A History of Physics over the Last Two Centuries

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By

Mario Gliozzi

Edited by Alessandra Gliozzi and Ferdinando Gliozzi

Cambridge Scholars Publishing

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MATTER AND ANTIMATTER

FOREWORD

Mario Gliozzi (our father) worked on *A History of Physics* right up to his death. To honour his memory, in 2005 we curated its posthumous publication by Bollati Boringhieri. The critical scientific and popular acclaim in Italy prompted us to suggest a version in English, to make the work available to a wider public. We also thought it opportune to complete the text with a final chapter illustrating the complex development of arguments, theories and experimental proofs that have characterised the *physics of fundamental interactions*.

The historian of science Mario Gliozzi was a pupil and friend of the renowned mathematician Giuseppe Peano, who bequeathed him his letters (subsequently donated by his children to the Library of Cuneo), some antique books and his library. As a pupil of Peano, Gliozzi was secretary of the Pro Interlingua Academy, coming into contact with the international historical-scientific world and being elected member of the *Académie internationale d'histoire des sciences.*

In one of his first research projects (presented by Peano to the Turin Academy of Sciences), Mario Gliozzi retraces the definition of the *metre* by Tito Livio Burattini. The 1934 work *"A History of electricity and magnetism from its origins to the invention of the battery"* won the Accademia dei Lincei prize and was the start of the *"History of electrology up to Volta"* issued in 1937. Gliozzi's historical studies comprise articles, treatises and anthologies of scientific writers.

The most challenging and certainly most stimulating work to which Gliozzi dedicated himself is, however, this "*A History of Physics".*

Before leaving the readers to judge the book for themselves, we would like to add a personal note about the author: Mario Gliozzi, our father. We have many childish memories of our family life, but one that, now we ourselves are old, is set in our minds: somewhere in the shadowed study of our old house in Turin, there was the continuous tack-tack of an *Olivetti Lettera 22,* proof of a dedicated and exemplary life.

The English translation is presented in two books. The first one "*A History of Physics from Antiquity to the Enlightenment*" has been translated by David Climie, M.A. Oxon (English Language and Literature). The present book entitled "*A History of Physics over the last two Centuries*" has been translated by Jacopo Gliozzi, great-grandson of the author and

PhD student in Physics at Urbana Champaign University (Illinois, USA), who also added some updating notes; we warmly thank both for their invaluable contribution.

We are very grateful to our friends and colleagues, in particular Prof. Matteo Leone, Prof. Roberto Mantovani and Prof. Clara Silvia Roero for advice and suggestions during the different phases of this work. Sincere thanks must also be extended to Prof. Vanni Taglietti for his indefatigable and wide-ranging help in the realisation of the project.

Alessandra and Ferdinando Gliozzi

1. FRESNEL'S OPTICS

WAVE THEORY

1.1 The interference principle

Thomas Young was born in Milverton on 13 July 1773 in a landowning family and, at a young age, was left in the care of his grandfather, an enthusiast of the classics who directed his precocious grandson to the study of ancient languages (Hebrew, Chaldean, Aramaic, Persian). In 1792, Young left to study medicine, receiving his doctoral degree in 1796; he then practiced as a physician in London, where he was also a professor of physics at the Royal Institution from 1801 to 1804.

Young's work was both vast and varied: an egyptologist of international renown, he made key contributions to medicine and physics, and was also appointed inspector at London Insurance Company; in the last fifteen years of his life, he dedicated himself to actuarial calculations. He was a member of the Royal Society of London and the Académie des sciences of Paris, and died in London on 10 May 1829.

In a 1793 paper he showed that the human eye can accommodate to different distances due to changes in the curvature of the crystalline lens. A few years later, he posited that the perception of colour is due to the presence of three different structures in the retina, each of which is sensitive to one of the three primary colours: red, yellow, and blue.[1] Both theories were studied and improved by Hermann von Helmholtz in his classic *Handbuch der physiologischen Optik* (1856-62).

