yet moves.

[13] Ed.: Wheatstone invented the Wheatstone English concertina around 1830.

François Arago (1786–1853) first proposed using Wheatstone's method in 1838 to address the questions raised by Descartes' and Fermat's work, by comparing the speed of light in air with that passing through water. His light source was a spark, split into two beams, one passing along a tube of water, and both then reflected by a rotating mirror. If the beam passing through the water slowed down, it would support the wave theory, if it sped up, it would support the particle theory. Arago spent a decade unsuccessfully trying to make this work. Arago, a very liberal republican, himself had a most adventurous life (Lequeux 2016). Educated at the École Polytechnique, the story is told that Napoleon Bonaparte requested in 1803 that all students sign a petition supporting his appointment as Emperor. François refused, to which Napoleon, on noting that he came top of the class responded "One can't send down the top student. If only he'd been at the bottom …" Soon after, Poisson appointed him secretary to the Paris Observatory. With Biot, he was sent to Spain to map out a meridian arc, in order to determine the length of the metre, defined after the French Revolution as one ten-millionth of the distance from the equator to the North Pole. (And also very close to the length of a pendulum with a two-second perio.). Unfortunately his surveying activities were misunderstood by the local population as those of a spy for a French invasion, and the twenty-two year old was imprisoned in the Bellver fortress in 1808. He soon escaped in a fishing boat to Algiers, but was once again captured by pirates and imprisoned at Palamos. After release and further adventures, including a trek along the North African coast from Bougie to Algiers, he reached Paris with his meridian notes intact. He was rewarded by election to the Académie des Sciences, appointed to a chair, and given a residence at the Paris Observatory for life. He was active in the development of photography, the railways and telegraph system, gave public lectures on astronomy for 35 years, and wrote invaluable memoirs of deceased Académie members. It was said of him that his "rapidity and facility of thought, his happy piquancy of style, and his extensive knowledge peculiarly adapted him to the position he was given as perpetual secretary of the Académie in 1830."

With the fall of King Louis-Philip, Arago joined the provisional government in 1848, the "year of revolutions," becoming minister of War and also of Marines and Colonies. In these positions he managed to improve rations and abolish flogging in the navy, and to abolish slavery in the French colonies. He is remembered by street names, schools, an auditorium and statues in Paris.

Arago's student Hippolyte Fizeau (1819–1896) collaborated closely with a colleague Leon Foucault (1819–1868) on many projects at the Paris Observatory, until it dawned on them both that the problems with Arago's apparatus could be addressed by sending the light beam back on itself from a stationary mirror (Tobin 1993). Fizeau, who was more theoretically inclined than Foucault (a superb experimentalist) decided on the scheme shown in **Figure 8** using a rotating toothed wheel, whereas Foucault adopted a rotating mirror, which proved a little more accurate. In Fizeau's scheme (**Figure 8**), light passes through the gap between teeth in a rotating wheel, to be reflected back from a mirror at the far end. By the time light returns, the gap has been replaced by a tooth, and the light (viewed from the side at S) is blocked. The speed of

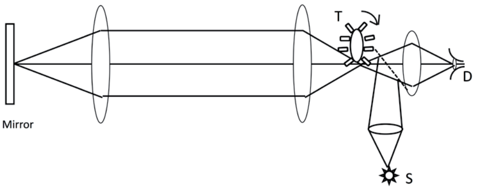

Figure 8. Fizeau's apparatus for measuring the speed of light, showing rotating toothed wheel T, source of light at S and detector at D. The light passes between the teeth, but by the time it comes back from the mirror a tooth has moved around to block it.

the wheel was adjusted until the light could either be seen (through the next gap) or not seen. With the wheel rotating at 1000 revolutions per second, and a thousand teeth on the wheel, he only needed about a thousand feet for the round-trip of the light, travelling at about a foot every nanosecond (10^{-9}s). The source was set up at his father's house in Suresnes, and the mirror 5.4 miles away at Montmatre, so that a speed of only 12 revolutions per second was sufficient. His result, in 1849, for the speed of light, was 3.14×10^8 m/s, against the modern value of 2.99×10^8, an error of about 5%, but only slightly larger than the astronomical measurements of the time. The result won him the Triennial Prize created by Emperor Napoleon III for 30,000 francs, or six times the annual salary of his rival Foucault at the Paris Observatory.

Leon Foucault spent twelve years perfecting his method, shown in **Figure 9**. Light sent from the source S1 via the rotating mirror M1 to the stationary mirror M2 will be reflected back to M1 after it has turned slightly, moving the final image to S2. By plotting the displacement between S1 and S2 against the rotation speed of M1 he obtained a straight line whose gradient gave the speed of light. But this was a particularly ingenious optical arrangement, for if M1 is rotated slowly in a continuous stream of light (so that the finite speed of light does not affect matters at all), the image of S1 reflected back is not displaced at all, regardless of the angle of rotation of the mirror M1. At high rotation speeds, the light is chopped up into pulses by the beam from the rotating mirror scanning across the fixed mirror M2.

