March 1, 2023

Francois Arago and the Birth of Optical Interferometry

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An excerpt from an upcoming book describes how a handful of 19th-century scientists laid the groundwork for one of the key tools of modern optics.

Francois Arago (1786–1853) was only 20 years old when the Bureau of Longitude selected him and his friend Jean-Baptiste Biot (1774–1862) to extend Le Meridien—the line of longitude passing through Paris—as far south as they could manage. In 1791, the Académie des Sciences had defined the meter as one ten millionth of the distance from the north to south poles along that line, making the meridian the fundamental basis of the new metric system of measurement.

The two friends set out in 1806, climbing mountains to triangulate to the next location along the meridian, repeating the process day after day for two years. Finally, in 1808, as they reached the Spanish coast on the Mediterranean, Napoleon launched his invasion of Spain, instantly making Arago and Biot enemy agents in a hostile land. Biot had the good sense to flee back to France, but Arago had one last mountain to climb, on the island Ibiza in the Balearic Sea off the coast from Valencia. The local authorities grew suspicious of his strange activities and arrested Arago as a French spy, throwing him in jail.

Arago managed to escape, climbing into a small fishing vessel and sailing 200 miles south to Algiers on the coast of Africa. He introduced himself to the Dey of Algiers, who agreed to

Engraving of Francois Arago, circa 1840. Photo by Kean Collection/Getty Images

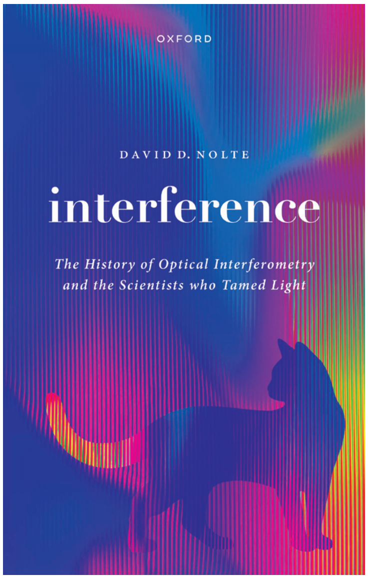
Francois Arago rose to the highest levels of French science and politics. Along the way, he met Augustin Fresnel and, together, they changed the course of optical science.

let him embark on a boat the Dey was sending to Marseilles with two lions and a troop of monkeys as gifts to Napoleon. The vessel was already within sight of Marseilles when a Spanish corsair intercepted them and took them as a prize to Roses, Spain.

Once more imprisoned, Arago was able to have a letter smuggled out to the Dey, informing him of the fate of his ship and gifts. The Dey was furious and induced the Spanish to free the ship and crew. Heading back across the Bay of Marseilles the ship was struck by a strong mistral wind that drove it relentlessly across the Mediterranean to the coast of Algeria, landing 170 km to the east of Algiers. The captain of the ship received new orders, stranding Arago with no means of transport. He traveled, disguised as a Muslim trader, across the desert and the coastal inlets, back to Algiers.

A year later, the Bureau of Longitudes declared him dead and gave official notice to his family. Before they had time even to grieve, Arago reappeared as if by magic at the port of Marseilles on the second day of July 1809. Through all his troubles and travels he had held onto his records and equipment, which he now deposited at the Bureau of Longitudes. He had completed the Paris Meridien as far south as the Balearian Islands.

Thus began Arago's career, which extended across fifty years as he rose to the highest levels of French science and politics (he became France's head of state during the revolutions of 1848). Along the way, he met Augustin Fresnel and, together, they changed the course of optical science.



This feature is an excerpt from an upcoming book, *Interference: The History of Optical Interferometry and the Scientists Who Tamed Light* (Oxford University Press, 2023), by David D. Nolte, reproduced with the permission of Oxford University Press. The material has been lightly edited for OPN style.

Arago and Fresnel

Augustin-Jean Fresnel (1788–1827) was neither the brightest of the four Fresnel siblings nor the most robust. By the age of eight he could barely read, lagging sadly behind even his younger brothers in school. Nonetheless, he had acquired a strange nickname among the village children, who called him "genius" because he had a knack for invention.