Some of Young's other contributions to physics include the introduction of the elasticity modulus that today carries his name, which he defined as the weight that, when hung at the end of a rectangular prism of unit cross section, causes it to stretch to twice its resting length[2]; an interpretation of tidal phenomena, which was later expanded by George Aury in 1884; and a theory of capillary action based on the hypothesis that the walls of a tube attract the liquid it contains, as Hauksbee and John

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[1] Th. Young, *A Course of Lectures on Natural Philosophy and the Mechanical* Arts, London 1845, Vol. I, pp. 139, 440. The first edition was published in 1807.
[2] *Ibid.*, Vol. I, p. 137.

Leslie had already noted in 1802. This theory was later independently improved by Laplace[3], who transformed Young's theory into mathematical form.

Arguably Young's most important accomplishment, however, was his work on the wave theory of light. In 1800, he published a paper on sound and light in which, as Euler had already done, he highlighted the analogies between the two types of phenomena: this was the starting point of his theory of interference.

In keeping with Young's nonconformist inclination, Newton's theory appeared highly unsatisfactory to him. It seemed especially inconceivable that the speed of light particles was constant whether they were emitted from a burning twig or an enormous source like the Sun. Above all, he saw Newton's theory of "fits", which attempted to explain the colouring of thin films, as muddy and insufficient. Replicating the passage of light through thin films and reflecting on the effect for a long time, Young had a brilliant idea. He realized that the colouring effect could be explained by a superposition of the light reflected immediately by the top layer of the film with the light that enters the film and then is reflected by its bottom layer. This superposition of the two light rays can either lead to weakening or strengthening in the monochromatic light applied.

It is not known how Young arrived at the idea of superposition; perhaps from the study of beats in sound waves, an effect in which there is an audible periodic strengthening and weakening of a sound. In any case, in four papers read to the Royal Society from 1801 to 1803, later reproduced in the *Lectures* cited above, Young communicated the results of his theoretical and experimental research. Throughout, he repeatedly made reference to a passage from Proposition XXIV in the third book of Newton's *Principia*, in which certain anomalous tides observed by Halley in the Philippines are explained as the effect of the superposition of waves. Indeed, Young drew from this same example to introduce the principle of interference: "Suppose a number of equal waves of water to move upon the surface of a stagnant lake, with a certain constant velocity, and to enter a narrow channel leading out of the lake. Suppose then another similar cause to have excited another equal series of waves, which arrive at the same channel, with the same velocity, and the same time with the first. Neither series of waves will destroy the other, but their effects will be combined: if they enter the channel in such a manner that the elevations of one series coincide with those of the other, they must together produce a

[3] Laplace's essays on capillary action were published from 1806 to 1818 in the "Journal de physique".

series of greater joint elevations; but if the elevations of one series are situated so as to correspond to the depressions of the other, they must exactly fill up those depressions, and the surface of the water must remain smooth; at least I can discover no alternative, either from theory or from experiment. Now, I maintain that similar effects take place whenever two portions of light are mixed; and this I call the general law of the interference of light."[4]

In order to obtain interference, the two rays of light from the same source (ensuring that they have the same period) must be incident on the same point, coming from nearly parallel directions, after having taken different paths. Thus, Young continued, when two rays of the same light reach the eye with nearly identical angles of incidence despite having traversed different paths, the light perceived is strongest when the difference in path length is a whole multiple of a certain characteristic length, while it is weakest when this difference is a half-integer multiple: this characteristic length is different for light of different colours.