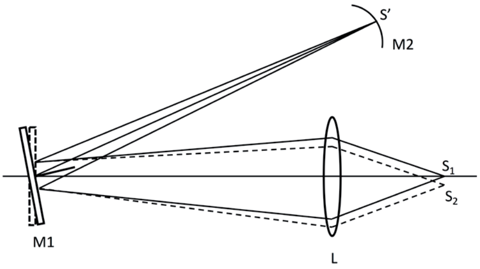

Figure 9. Foucault's rotating mirror system for measuring the speed of light. The mirror M1 rotates continuously about the normal to the page, sweeping the beam across mirror M2.

His mirror (**Figure 10**) was driven by a bellows-powered air-turbine (based on a siren), built for him by his friend Cavaille-Col, who had built the Notre Dame pipe organ. The tone generated by a fast rotating mirror could be compared with a piano, to give the frequency, as Wheatstone had first done, or more accurately using another toothed wheel and a stroboscope. Michelson used a tuning fork. The light source was focused sunlight, using a moving heliostat mirror which compensated for the rotation of the Earth to keep the Sun's focus stationary. The optical path could be folded by additional mirrors, for a total length of 20 metres. His result, published in 1862, was 298,000 ±500 km/s, very close to the value we use today. Foucault also measured the speed of light in water, resulting in an intense race with Fizeau, who had done the same using his method. The work was reported in Paris newspapers as "measuring the distance to the sun in the laboratory." Foucault reported his result slightly before Fizeau, and both results supported the (correct) idea that light slows down in water, and is a wave. It was, of course, Foucault, who in 1851 erected the huge pendulum in the dome of the Panthéon in Paris which directly revealed the Earth's rotation (Tobin 1993). This is simply understood if we imagine the pendulum at the North Pole, swinging in a fixed plane (fixed by the starting push, not by any absolute frame of reference) with the Earth rotating below.

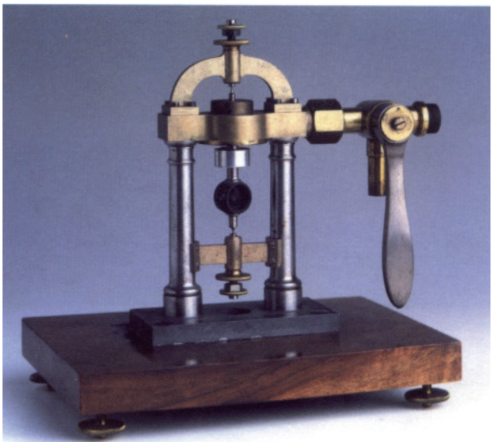

Figure 10. Foucault's 1862 rotating mirror (the black disk at center), driven by compressed air from a pipe-organ pump. (From Tobin 1993.)

These rotating mirror measurements were continued with increasing accuracy until the 1920s by Albert Michelson, Marie Cornu and others. Cornu worked through the time of the siege of Paris in 1870 by Bismarck and the Paris Commune, in which Paris was more severely damaged by shelling than at any time before or since, as shown in contemporary photographs. Messages were sent out in balloons and returned by homing pigeons during the siege.

Fresnel, Huygens and Young

Around 1650, Grimaldi, a Jesuit priest, reported the fuzzy shadow edge cast by a sword blade, which was hard to explain if light consisted of small particles travelling in straight lines. Leonardo da Vinci had previously suggested that light was a wave. Alternatively, if light was a wave, like sound, why did it not travel around corners? As evidence for interference effects accumulated, support for a wave theory of light increased steadily throughout the nineteenth century, until one of Einstein's 1905 papers established the modern idea that light travels as a wave, but arrives as a particle. Newton had been ambivalent: his "Newton's rings" (and his explanation for the colours in soap bubbles) supported a wave theory, but most of his writing supported light as a stream of particles. Here is what Newton writes about the wave–particle duality in 1704 in his book *Opticks*:

> If a stone be thrown into stagnating water, the waves excited thereby continue to arise in the place where the stone fell into the water, and are propagated from thence in concentric circles upon the surface of the water to great distances. And the vibrations or tremors excited by vibrations in the air by percussion continue a little time from the place of percussion in concentric spheres to great distances. And in like manner, when a ray of light falls on the surface of any pellucid body and is there refracted or reflected, may not waves of vibration, or tremors, be thereby excited in the refracting or reflecting medium at the point of incidence … and are not these vibrations propagated from the point of incidence to great distances ? And do they not overtake the rays of light, and by overtaking them successively do they not put

them into the fits of easy reflection and easy transmission described above.

The three great champions of the wave theory were Christiaan Huygens (1629–1695), Thomas Young (1773–1829) and Augustin-Jean Fresnel (1788–1827). Huygens was led to his wave theory, perhaps the first, around 1678 from observations of "Newton's cradle" (actually invented by Robert Hooke), a line of steel balls in contact, suspended by strings, as sold now at museum stores. When the first is struck, the last one jumps off the end, while the intermediate balls appear to remain stationary. (In fact, a pulse of elastic energy is transmitted at the speed of sound). He imagined space filled by an Aether consisting of minute hard invisible balls, supporting the pulse propagations of light. Inspired also by observations of ripples in a still pond when a stone is dropped into it, his wavefront construction, showing every point on a wavefront acting as a new source of waves, became one of the most important ideas ever in science. This led to Fresnel's mathematical formulation of near-field light propagation and diffraction in 1818, well before Maxwell's equations for light. The mathematics in Fresnel's 1818 paper is identical to that found in any modern textbook on near-field diffraction. This accounts for the blurring in an unfocused image, an important effect in all forms of imaging, from light microscopes to telescopes, but particularly in semiconductor lithography, where it can limit the size of transistors.