For instance, as the children played war in the streets and fields, they fashioned toy cannons out of birch trees and staged mock battles. Augustin improved on the cannons, finding just the right trees to bore, and just the right projectiles to launch with just the right force, so that the toys became real weapons. The children watched in awe and amazement at the stately arc of dirt-clod cannon balls before they smashed into the ground, spraying the combatants with debris. The village adults had to step in and ban the battles before anyone was seriously hurt.

Years later, as a diversion from the tedious work he was doing for the Department of Roads and Bridges, Fresnel began to peruse books on the theory of light. (He could not read English and so did not know of Thomas Young [1773–1829] and his work on the double slit.) He wrote up a short letter with his thoughts on the possible wave nature of light, as evidenced by diffraction effects, and he sent it off to his uncle, Mérimée Fresnel, a well-known artist and art restorer living in Paris. Mérimée moved in educated circles, and one evening he found himself seated at a formal dinner next to Arago, casually mentioning his nephew's views on the mechanism

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of interference and its possible role in the formation of diffraction fringes.

Arago immediately recognized the merit of the argument and encouraged Fresnel's uncle, who wrote to Fresnel of the successful reception of his ideas. On a later trip through Paris, Fresnel arranged to meet Arago.

The wave-particle battle

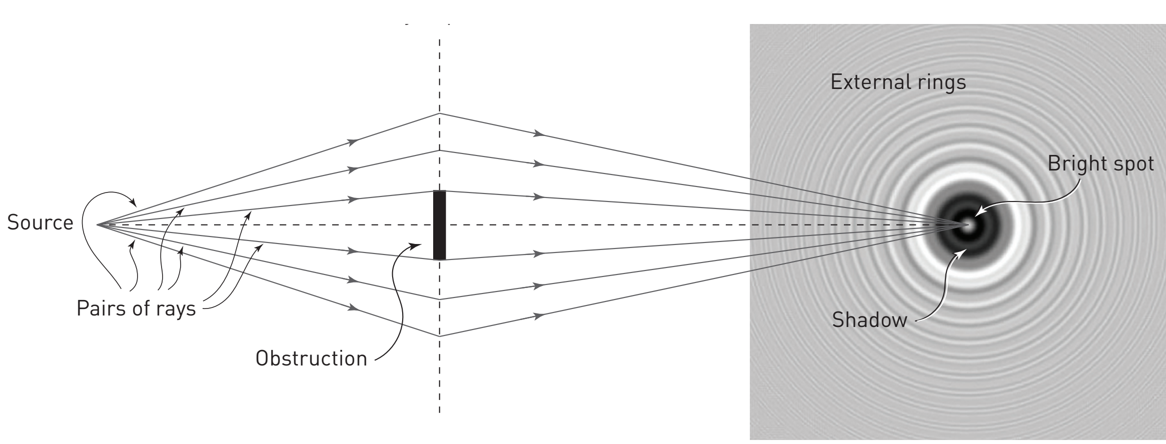
In early 1817, the intellectual battle between waves and particles was being bitterly contested. Simon Pierre Laplace (1749 – 1827) and his supporters—the "emissionists"—were pitted against a nearly solitary Arago, an "undulationist." In a gambit to put a stop to the foolishness of the undulationists, Laplace arranged for the biannual prize of the Académie des Sciences to be given for the best solution to the problem of diffraction, fully expecting to receive a definitive account of the ray theory from one or more of the emissionists' carefully coached students.

The competition was announced in spring 1817, with a deadline of August 1818 and to be awarded in 1819. The prize problem was worded entirely in the context of the corpuscular theory of light, leaving little room for a contribution from a wave point of view. Nonetheless, Arago alerted Fresnel to the opportunity, expressing his desire that Fresnel submit his latest work on diffraction integrals.