In 1802, Young confirmed this principle with his now-classic double slit experiment, perhaps inspired by an analogous experiment performed by Grimaldi[5]. The experiment is well-known: two small slits are adjacently cut in an opaque screen, which is subsequently illuminated by sunlight passing through a small aperture. The two luminous cones that form behind the opaque screen are dilated by diffraction and partially overlap. Instead of increasing uniformly in intensity, the light in the overlapping region forms a series of fringes that alternate between light and dark. If one of the two slits is shut, the fringes disappear and only the ordinary diffraction rings from the other are present. The fringes disappear even if both of the slits are illuminated directly by sunlight or a flame, as Grimaldi had done. Applying the wave theory, Young gave a simple explanation for this phenomenon: the dark fringes appear where the trough of a wave passing through one slit coincides with the crest of a wave passing through the other slit, such that their effects cancel; the bright fringes appear where the waves passing through the apertures have coincident crests and troughs. The experiment also allowed Young to measure the wavelength of various colours, obtaining 1/36,000 of an inch (about 0.7 microns) for red light and 1/60,000 of an inch (about 0.42 microns) for violet, on the other end of the spectrum: these were the first

[4] T. Young, *An Account of Some Cases of the Production of Colours not Hitherto Described*, in "Philosophical Transactions", 92, 1802, p. 387.

[5] § 5.34 of M.Gliozzi: *A History of Physics from Antiquity to the Enlightenment*, Cambridge Scholars Publ. 2022.

recorded measurements of the wavelengths of light, and for being the first they were rather accurate as well.

Young drew a variety of consequences from this experiment. Using the wave interpretation, he examined the colouring of thin films and explained the effect to the most minute detail, more or less as it is presented in textbooks today; he derived the empirical laws found by Newton and, taking frequency to be invariant for light of a given colour, he explained the tightening of diffraction rings in Newton's experiments when air was replaced with water by using the fact that the velocity of light is reduced in more refractive media: the hypothesis put forward by Fermat and Huygens thus began to be backed by some experimental evidence.

We add in passing that the expression "physical optics" was coined by Young to refer to the study of "the sources of light, the velocity of its motion, its interception and extinction, its dispersion into different colours; the manner in which it is affected by the variable density of the atmosphere, the meteorological appearances in which it is concerned, and the singular properties of particular substances with regard to it."[6]

While Young's works were the most important progress made in optics since Newton, they were met with skepticism by the physicists of his time and even subjected to derision in England. This was partly due to Young's abuse of the interference principle, as he applied it to phenomena where interference was certainly not present, partly to the scant recognition afforded to novel ideas, which was even greater than that it is now, and partly, as Laplace admonished, because Young had employed rather sloppy and at sometimes simplistic mathematical demonstrations, evidently resulting from his lack of mathematical training as a student.

Abuse of the interference principle, for which Young was thoroughly criticised, continued well after his time. Perhaps the best known case is that of Arago, who in 1824 published a theory in which the sparkling of stars was interpreted as an interference effect. This theory was adopted by the scientists of the 19th century and is still today reproduced in certain texts, despite the fact that it is clearly based on an error, as was pointed out in a series of detailed works in the second half of the century that culminated with the research of Lord Rayleigh (John William Strutt). According to Rayleigh, Averroës' interpretation of the phenomenon (and its later extension by Riccioli) was largely correct: sparkling is due to the light's refraction in the Earth's atmosphere and varies because of irregularities and atmospheric motion.

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[6] Young, *A Course of Lectures* cit., Vol. I, p. 434.

Let us return for a moment to the wavelength measurements carried out by Young to point out that the instrument he used was an interferometer, as are mirrors and the Fresnel biprism (§ 1.3): interferometers are instruments with which one can measure very small distances, of the order of half a micron (0.0005 mm). In 1866, Armand-Hyppolyte-Louis Fizeau gave one of the first examples of a practical application of interference, using it to measure extremely small lengths. In particular, he applied an interference-based method to the measurement of the thermal dilation of solids. Since then, interferometers and the application of his interference methods have multiplied so rapidly that we do not have enough space to recount their progression.

We make an exception for the interferometer itself, which we will discuss in paragraph 8.6. This instrument was conceived of by Albert Abraham Michelson and later described in an 1881 paper that directly influenced the development of the theory of relativity (§ 5.5). We would also be remiss not to mention the application suggested by Michelson and Edward William Morley in an 1887 paper: establishing a wavelength of visible light as a standard of length. To demonstrate the concreteness of this proposal, in 1893 Michelson measured the length of the international prototype metre in wavelengths of light emitted by cadmium. The idea of changing the definition of the metre was discussed at length in the first half of the 20th century: in 1960, the international scientific community agreed to define an *optical metre* based on the wavelength of an orange line in the spectrum of an isotope of krypton.