Fresnel was a highly religious civil engineer during the time of Napoleon. In 1817, Fresnel submitted his thesis to the Académie des Sciences for its Grand Prix on the topic of diffraction. Poisson, a committee member, pointed out that Fresnel's theory predicted a bright spot in the centre of the shadow beyond a coin, illuminated face-on by a small light source from the front, which was clearly absurd. When Arago, the chair of the committee, demonstrated exactly this spot experimentally using a 2-mm metal disk glued to a glass slide, Fresnel was awarded the prize. (A very small source of light must be used to observe this effect, in a very dark room, to provide spatial coherence.) This experiment, now demonstrated regularly using a laser light source in student laboratories, has become known as "Arago's bright spot," and provided decisive support for the wave theory of light. Fresnel also demonstrated that the undulations of light waves were transverse (like ocean waves), not longitudinal like sound. This created a serious problem for supporters of the Aether, since any elastic medium would support both longitudinal and transverse waves. But most significantly for our story this brilliant scientist produced a theory of Aether drag in 1818. Accepting that the refractive index was a ratio of light speeds, Fresnel postulated that the Aether wind becomes compressed when it passes through a medium such as glass or water, modifying the refractive index and changing the speed of light. His prediction agreed nicely with the measurements of Fizeau on the speed of light in moving water, which changed with the water speed. We now know that this was fortuitous, as Max von Laue showed in 1907. Einstein's theory predicts just this result without assuming the existence of any Aether, using his relativistic velocity addition formula. This fortuitous agreement was greatly to confuse scientists throughout the nineteenth century, during which experimental evidence in support of Fresnel's Aether drag theory accumulated. The acceptance of Fresnel's theory added to the shock when Michelson's work failed to find any evidence of an Aether wind in 1887. But the work Fresnel was most proud of (which he insisted be recognized on his tombstone) was his invention of the Fresnel lens used in lighthouses (Levitt 2013), which saved many lives at sea with its collimated search-light beam, rotated around the horizon.

Unlike Arago, Fresnel did not read or speak English. He was therefore unaware of the work of the great polymath, Thomas Young, his contemporary in London, who had already, in 1801, provided irrefutable evidence that light was a wave in one of the greatest experiments in the history of physics. Young's many achievements, including translation of the Rosetta stone, the definition of Young's Modulus and surface tension in materials science, the first correct definition of kinetic energy, and his explanation for the accommodation of the human eye, are well known (Robinson 2006). Inspired by the water waves seen in a shallow trough, he demonstrated controlled interference between light waves for the first time. Here is how he described his experiments in 1803 (Young 1845):

> I made a small hole in a window shutter, and covered it with a piece of thick paper, which I perforated with a fine needle. For greater convenience of observation, I placed a small looking glass without the window shutter in such a position as to reflect the sun's light in a direction nearly horizontal, upon the opposite wall, and to cause the cone of diverging light to pass over the table on which were several little screens of card paper. I brought into the sunbeam a slip of card about one thirtieth of an inch in breadth, and observed its shadow, either on the other wall or on cards held at different distances. Beside the fringes of color on each side of the shadow, the shadow itself was divided by similar parallel fringes, of smaller dimensions … Now these fringes were the joint effects of the portions of the light passing one each side of the slip of card, and inflected, or rather diffracted, into the shadow. For, a little screen being placed a few inches from the card, so as to receive either edge of the

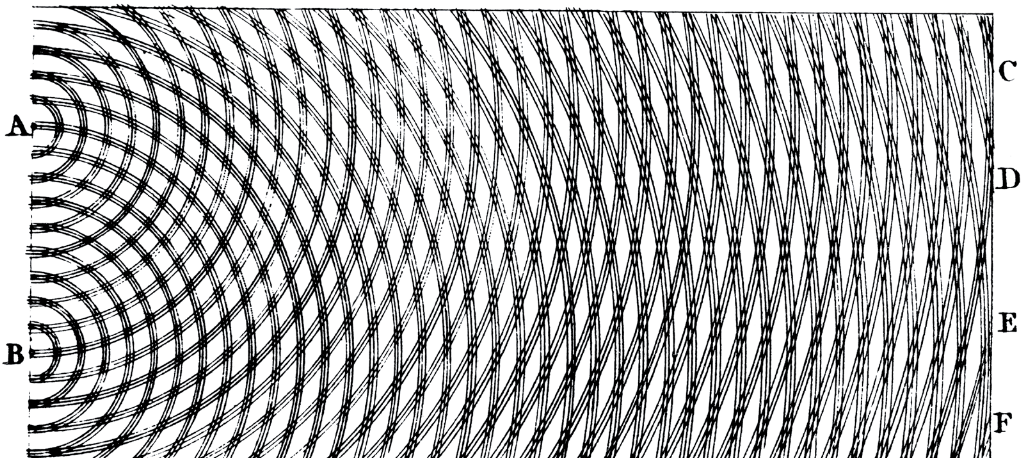

Figure 11. The drawing Young published to show interference between waves from two different small sources at A and B. The interference is constructive around D and E. (The sources A and B could alternatively be points where two small stones hit a still pond at the same time). (From Robinson 2006.)