One of the referees of the prize competition was Siméon Denis Poisson (1781–1840) who was intrigued by the mathematics of Fresnel's work even though he was himself a supporter of the particle theory of light. Using Fresnel's new method, Poisson tackled a problem that Fresnel had omitted from his prize essay—diffraction from an opaque circle. It must have been with some glee that Poisson reported to the committee an absurdity he discovered using Fresnel's technique. According to his calculations, a small bright spot should occur at the very center of the shadow of the disk regardless of how large the circle was or how close the observation screen was placed. This nonsensical prediction, arrived at using Fresnel's own technique, was now turned against him, seeming to decide against Fresnel receiving the prize. But Arago was not swayed.

The details of when Arago observed the tiny bright spot in the shadow of the circle and who was present are not known. The final demonstration was probably

Engraving of Augustin-Jean Fresnel, circa 1882.



Spot of Arago (Poisson's spot). Pairs of wave paths, scattered from the object plane according to the Huygens-Fresnel principle, add constructively to form a bright spot in the center of the shadow of the opaque disk.

An experiment by Arago and Fresnel was the first interferometer, using interference for the first time to measure a material property.

carefully choreographed, almost certainly done with dramatic flair for maximum impact on the emissionists Laplace and Biot as well as on Poisson, who had the honor of having predicted this unusual phenomenon. The demonstration had the desired effect; Fresnel was awarded the prize for the computational power of his integrals. But Poisson and other emissionists stubbornly denied that it was proof of the wave nature of light.

The dawn of interferometry

During the two years from 1816 to 1818—after Fresnel and Arago had met but before Fresnel submitted his prize-winning journal article—Arago realized that the separated paths in Young's double-slit experiment provided an opportunity to have one path travel through air while the other could pass through a transparent material with a different refractive index. For instance, a thin sheet of mica could be placed over one of the slits while the other slit remained clear.

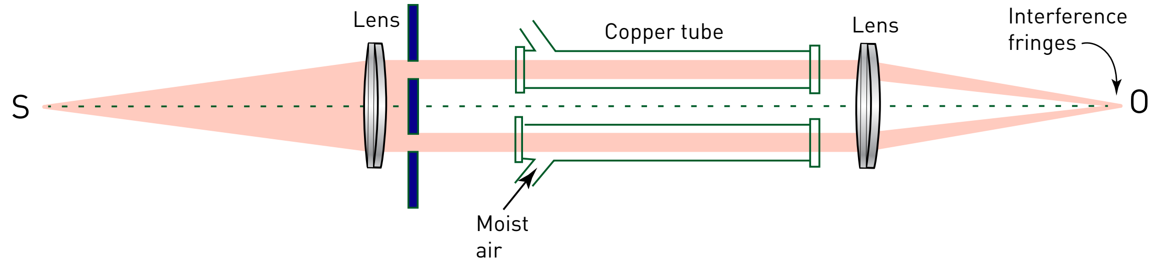
Arago and Fresnel performed this experiment together at the Paris Observatory, and they noticed that the fringe pattern shifted by a non-negligible amount. Based on the wave theory of light, the shift represented a delay in the arrival of a wave front at the observation plane, caused by the refractive index of the mica slowing the speed of light. This experiment by Arago and Fresnel was the first interferometer, using interference for the first time to measure a material property.

In the year after this simple double-slit experiment, Arago constructed a much more sophisticated interferometer that could measure refractive-index changes across long path lengths. Arago placed a point source at the front focal point of a lens and masked off the light after the lens to create two parallel pencil beams. One pencil of light passed through a copper tube filled with moist air, while the other traveled down the adjacent copper tube filled with dry air. After exiting through the glass plates, a lens focused the two beams down into one.

When the path lengths were identical, fringes formed at the output, and as moisture was pumped out of one of the tubes, the fringes shifted perceptibly. Light propagating through a meter of saturated moist air suffered a fringe displacement of only one-and-one-quarter wavelength, representing a refractive index of moist air that differed from dry air by about one part in a million.

Despite the obvious usefulness of Arago's interferometer from our perspective today, it was a one-off experiment answering a very specific question at that time. It was then abandoned for nearly 30 years, in part because it did not use light very efficiently. From a single bright light source, only two small pencils of light were extracted, and the resulting fringes were so dim that they required the extreme sensitivity of the human eye to observe the fringes in a very small region where the beams overlapped.