1.2 The polarization of light

Huygens discovered a phenomenon that he candidly admitted that he did not know how to interpret[7]: light that passes through Iceland spar exhibits peculiar properties, such that when it is incident on a second spar with a parallel cross section to the first, it only refracts normally; if the second spar is rotated at an opportune angle, however, double refraction occurs, and the intensity of the refracted rays depends on the angle of rotation.

In the early years of the century, this phenomenon was studied by an officer in the French corps of engineers, Etienne-Louis Malus (1775-1812), who discovered in 1808 that the light reflected by water below an angle of 54 °45’ acquires the same properties as light that has passed

[7] § 6.24 of M.Gliozzi: *A History of Physics from Antiquity to the Enlightenment*, Cambridge Scholars Publ. 2022.

through spar, as if the water's reflecting surface were akin to spar's cross section.

The same effect was later observed with all other types of reflection, occurring below characteristic angles of incidence that vary with the index of refraction of the substance; for reflection of metallic surfaces the effect is a bit more complicated, however.

In a paper published later that same year, Malus, through experiments using a polariscope made up of two mirrors at an angle, that today is named after Biot, gave the law that carries his name: if a beam of spar-polarised light of intensity *I* is normally incident on a second piece of spar, the intensities of the ordinary and extraordinary refracted rays that are produced (I_0 and I_e, respectively) are

$$I_0 = I \cos^2 \alpha \, ; \, I_e = I \sin^2 \alpha$$

where α is the angle between by the cross sections of the two pieces of spar. Around the same time that Malus conducted these experiments, the Paris Académie des sciences held a contest (1808) for a mathematical theory of double refraction that could be confirmed by experiment. Malus participated and won with a seminal 1810 paper titled *Théorie de la double réfraction de la lumière dans les substances cristallisées*. In relating his discovery, Malus interpreted it using Newton's point of view, though not taking it "as an indisputable truth". For Malus, rather, it was purely a hypothesis that allowed his calculations to work out. Having thus taken the side of the corpuscular theory of light, he sought an explanation of the effect in the polarity of light particles that Newton had discussed in his query XXVI[8]. "Natural" light, as it is known today, is composed of asymmetrical corpuscles oriented in every direction. When these corpuscles are reflected or pass through birefringent crystals, they orient themselves in the same direction: Malus called such light *polarised,* a term that is still used today.

The polarization studies begun by Malus were continued in France chiefly by Biot and Arago, and in Britain by David Brewster, who had attained fame in his days more for his invention of the kaleidoscope (1817) than for his important contributions to mineral optics. In 1881, Malus, Biot, and Brewster independently discovered that refracted light is also partially polarised, reaching maximum polarization when the reflected and refracted rays are perpendicular to each other.

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[8] § 6.20 of M.Gliozzi: *A History of Physics from Antiquity to the Enlightenment*, Cambridge Scholars Publ. 2022.

Jean-François-Dominique Arago (1786-1852) demonstrated that moonlight, light from comets, and rainbows are all polarised, confirming that the light emanating from these sources is actually reflected sunlight. The light emitted obliquely by incandescent solids and liquids also proved to be polarised, indicating that it originates from an internal layer of the material and refracts when it comes into contact with the air. The most important and well-known discovery made by Arago, however, was chromatic polarization, which he obtained in 1811. By passing polarised light through a 6 mm thick sheet of rock crystal and observing the refracted rays through a piece of spar, he obtained two images of complementary colours. For instance, if the one of the images was initially red, for different rotation angles of the spar it could turn orange, yellow, or green.