> shadow on its margin, all the fringes which had before been observed in the shadow on the wall disappeared …

In other words, the interference fringes in the shadow region caused by light passing around either side of the card and overlapping at the viewing screen disappeared if he blocked the passage of light on one side of the card, demonstrating interference. But Young is much more famous for a second similar experiment around 1807 in which he used a needle to make two small holes in an illuminated card. On a distant screen he saw the interference fringes shown in **Figure 11**. It is not entirely clear that he actually did this experiment, unlike the first, but these "Young's fringes" are readily formed in this way using modern equipment, and have been described by Richard Feynman[14] as "containing all the mystery of quantum mechanics." This is because, using a light source so weak that only one photon at a time leaves the source (even an hour apart), it will be found that the dots at the detector screen indicating arrival of photons slowly build up, like a Pointillist painting, into the pattern of interference fringes seen by Young when using continuously flowing light. *How does each photon know where to arrive to build up this pattern?* Quantum mechanics predicts exactly this phenomenon, but the underlying reasons are not understood, and form the background for much of the debate about quantum weirdness (Gribbin 2014).

It is interesting that Newton had anticipated the discovery of interference, in which overlapping waves coming from different directions can build up wave height. Newton had used this idea to explain the tides at Batsha Bay in the Gulf of Tonkin in Vietnam, where travellers reported the strange phenomenon of a completely static water level for one entire day every fourteen days, between which there was only a single slow tide, increasing and falling.[15]

Fresnel, unaware of Young's work, had rediscovered interference effects in 1815, but acknowledged Young's priority in a letter to him in 1816. Following Fresnel's death, Arago in his memoir of him writes vividly of his encounter with Young and particularly his wife:

> In the year 1816, I passed over to England with my learned friend M. Gay-Lussac. Fresnel had then just entered in the most brilliant manner into the career of science by publishing his *Mémoire sur la Diffraction*. This work … became the first object of our communication with Dr. Young. We were astonished at the numerous restrictions he put upon our commendations, and in the end he told us that the experiment about which we made so much ado was published in his own work on *Natural Philosophy* as early as 1807. This assertion did not appear to us correct, and this rendered the discussion long and minute. Mrs Young was present, and did not appear to take any interest in the conversation, but, as we know, that fear, however puerile, of passing for learned ladies — of being designated bluestockings — made the English ladies very reserved in the presence of strangers, our want of politeness did not strike us till the moment Mrs Young rose up suddenly and left the room. We immediately offered our most urgent apologies to her husband, when Mrs Young returned, with an enormous quarto under her arm. It was the

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[14] Feynman (1992), p. 130.

[15] See Cartwright (2003).

> first volume of the *Natural Philosophy*. She placed it on the table, opened it without saying a word, and pointed with her finger to a figure where the curved line of the diffracted bands, on which the discussion turned, appeared theoretically established.

Arago, writing here not long after the French Revolution (*Liberté! Égalité! Fraternité!*), and a liberal at heart, perhaps wants us to understand that the educated ("*blue-stocking*") ladies of France were more "liberated" than their English counterparts.

Electromagnetism in the 19th century

The understanding that light was an electromagnetic wave, related somehow to electrostatics (stationary charges) and magnetism (the magnetic fields which arise when charges are in motion), came slowly throughout the nineteenth century (Darrigol 2000, 2012). At the start of that century, these two topics were considered entirely unrelated, and the nature of electricity was not understood at all. The towering figure responsible for the synthesis and foundation of the entire subject of electrodynamics was James Clerk Maxwell (1831–1878). Maxwell's theory was largely based on the work of the great experimental genius Michael Faraday, about whom much has been written (Thompson 1901). For our purposes, two of Faraday's discoveries were critical: first, his invention of what is now called Field Theory. Here, on seeing metal filings line up in arcs on a card placed across the poles of a horseshoe magnet, Faraday imagined that they lay along lines of tension (field lines) in the Aether, like rubber bands (with sideways forces). Perhaps he bumped the magnet, causing the grains of metal to vibrate, since in a letter to Maxwell he also suggests that this might be the mechanism of electrical radiation. He wrote that he "*considered radiation as a high species of vibration in the lines of force which are known to connect particles and also masses of matter together*," a brilliant physical insight for the time. His second crucial discovery relevant to the speed of light was rotation of the direction of polarization of light passing through a medium subject to a magnetic field: the magneto-optical effect. This was the first experimental connection between electricity and light, apart from the electrical sparks studied by Benjamin Franklin in thunderstorms. William Thomson (later Lord Kelvin) formulated a mathematical theory of the effect, which provided the crucial displacement currents for Maxwell's theory. These arose from spinning magnetic vortices, or idler wheels, in his Aether medium, as shown in **Figure 12**. In his three great papers from 1861 (Simpson 2006)[16], Maxwell constructed a mechanical model of an elastic Aether which would support the propagation of electromagnetic waves. These were based in turn on ideas taken from Fourier's theory of heat, from existing work on fluid dynamics (electricity could be imagined as a flowing fluid), and on Newton's equations for elastic media describing the forces between electrical charges and currents established previously by Coulomb and Ampere. In his last paper of 1865, based on energy-conservation methods, he discards the Aether scaffold entirely. The paper ends with a simple prediction for the speed of light (independent of the speed of any light source) in terms of the two "elastic" constants of the Aether only, constants we now describe as the permittivity and permeability of a vacuum. Heaviside later described the Aether as "a dielectric." It was the symmetry

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[16] Simpson (2006) contains Maxwell's three great papers on electrodynamics and detailed analysis.

in these equations created by the displacement current (a time-varying magnetic field produces an electric field, and vice-versa) which provided the important clue for Einstein in his 1905 relativity paper. Maxwell's great book of 1873 contained his twenty equations in an appendix, later reduced to the modern four equations by Heaviside in 1884.