This disadvantage was later removed by Fresnel, who conceived of an optical configuration using two slightly angled mirrors that captured all the light rays to produce bright fringes that could be observed over a large area. This bright wide-field interferometer played an important role in the first demonstration of the temporal coherence of light performed by a famous duo of optical physicists: Fizeau and Foucault.



Arago's interferometer (1817).

Fizeau and Foucault

The French physicist Armand-Hippolyte-Louis Fizeau (1819–1896) was born in Paris into a wealthy family as the son of a successful doctor. What started out as an intense hobby in physical optics turned into a vocation when he began studying at the Paris Observatory under the tutelage of Arago, who recognized an untapped talent in this largely self-taught student.

On 19 August 1839, Arago gave a public lecture on an invention by L.-J.-M. Daguerre that allowed the image formed in a camera obscura to be captured permanently on a light-sensitive plate. Fizeau was fascinated by the daguerreotype and had begun experimenting with ways to improve the contrast of the prints when he met a kindred spirit in Jean Bernard Léon Foucault (1819–1868), who had tremendous experimental skills.

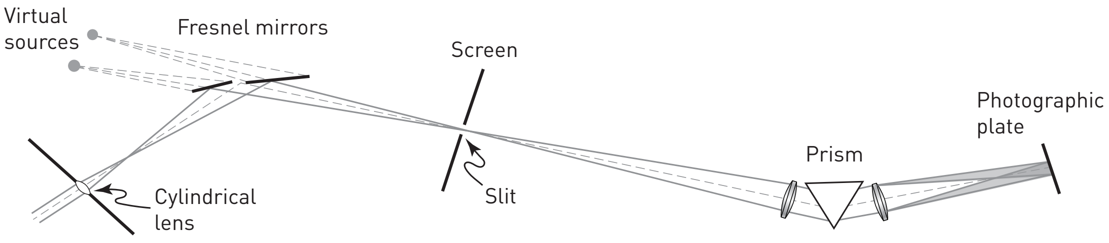
Fizeau and Foucault formed a close friendship and began to study and improve early photography. Beginning in 1843 they worked for two years on photographic processes that culminated on April 2, 1845 in the first scientific photograph of the surface of the sun that was able to clearly delineate the images of sunspots. (Their daguerrotypes were not published by Fizeau and Foucault, but one was published by F. Arago and J.A. Barral, *Astronomie populaire* [Paris: Gide et J. Baudry, 1854].)

By this time, they also had been experimenting with interference effects, initially following Young and Fresnel, but then forging beyond with new approaches that struck to the core of the difficult physics of coherence. In November 1845 Fizeau and Foucault performed one of the most elegant optical experiments of the nineteenth century. Today the experiment would be called spectral interferometry, but at that time it had no precedent.

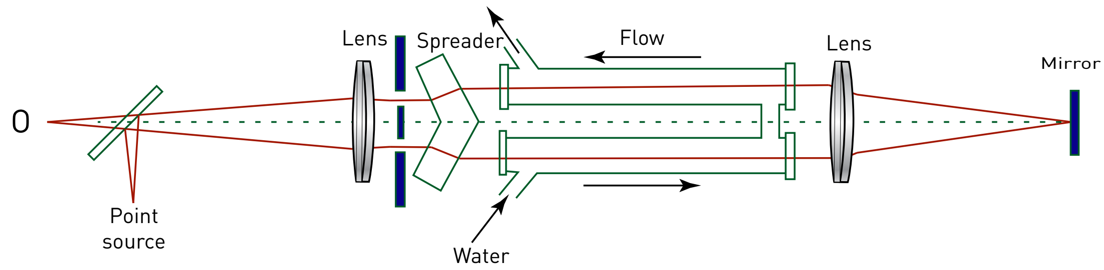
A persistent problem with interference effects was the extreme sensitivity of the effects to the different path lengths taken by separate interfering waves. Under the best conditions, with the brightest sources, it was possible to detect only about half a dozen fringes to either side of the main interference peak. The cause of this limitation was the broadband nature of white light, which is composed of many different wavelengths. There had been attempts to pass white light through colored filters to make it more monochromatic, but too much intensity was lost in the process.

