Augustin Fresnel and the wave theory of light

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Augustin Fresnel was born in 1788, in the Normandy village of Broglie where his father was employed as an architect by the duc de Broglie. The author of the wave theory of light was thus born on lands that would later belong to Louis de Broglie, the author of the wave theory of matter, whose birth came a century later. Fresnel's work was accomplished in less than a decade[1].

Augustin Jean Fresnel in 1825. Drawing and engraving by Ambroise Tardieu. *(Credit: Paris Observatory)*

To escape the tumult of the French Revolution, his family withdrew to their house in Mathieu, near Caen. Augustin was not interested in literature, but his teachers and schoolmates were fascinated by his practical ingenuity and mathematical prowess. After completing his high-school education in Caen, he was admitted to the École polytechnique in 1804, a year after his brother Louis, and 3 years before his younger brother Léonor.

Fresnel's talent was noticed by his professors, Monge, Poisson and Legendre. After graduating, he joined the Department of Civil Engineering and began a career as an engineer in 1809, working on a new road network.

An ever-inquiring mind

Fresnel was inexorably drawn to fundamental science, and in 1814 started to ponder the nature of light. Was it corpuscular – the view imposed by the towering figure of Newton – or wave-like?

His interest had been sparked by reading a newspaper article. On May 15th 1814, he wrote to his brother Léonor that "*I saw in* Le Moniteur *a few months ago that Biot presented a very interesting paper to the Academy of Sciences on the polarization of light. I have tried hard, but I cannot figure out what that is*". Determined to find answers to questions his professors had never explored, he asked his brother to send him some books. However, in a letter sent a year later on July 12th, his friend and protector Arago admitted that *"I do not know of any book that describes all the experiments on light. Mr Fresnel can only acquaint himself with that part of optics by reading the works of Grimaldi and Newton, and the memoirs of Brougham and Young."* A frustrated Fresnel replied on September 23rd 1815 that, *"as for the work of Young, I had a strong urge to read it, but I don't know English, so I can only understand it with the help of my younger brother. When he is not here, the book becomes unintelligible to me."* Fresnel did not suspect that he would end up writing the book he had wanted to read.

Fresnel's early works

Thomas Young (1773-1829), who performed his famous interference experiment in 1802, was the first to criticize Newton's ideas, and to suggest revisiting Huygens' wave theory of light. However, as we have seen, Fresnel was not initially aware of Young's research, and indeed was largely ignorant of most of the relevant theories. It is not even clear he knew about Huygens' theory when he started his investigations.

Napoleon's return from exile on the island of Elba was to give Fresnel the opportunity he needed to work on his ideas! Like many of his companions, he publicly rose up against the Emperor, calling the Hundred Days *"an attack on civilization"*. Suspended by the Civil Engineering Department (he was reinstated in July 1815, after Waterloo) and placed under police surveillance, Fresnel duly returned to the family home in Mathieu and dedicated his enforced leisure to his thoughts about light.

Fresnel initially studied diffraction, using improvised equipment to explore the shadow of a narrow wire lit by a ray of sunshine. He noticed that with a magnifying glass, he could observe and measure the diffraction fringes with a high degree of precision. Interestingly, the error estimates Fresnel gave in his articles allowed Jed Z. Buchwald to determine Fresnel's exact visual acuity[2]!

[1] A full and remarkable account of Fresnel's discoveries, his central role, and the contributions of his colleagues is provided by J. Z. Buchwald in *The Rise of the Wave Theory of Light*, The University of Chicago Press, 1984; 498 pages.
[2] J.Z. Buchwald, Op. cit., page 124.