Biot repeated these experiments the following year and showed that to obtain a fixed colour, the rotation of the spar had to be proportional to the thickness of the sheet. In 1815, he further discovered the phenomenon of rotational polarization and the existence of dextrorotatory and laevorotatory materials. Incidentally, it was only in 1848 that Louis Pasteur (1822-1895), who was later immortalized for his work in biology, demonstrated that tartaric acid could exist in both dextrorotatory and laevorotatory form, starting a new chapter in organic chemistry research that was later expanded by Joseph Achille Le Bel (1847-1930) and Jacobus Hendricus Van't Hoff (1852-1911).

We now return to Biot, who discovered, also in 1815, that tourmaline is birefringent with the special property that it absorbs the ordinary ray and emits only the extraordinary one. Based on this effect, Herschel built the *tourmaline polariser* in 1820, a simple apparatus that has remained more or less the same to this day. The biggest inconvenience of this polariser is its colouration effect, which is avoided by the prism built in 1820 by the British physicist William Nicol (1768-1851); Nicol's prism also only transmits the extraordinary ray. Nicol combined two such birefringent prisms in 1839, creating a device whose use is still widespread today.

In conclusion, the fundamental phenomena of light polarization, a vast and interesting chapter of physics that is outlined in all modern physics texts, were by and large discovered by French physicists between 1808 and 1815. Furthermore, because the discovery of these intriguing phenomena occurred within corpuscular framework, it appeared that this theory was given new life.

1.3 Fresnel's wave theory

The spike in popularity of the corpuscular theory was short-lived, however. A young civil engineer, Augustin-Jean Fresnel (Fig. 1.1), having joined a small royalist militia as a volunteer to stop Napoleon, who had just returned from Elba, was suspended from his employment and forced to retire to Mathieu (near Caen) during the Hundred Days. Lacking almost any optical training, Fresnel dedicated himself to the study of diffraction throughout his forced leisure, using a makeshift experimental setup. The first fruits of his work were two papers presented on 15 October to the Académie des sciences in Paris. Arago, who was charged with examining them and reporting their results, found them so interesting that he offered for Fresnel to temporarily move to Paris to repeat the experiments in better conditions, as he had been summoned back to work, by the sudden restoration of Louis XVIII.

Fig. 1.1 – Augustin-Jean Fresnel

Fresnel had already begun to study the shadows produced by small obstacles placed in front of light beams, observing like Grimaldi that fringes appear not only on the exterior of the shadow but also on the interior (a point unaddressed by Newton). Studying the shadow produced by a thin string, he rediscovered the interference principle. He was struck by the fact that when the string was placed directly above the edge of a screen, the internal interference pattern disappeared. He therefore deduced that concurring rays coming from two sides are necessary to produce an internal interference pattern, as the fringes inside the shadow disappear when the light coming from one direction is intercepted. Fresnel described the effect: "The fringes cannot arise from a simple mixture of these rays, since each side of the wire separately casts into the shadow only a continuous light; it is their meeting, the very crossing of these rays which produces the fringes. This consequence, which is only, so to speak, a translation of the phenomenon, totally opposes the hypothesis of Newton and fully confirms the theory of vibrations. One easily sees that the vibrations of two rays that cross at a very small angle can oppose one another when the node of one corresponds to the antinode of the other."[9]

The idea was clear, but the statement of the principle was imprecise and subsequently corrected by Fresnel, who specified that all the waves weaken when the "dilated nodes" of one are superposed with the "condensed nodes of the other"; they strengthen, on the other hand, when their motions are "in harmony". In short, it was an interference principle that, once he had fully grasped it, led Fresnel to retrace Young's steps and in particular to explain the colouring of thin films.