By accurate measurement of the permeability and permittivity using a current balance of his own devising (described below as "measuring the quantity of electricity"), Maxwell was able to deduce the speed of light from his formula. In 1864, announcing one the greatest discoveries of 19th century science (that light was an electromagnetic wave), he wrote:

> The velocity of light in air, by M. Fizeau's experiments, is v = 314, 858, 000, according to the more accurate experiments of M. Foucault it is v = 298,000,000. The velocity of light in the space surrounding the Earth, deduced from the coefficient of aberration and the received value of the radius of the Earth's orbit, is v = 308,000,000. Hence the velocity of light deduced from experiments agrees sufficiently well with the value of v deduced from the only set of experiments we as yet possess. The value of v was determined by measuring the electromotive force with which a condenser of known capacity was charged, and then discharging the condenser through a galvanometer, so as to measure the quantity of electricity in it in electromagnetic measure. *The only use of light used in the experiment was to see the instrument.* The value of v found by M. Foucault was obtained by determining the angle through which a revolving mirror turned, while the light reflected from it went and returned along a measured course. *No use whatever was made of electricity or magnetism.*
>
> The agreement obtained seems to show that light and magnetism are affectations of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electrodynamic laws.

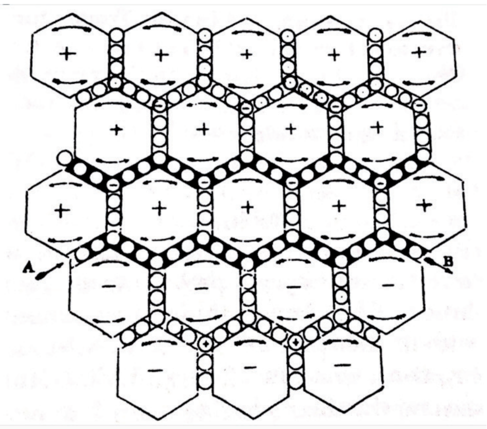

Figure 12. Maxwell's model of the elastic Aether with spinning vortices, used for his theory of light waves, from his 1862 paper. (From Simpson 2006.)

It seems almost miraculous that Maxwell could arrive at these Lorentz-invariant equations (meaning that the speed of light is constant as measured in different moving frames) by using Newtonian equations (known not to be Lorentz invariant). Maxwell's work is one of the greatest examples of the way in which physicists used an imaginary system, in this case the elastic Aether, as a metaphor on which to base a mathematical model. Einstein, who said that "imagination is more important than knowledge," was to show that the metaphor was superfluous. But, without it, we would not have Maxwell's equations, the basis of all modern electrical engineering and telecommunications.

Maxwell, whose wife Katherine was highly religious, could recite long passages from the scriptures. He was a skilled horse-rider, played the guitar and wrote much occasional verse. His biographers (Campbell & Garnett 1884) give a charming portrait of Maxwell at work in his laboratory, quoting from one of his letters in 1878 soon after the telephone was invented:

> We have all been conversing on the telephone. Garnett actually recognized the voice of a man who called by chance! But the phonograph will preserve for posterity the voices of our best singers and speakers. I have been making a clay model of Prof W. Gibbs's thermodynamic surface.

Campbell, who knew Maxwell well, writes of him:

> He had a strong sense of humour, and a keen relish for witty or jocose repartee … his mirth was never boisterous, the outward sign being a peculiar twinkle and brightness of the eyes. Of serenely placid temper, genial and temperate in his enjoyments, infinitely patient, he at all times opposed a solid calm of nature to the vicissitudes of life (such as his painfully protracted death of bowel cancer) … In experimental work he was very neat-handed. When working, he had a habit of whistling softly a sort of running accompaniment to his inward thoughts. He could pursue his studies under distractions such as loud conversations. Then he would take his dog into his confidence, and would say softly, at intervals "Tobi, Tobi … it must be so. Plato, thou reasonest well." He would then join in the conversation.

It was around this time that the Atlantic telegraph cable was laid, as shown in **Figure 13**. Engineers were baffled when the Morse code signals did not arrive at the speed of light. Kelvin explained that the capacitance of the wire spread out the pulses. The first message from Queen Victoria to President Buchanan took 16 hours for 99 words — at a rate of 0.2 bits per second! Maxwell died in 1879, eight years before Heinrich Hertz discovered radio waves.