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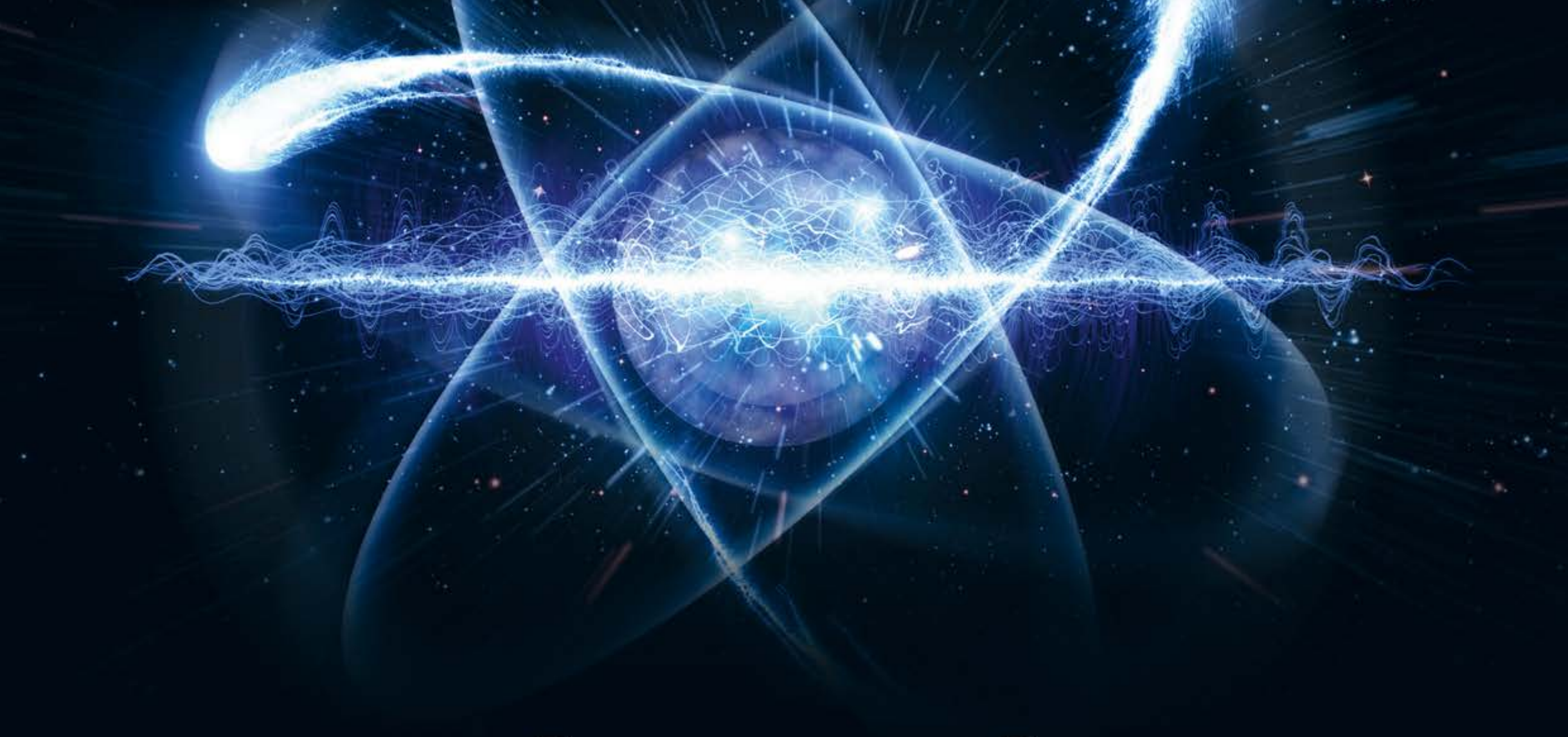