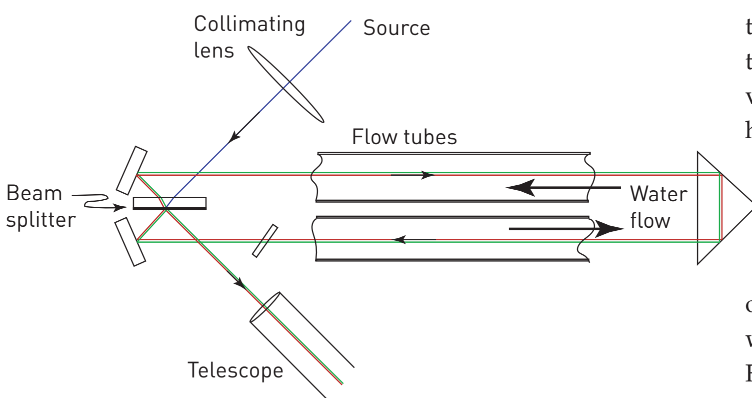
Armand-Hippolyte-Louis Fizeau (left) and Jean Bernard Léon Foucault (right).
Wikimedia Commons

Fizeau and Foucault hit upon a brilliant solution to this problem: using a Fresnel mirror to produce relative path differences while maintaining high intensity, and then dispersing the interfering beams through a prism to create a spectrum . By using a set of lenses, they recombined the spectra on an observation plane that held a photographic plate. The result was a brightly colored spectrum spanned by thousands of fringes. Path differences as large as 7,000 wavelengths (several millimeters) could still produce interference fringes. This experiment was the first demonstration of the classic



The spectral-interferometry setup of Fizeau and Foucault (1845).





Top: In 1851, Fizeau used a double-pass version of Arago's interferometer to measure Fresnel's "ether drag" formula. Bottom: The Michelson-Morley configuration of Fizeau's experiment used a beam splitter, which provided much higher intensities than Arago's masked pencils of light.

trade-off between spectral bandwidth and temporal coherence length.

Not stopping there, Fizeau and Foucault extended their measurements on the long-wavelength side of the spectrum by using tiny thermometers to measure the first interference effects for infrared light. They also placed polarizing crystals in the system and demonstrated the first interference fringes represented by polarization rather than by intensity. These experiments by Fizeau and Foucault went far beyond the work of Fresnel, launching the now-vast field of coherent optics. Spectral interferometry is used for the characterization of femtosecond laser pulses, and makes it possible to image inside translucent media in a spectral-domain optical coherence tomography.

From interferometry to relativity

In the succeeding years, Fizeau and Foucault returned to Arago's interferometer several times. It even drove a wedge between them, as they began competing against each other. Foucault used it to make the first direct measurement of the absolute speed of light through refractive media, performing an experiment that Arago himself had hoped to do but had been prevented from by his failing eyesight late in life. Arago had tacitly named Fizeau to do the experiment—but Foucault got there first.

Fizeau responded by using Arago's interferometer to make one of the most important interferometric measurements in the history of optics: the measurement of the speed of light in moving water. This experiment tested a theoretical result by Fresnel that was known as the ether drag coefficient, purportedly caused by the partial entrainment of the luminiferous ether by moving matter. Years later, Albert Michelson confirmed Fresnel's drag coefficient with Edward Morley, using Michelson's own improved interferometer configuration in place of Arago's.

It was positive result for the drag coefficient, originally measured by Fizeau using Arago's interferometer—rather than Michelson and Morley's null results on the motion of the Earth through the ether—that prompted Einstein years later to propose his relativity principle. He used the Fresnel drag coefficient for light traveling through moving water, measured by Fizeau and Michelson, as the basis for his equation for the relativistic addition of velocities. OPN

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