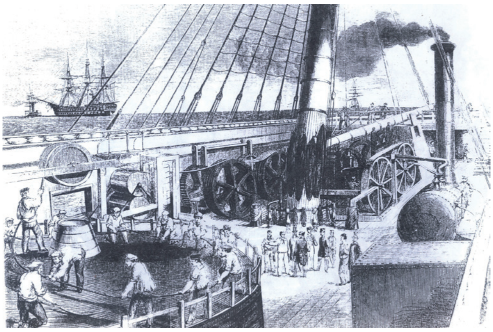

Figure 13. Lord Kelvin (on deck at center of group) on board the HMS Agamemnon (US Niagara in distance) during the laying of the first transatlantic telegraph cable in 1857. Morse code was expected to run under the Atlantic at the speed of light — it didn't! (Provided to the author from US Navy archives.)

Albert Michelson and the Aether wind

Albert Michelson, the first American to win the Nobel prize, was born in Poland, to a family who soon moved to San Francisco. President Grant supported him at the Annapolis Naval Academy, where he graduated in 1872. Soon after he dedicated his life to experimental science aimed at locating that absolute frame of reference in the Universe, the Aether (Michelson 1903). In Helmholtz's laboratory in Berlin he invented his famous interferometer (perhaps derived from the Jamin interferometer[17]) and published first results from it in 1881. Here he sought to measure a difference in the speed of light running across, and along the Aether wind, but

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[17] https://en.wikipedia.org/wiki/Jamin_interferometer

found none. Like the Jamin, his interferometer benefits greatly by division of the amplitude of the wavefield across the entire area of the wavefield, rather than Thomas Young's weaker division of wavefield at two points. It is likely that Michelson got the idea for his great experiment from the article Maxwell wrote for the 9th edition of the *Encyclopædia Britannica* in 1878, the year before he died, in which he assumed that the Aether was fixed to the centre of our Milky Way galaxy, around which the Sun orbits. Maxwell proposed using Rømer's method first to measure the speed of light traversing the Earth's orbit around the Sun in one direction, and then to repeat this when the light coming from Jupiter to Earth was travelling in the opposite direction, after Jupiter had gone half way around its orbit around the Sun. Maxwell had written to a colleague of Michelson's, David Todd, asking for the required astronomical data on Io's orbits, in a letter which Michelson read in 1879. (Einstein was five days old). Maxwell pointed out that his proposal was a stronger one-way "first-order" effect than the round-trip "second-order" measurements of Fizeau and others.

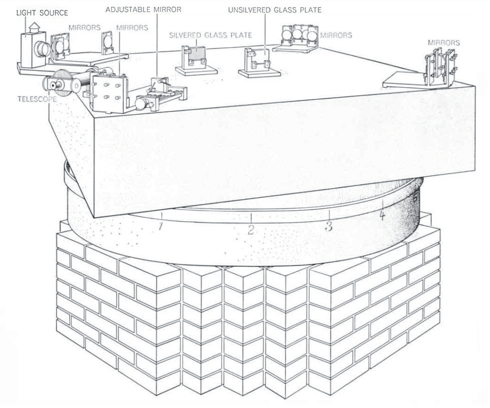

Figure 14. Michelson's interferometer, used to detect any motion of the earth through the Aether. To reduce vibration the optics were mounted on a five-foot square sandstone slab a foot thick, and the supporting brick pier reached down to bedrock. To allow it to be rotated smoothly, the interferometer floats on a trough of liquid mercury, which also relieved any stresses in the materials. (From Shankland 1964b.)

Discouraged by the negative result and lack of response to his 1881 Berlin paper, Michelson despaired of a further career in physics. But he found himself at dinner in Baltimore with the Lords Kelvin and Rayleigh in 1884, who had read his paper and strongly encouraged him to try again in his new position at Case Western University. An extended correspondence thus began between Michelson and Rayleigh. The famous interferometer which Michelson and his colleague Morley built at Case is shown in **Figure 14**, which Michelson spent two years perfecting. Briefly, coherent light from a sodium lamp is divided into two paths, running, say, across and along the direction of the Aether wind, and then recombined, to interfere. These interference fringes are extremely sensitive to the smallest differences in the speed of light along the two paths. Like water waves on a flowing river, they expected the light waves to pick up, as a tailwind, the speed of the Aether wind, thus moving the interference fringes. Repeating observations six months later, when the Earth had reversed its velocity through the Aether, they expected to see changes in the positions of the fringes, but did not. They could also rotate the entire interferometer, which floated on mercury (Morley's idea) to look for fringe movement, but any movements were negligible. They could detect an Aether wind velocity as small as 5 km/s, compared to the Earth's speed of about 30 km/s.

Thus was published in 1887 what some have described as "the greatest null result in the history of science," that the speed of light is to be the same in any direction (Shankland 1964a). Not often mentioned in textbooks is their conclusion that the hypothesis of a stationary Aether (an absolute frame of reference in the Universe) was untenable. Most scientists were extremely reluctant to accept this idea, since it suggested the alternative and highly implausible idea of "complete drag," that the Aether was fixed to the Earth and rotated with it, or, as Michelson suggested in his paper, his work supports the "partial drag" theories, in which a layer of Aether near the surface of the Earth was dragged around with it. An important technical discussion followed in the literature as to what exactly was being measured — the phase (wavefront) or the group (pulse) velocity, led by Rayleigh. It was concluded that all experiments measured group velocity except Bradley's, which measured phase velocity.