The history of ideas in optics

One of the major questions in optics arose from the observation of light rays. These only appear when light is partially screened out, and yet light seems to be a medium in which the whole world is bathed. The concept of light rays is fundamental, but how can they be explained?
Published in 1704, Newton's *Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light* was regarded as the authoritative work on the subject throughout the 18th century. In it, Newton set out his *corpuscular or emission theory*, whereby light consists of molecules emitted by luminous bodies. This idea explained rays of light, insofar as these corpuscles were said to travel in straight lines. Newton was familiar with interference phenomena, but discounted the wave theory of light, claiming that interference came from interactions between the molecules and matter.
However, there had previously been two important observations. Diffraction had been discovered by Francesco Maria Grimaldi, who drilled a small hole in a window shutter and observed that, instead of a small dot, a ray of sunshine produced a pool of light reminiscent of the surface of a stream. In his treatise *Physicomathesis de lumine*, posthumously published in 1665, he concluded that *"light is a substance that may travel in waves"*. The other observation, which dated back to the Vikings, concerned the birefringence of Iceland spar (some crystals split light into two rays!), analyzed by Erasmus Bartholin in 1669.
At around the same time, Christiaan Huygens (1629-1695) was putting forward some remarkable ideas, drawing analogies with mechanical vibrations in order to construct a wave theory of light, whereby each point of a wave front is the source of spherical wavelets whose envelope then determines the wave front at a later instant. He could explain the Snell-Descartes law of refraction, but not the existence of light rays. His triumph was the explanation of double refraction with a molecular model for an anisotropic medium. However, Huygens was completely overshadowed by Newton and only brought back into favor by Fresnel.

In order to refute Newton's assumption of an interaction between the wire and the molecules of light, Fresnel put a screen on one side of the wire and reported that *"I at once had the following thought: since intercepting the light from one side of the wire makes the internal fringes disappear, the concurrence of the rays that arrive from both sides is therefore necessary to produce them."* A few years later, Arago dubbed this concurrence *interference*, based on the principle established by Young. It was this interference that explained the dark fringes: *"The vibrations of two rays that cross each other at a very small angle can contradict each other when the crest of one corresponds to the trough of the other"*.

Fresnel pursued his experiments between 1814 and 1818, introducing the notion of wavelengths, exploiting the Huygens principle, and formulating the mathematical framework for calculating diffraction intensities, by introducing and calculating (to nine significant figures!), the integrals that bear his name. In 1816, he carried out his double mirror experiment.

His first memoir (1815) was nothing short of an all-out attack on Newton's theory, a challenge to a mighty duel across 140 years: *"I observed that shadows never clearly end as they should if light only propagated in its initial direction. Instead, the light spreads within the shadow, and it is difficult to define the point at which it disappears."*

Scientific fame

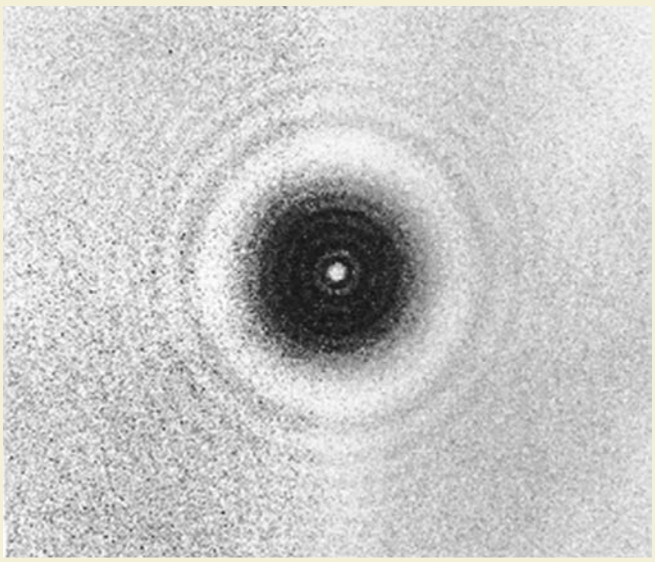
In 1816, after the blockade had ended, Fresnel was somewhat disappointed to learn from Arago, who had travelled to England with Gay Lussac, that Young had reached the same conclusions as him some years earlier. He was, however, a good loser, and eventually became a close friend of Young, telling him, *"What you left for me was as difficult as what you had done. You had picked the flowers, and I laboriously dug to reach the roots"*.

The first Academic award came in 1819. The Academy of Sciences had decided 2 years earlier to dedicate its biannual Grand Prix of Mathematical Sciences to the experimental and theoretical study of diffraction. Encouraged by Arago and Ampère, Fresnel entered a memoir and won the prize. The rapporteurs were Laplace, Biot and Poisson, who favored emission theory, and Arago and Gay Lussac who favored wave theory.

In his prize memoir, Fresnel revived the Huygens principle, emphasizing its depth and importance. This was to become known as the Huygens-Fresnel Principle (deposited in a sealed envelope at the Academy, opened 4 years later).

There was a moment of bewilderment when Poisson pointed out that, according to the theory of diffraction, as the waves would be in phase, a bright point should paradoxically be observed in the center of the shadow of a small disk! Fresnel subsequently confirmed this observation in an experiment (*Figure*).

Fresnel introduced the notions of wavelength and the propagation of vibrations through the ether, with both spatial and temporal periodicity. His ideas were originally based



Bright spot in the center of the shadow of a small disk or sphere. (Source: Institut d'Optique Graduate School, France)

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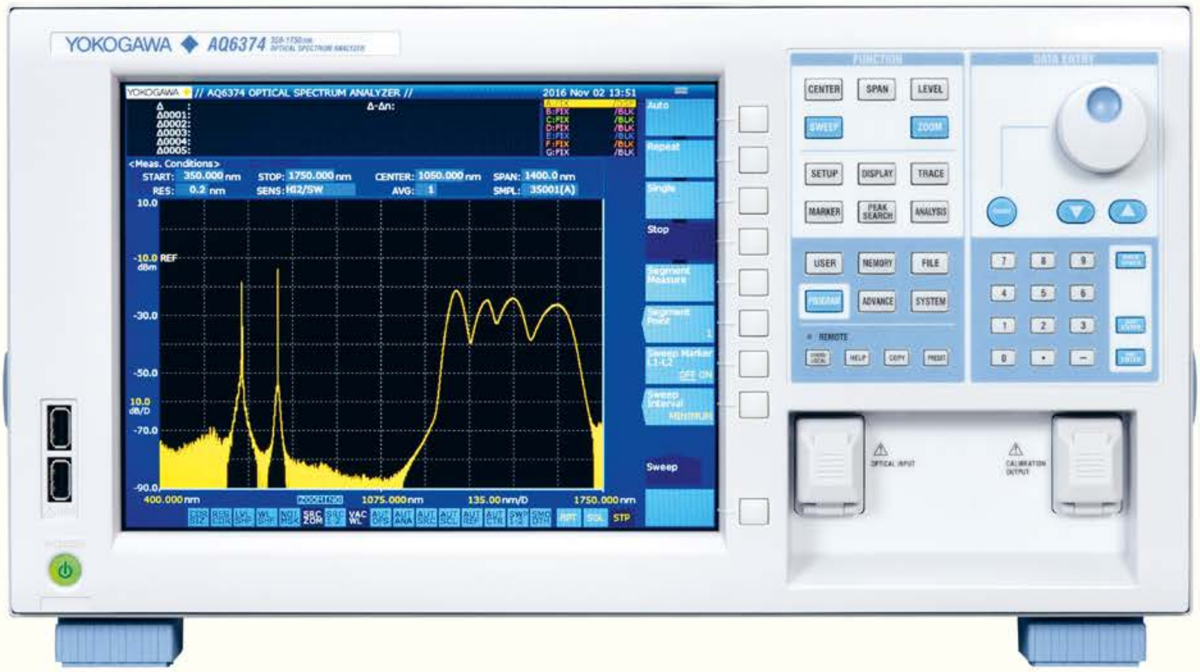

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on an analogy with pendular motion. He had noticed that the amplitude of vibrations propagated by a system can be separated into its components, just as the components of a force can. He therefore calculated the overall effect of a set of light waves, or vibrations, on one another.