Einstein: the great clarification

The last years of the nineteenth century produced a frenzy of intellectual activity in the effort to make sense of all this, with the most important contributions coming from Hendrick Lorentz (the physicist Einstein admired the most), George FitzGerald, and later Henri Poincaré. FitzGerald was the first to suggest, in a completely overlooked paper in 1889 (in the obscure new American journal *Science*), the apparently crazy idea that objects (such as Michelson's interferometer) would contract in the direction of their motion at high speed, accounting for Michelson's null result. This was consistent with Heaviside's earlier publication showing that the field lines and potential surface around a moving charge do contract in the direction of motion, so that if matter consisted of charged particles, it should shrink. FitzGerald, a scientist generous with his highly creative ideas and supportive of others, also pre-empted the discovery of radio (FitzGerald 1883). Lorentz had suggested, before Einstein's 1905 paper, the even more astonishing idea that time itself slows down if you go fast enough, relative to someone at home, as had Larmor (1900).

In summary, around 1900, when Lord Kelvin spoke at the Royal Institution, the situation was as follows:

1. Maxwell's equations, which provided a constant velocity of light, suggested an absolute reference frame, supporting a stationary Aether through which the Earth moved.
2. Michelson's experiment: no stationary Aether, possibly George Stokes' improbable "complete drag" theory, where the Aether is attached to the Earth and rotates with it.
3. The violation of the Galilean transformation for light. Unlike waves on a river, the speed of light waves did not seem to add to the speed of the Aether "current."
4. The aberration of starlight — no "complete drag." No tilt of a telescope is needed if the Aether is fixed to planet Earth.
5. Excellent agreement of several measurements of Aether drag with Fresnel's theory, such as Fizeau's demonstration that the speed of light in flowing water was proportional to the water speed.
6. Newton's laws were independent of inertial frame under Galilean transformation, but Maxwell's were not — the speed of light was the same in every frame. Inertial frames are those moving with constant speed with respect to each other.

There were three ways to reconcile these results: First, find the Aether, an absolute frame of reference. Second, repair Maxwell's equations, so that they obeyed a Galilean transformation. Third, fix Newton's equations, so that they obeyed the new Lorentz transformation, which kept the speed of light constant in all inertial frames.

Einstein's 1905 paper on "The electrodynamics of moving bodies," in which he introduced relativity, clarified and reconciled all these issues at a stroke, by incorporating both seemingly crazy ideas (time dilation and length contraction), abolishing the Aether entirely, and claiming that the speed of light was a constant (given by Maxwell's value), independent of the speed of its source. This means that the speed of light coming toward you from car headlights at night does not depend on the speed of the car. With no Aether, and a constant speed of light, the result of Michelson's experiment was immediately explained. With extraordinary confidence for a twenty-six year old patent attorney in Bern, Einstein (who had portraits of Faraday, Newton and Maxwell in his office) chose the third option, modifying Newton's equations to make them Lorentz invariant, the change that produced $E = mc^2$ in another paper published later in 1905. This means that mass m is a form of stored energy E, as released in the nuclear reactions in our sun and the stars (Rhodes 1986). But sorting out this mess was an achievement of genius — whereas the symmetries in Maxwell's equations and the results of the Michelson-Morley experiment supported his notion that all motion was relative, the results from the aberration of starlight and Fizeau's finding that the speed of light depended on the speed of a moving water medium, were at first harder to understand (Pais 1982)[18]. The agreement with Fresnel's theory turned out to be fortuitous, as we have mentioned. Einstein's paper contained other new results: a derivation of a new relativistic transverse Doppler effect, and a relativistic treatment of the aberration of starlight using the correct velocity addition law. The breakthrough came with his new understanding of the relativity of simultaneity and time dilation, which reconciled all these results, and led to a completely new understanding of the nature of time itself.

Einstein realized that time intervals are measured by the coincidence of events, but these depend on the relative velocity of observers, as we explain below.

Einstein's paper made two assumptions, that the speed of light was the same in all inertial frames, and that all physics experiments (such as games of snooker played on smoothly running trains going at different speeds in different directions) should give the same results in all inertial frames. These frames were co-ordinate systems moving with constant velocity with respect to each other, one of which could be "stationary." He provided the correct transformation rule to allow the stationary observer to predict what an observer in a second moving frame (such as a car moving at constant speed) would measure, regarding events seen from both frames. This "Lorentz transformation" had been published the previous year (1904) by Lorentz, derived in electrodynamics from the requirement that light have Maxwell's velocity in all inertial frames. Einstein does not reference this paper, although he was well aware of the work of Lorentz and

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[18] Pais (1982) is the best biography of Einstein, containing much historical and technical information from someone who worked with him.

Michelson. His derivation of the Lorentz transformation is based on entirely different physical arguments. He then applied this transformation to the measurement of time and length intervals and so predicted time dilation and length contraction. The essence of one of these physical arguments (and of special relativity) can be described as follows.