Every element of the wave surface can be considered to emit elementary wavelets. In contrast to Huygens' results, however, Fresnel found that these wavelets interfere, thereby giving him an explanation for light rays, or beams. As the interference of these wavelets at some distance from the main direction of the beam of light is completely destructive, this beam, which is wave-like in nature, preserves its geometric characteristics during its propagation (the first complete proof was given in 1870, by Kirchhoff and Helmholtz).

Polarization and the optics of anisotropic media

In May, 1818, Fresnel was transferred to Paris, where he studied the polarization of light discovered by Malus, and chromatic polarization discovered by Arago. He established that light waves differ fundamentally from sound waves, in that they are transverse. This highly controversial finding, which even Arago questioned, allowed him to formalize the notion of polarization.

In 1819, he studied birefringent crystals, and turned his attention to double refraction and the associated properties of polarization. In a memoir and supplements published between November 1821 and March 1822, he worked out the theory of double refraction in uniaxial and biaxial crystals, the crowning achievement of his scientific work.

Fresnel the engineer

In 1818, Fresnel was seconded to the Lighthouse Commission. Commercial shipping had resumed and it was vital to improve maritime safety and provide clearly marked shipping lanes. Following an original idea by Buffon, Fresnel devised multi-part lenses for use in lighthouses. The resulting *Fresnel lenses* were made up of concentric annular prisms and had the same optical performances as large lenses with a strong curvature, which were impossible to build and transport.

This technology was worked out between 1819 and 1825, with the first full-scale test conducted after nightfall in Paris in September 1821, on the Arc de Triomphe. The light could be seen 25 km away, and its brightness and luminosity exceeded all expectations. Very soon, all lighthouses were equipped with Fresnel lenses.

The end

Fresnel was elected to the Academy of Sciences on May 12th 1823. His remarkable achievements were rewarded not only by his fellow scientists, but also by the Lighthouse Commission and the Department of Civil Engineering. However, his health rapidly declined, and it became obvious that he had tuberculosis.

He therefore stopped his scientific work and dedicated himself to his engineering tasks. One week before his death in 1827, Arago, his faithful friend, admirer and protector, came to present him with the Rumford Medal, which was awarded to him by the Royal Society *"for his development of the Undulatory Theory as applied to the Phenomena of Polarized Light, and for his various important discoveries in Physical Optics"*. The Royal Society had appointed him as an associate member in 1824.

In 1861, Gustave Rouland, Minister of Public Instruction and Worship, decided that Augustin Fresnel's *Complete Works* should be published, although this was to take longer than anticipated, owing to the deaths of the first three editors, Henri de Sénarmont, Emile Verdet and Léonor Fresnel. They are available in three volumes from Forgotten Books (Classic Reprint series). ■

AGENDA

OSA Digital Holography and 3-D Imaging topical meeting
19-23 May 2019 – Bordeaux (France)
www.osa.org

AOP2019
31 May-4 June 2019
Lisboa (Portugal)
www.aop2019.org

JCOM 2019
7 June 2019 – Brest (France)
www.sfoptique.org

Photorefractive Photonics and beyond (PR'19)
18-21 June 2019 – Gérardmer (France)
pr19.event.univ-lorraine.fr

ONLYLIGHT
19-20 June 2019 – Lyon (France)
http://onlylight-event.com/

CLEO/Europe-EQEC 2019
23-27 June 2019 – Munich (Germany)
www.cleoeurope.org

Laser World of Photonics
24-27 June 2019 – Munich (Germany)
https://world-of-photonics.com

JNOG 2019
2-4 July 2019 – Palaiseau (France)
www.sfoptique.org

SPIE Optics+Photonics
13-15 August 2019 – San Diego (USA)
http://spie.org

LIP2020
22-28 August 2019, Warsaw (Poland)
http://lip-conference.org/

PRE19
4-6 September 2019 – Nice (France)
pre19.sciencesconf.org

Diffractive Optics 2019
16-20 September 2019
Jena (Germany)
www.europeanoptics.org

ECOC - European Conference on Optical Communication
22-26 September 2019
Dublin (Ireland)
www.ecoc2019.org

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