Imagine flying from Sydney to Canberra at night. Assume that the lights of both cities are turned on at the same instant. A person on a high mountain exactly midway between the cities would see both city lights come on at once. But for an observer in a fast aircraft, since light has finite speed, during the time the light was travelling from Canberra to the aircraft, the aircraft would have moved forward a little. For that observer the Canberra lights were indubitably turned on first. This is the relativity of simultaneity, and the important point is that both observers are correct, and every observer in a different frame would judge the sequence of events differently. Because Einstein's theory does not allow causal influences to travel faster than light, it is not possible to violate causality in this way: events cannot precede their cause. The relative simultaneity paradox arises from the nature of space–time itself. Extending this type of argument led Einstein to the idea that moving sticks get shorter (as measured in a stationary frame) and moving clocks run slow (compared to a stationary clock). This has been demonstrated many times, for example by sending one of two synchronized clocks on the space shuttle and comparing them on return.[19]

It was said that it was easier to understand the mathematics of special relativity than the physics of it, and very difficult to accept replacements for Newton's laws, due to his immense authority. As one professor in physics has commented "in physics, mathematics can easily be a substitute for thought," a view which Thomas Young wrote strongly in support of. (Young wrote his equations in words.) A recent delightful and amusing book discusses the exaggerated importance given to the "beauty" criterion for new equations in the sub-atomic high-energy particle physics community (Hossenfeld 2018). This was never the case for Einstein, especially as a young man, for whom physical intuition always came first. In his later years he did turn increasingly toward more formal mathematical manipulations in his unsuccessful pursuit of his unified field theory.

Conclusion

This remarkable intellectual history of ideas started with Newton's action-at-a-distance principle, the idea that gravity and light act instantaneously across the Universe. This held sway until the time of Rømer and Bradley, who provided the first strong experimental evidence for a finite speed for light. These measurements were vital in helping to provide a time and distance scale for the Universe, solar system and Earth (important for Darwin's theory). Competing explanations for refraction brought disagreement between those who thought light was a wave and those favouring a particle model in an elastic, invisible Aether which somehow could not support longitudinal waves.

Thomas Young next showed that light, split into two beams, can be recombined to produce interference fringes, in exact accordance with a wave theory of light. Faraday, the great experimentalist, was the catalyst for many major theoretical insights. He saw in his iron filings tensioned lines of force, along which waves might travel, giving birth to

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[19] Ed.: sat-nav systems successfully adjust for these effects.

field theory and a finite velocity for light. His discovery of the rotation of the polarization of light led Maxwell to the concept of his displacement field. Later, this helped to explain how radio waves propagate, as FitzGerald was the first to understand. Magnetism, electrostatics, and optics were unified by Maxwell, with his mechanical model of the Aether, later discarded, and his demonstration that light was an electromagnetic wave, for which he provided a constant speed (in terms of electrical constants) which did not depend on the speed of the source of the light. This added support for the existence of a frame of absolute rest in the Universe, the Aether, which supported the propagation of light waves.

Fresnel's Aether drag theory supported experiment for a century, while the brilliant terrestrial measurements of Fizeau, Foucault and Michelson both improved on the accuracy of lightspeed measurements and addressed the problem of light propagation in a moving medium. This culminated in Michelson's null result, which gave the same speed for light in all directions on a moving Earth.

Poincaré and Lorentz anticipated many of Einstein's 1905 results but retained the idea of an Aether. Einstein finally wrapped it all up and clarified everything in 1905 in a theory which also, as a result, could extend Newton's laws to the very high energies and speeds of nuclear physics and so predict the energy release from atom bombs. His theory connects space and time through the speed of light.

This brief history of measurements of the speed of light and of the concept of the Aether has overlooked many fascinating associated discoveries, such as the discovery of radio (anticipated by the remarkable David Hughes) by one of the greatest experimentalists and theoreticians, Heinrich Hertz in 1887 (Hertz 1893, Fahie 1899). Hertz applied Maxwell's equations to his discovery (at first called "invisible light") and promoted the adoption of Maxwell's work in Europe, despite the alternative formulation of his supervisor, Professor Helmholz. Nor have we discussed "superluminal" schemes for communicating at speeds faster than light (Herbet 1988), closely related to Bell's theorem (Mermin 1990), today's quantum encoding methods using entangled states, and quantum computers (Gribbin 2014, Gerry & Bruno 2013). Sufficient to say that no superluminal schemes have succeeded. Greek astronomy, radio, Hughes, entangled states and Bell's theorem are discussed in more detail in Spence (2019).

The speed of light is one of a very small number of fundamental constants in physics which truly determine the nature of our Universe and the form of matter within it. It is the constant c in Einstein's most famous equation $E = mc^2$ linking mass and energy, and its measurement has driven advances in technology, notably in interferometry, GPS navigation and astronomy, by some of the greatest builders of scientific instruments. The speed of light has been described by S. R. Filonovich (1986) as the constant which provides "a clear manifestation of the unity of our physical world." And the discovery that light does not travel instantaneously tells us, as we look up into the night sky at distant stars, that we indeed are looking back in time. The history of the measurement of the speed of light follows one of the greatest intellectual adventures in human history, at the heart of progress in science over the last four hundred years, and central to the wave–particle duality, the idea that light can be thought of as either a wave, or a particle.

We must end this odyssey by pointing out that the speed of light is no longer measured: it was given a defined value in terms of other standards (of length and time) in 1983 (Barrow 2002). In May 2019 the last international standard based on an artifact (the kilogram of mass) was also eliminated and re-defined in terms of other standards.[20]

In trying to understand the nature of the medium which conveys light in vacuum, we might end by observing that the modern quantum field theory of the vacuum state (supporting, for example, the zero-point energy and the Higgs boson) perhaps just replaces one kind of Aether with another.

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[20] See Hibbert (2017) on its demise. [Ed.]

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