In Paris, Fresnel learned from Arago of Young's double slit experiments, which seemed to him more than suitable in demonstrating the undulatory nature of light. However, not all physicists agreed. Indeed, the adherents of Newton attributed the phenomenon to an effect at the edges of the slits. To convince even the most obstinate of scientists, it was necessary to devise an experiment in which all possible attraction between matter and light rays was eliminated. Fresnel succeeded in this, in 1816 communicating the well-known "double mirror experiment" and in 1819 the "biprism" experiment, which have now become so standard that we do not waste the reader's time spelling them out. In 1837, Humphrey Lloyd showed that optical interference can be obtained even with a single mirror, as the light incident on the mirror can interfere with the reflected light. An important advance was made by Julius Jamin (1818-1886), who in 1856, while analysing an observation made by Brewster in 1831, constructed his well-

[9] A.J. Fresnel, *Œuvres complètes*, Paris 1866, Vol. I, p. 17.

known *Jamin interferometer* using two parallel glass plates, which were externally coated in silver by Georg Hermann Quincke (1834-1924) in 1867. As it is known, Jamin's device produces interference through the path length difference of two rays; only a minute change in the refractive index of medium in which one of the two rays propagates is needed to observe the characteristic fringes and measure the extent of the effect. Interferometers of this type are used to study variations in the index of refraction with changing temperature, pressure, concentration, the presence of a gas, and other variables.

We add in passing that John Herschel was inspired by the double mirror experiment in 1833 to conduct the analogous experiment for the interference of sound waves using a two-ended tube. This experiment was later improved in 1866 by Quincke, whom the experimental apparatus is named after. The use of manometric flames for a more objective observation was proposed in 1864 by Karl Rudolph Konig (1832-1901), who substituted Quincke's rubber tubes with two extendable metallic ones, like a trombone.

Let us return once more to the work of Fresnel. Having saved the interference principle from the attacks mounted by Newton's devotees, wave theory laid out three principles: the principle of elementary waves, the principle of wave envelopes, and the interference principle. These three principles remained disconnected until Fresnel brilliantly united them in his novel description of wave envelopes. For Fresnel, a wave envelope was not a simply a geometrical envelope, as for Huygens. According to the Frenchman, at any given point of the wave, the total effect is the algebraic sum of the pulses produced by all the elementary waves it contains; the sum of all these contributions, which are superposed according the interference principle, can also vanish. Fresnel performed the calculation, though not very rigorously, reaching the conclusion that the effect of a spherical wave on an external point is reduced to that of a small crown of the wave whose centre is aligned with the light source and the illuminated point, there being no other global effects.

Thus, was overcome the century-old problem that had always hindered the success of wave theory: reconciling the rectilinear propagation of light with its supposed wave mechanism. Each illuminated point receives light from the small region of the wave that is in its immediate vicinity, and thus the process occurs as if light propagates in a straight line from source to point. While it is true that waves should bypass obstacles, this principle cannot be considered in a purely qualitative manner, as the amount of diffraction around an obstacle is a function of the wavelength and requires quantitive evaluation. Examining diffraction phenomena, Fresnel calculated the amount of bending based on his theory, which was seen to agree impressively with experimental results.

Because of their lack of mathematical rigour, Fresnel's first papers on diffraction were not well received by Laplace, Poisson, and Biot, a trio of analytical scientists who placed great importance on firm mathematical underpinnings.

After a brief hiatus mandated by his engineering career, Fresnel returned to his theory with an important paper on diffraction that he presented in 1818, entering it in a contest organized by the Académie des sciences. The paper was reviewed by a commission made up of Laplace, Biot, Poisson, Arago, and Joseph-Louis Gay-Lussac: the first three were staunch Newtonians, Arago was partial to Fresnel, and Gay-Lussac was relatively inexperienced in the field but known to be a fair judge. Poisson observed that Fresnel's theory would lead to conclusions in stark contrast with common sense, as its calculations indicated that light can appear at the centre of the shadow created by an opaque disk of the right dimensions, while the centre of the conical projection of a small circular aperture, at the right distance, can appear dark. The commission invited Fresnel to experimentally demonstrate these consequences of the theory, and Fresnel, unperturbed, methodically confirmed them to the last detail, demonstrating that in this case common sense was wrong and Poisson had put too much faith in it. After these demonstrations, on unanimous recommendation of the commission, the Académie awarded the prize to Fresnel and in 1823 elected him a member.

Having established the theory of diffraction, Fresnel moved on to the study of polarization phenomena. Corpuscular theory, in trying to explain the many phenomena that were discovered in the first 15 years of the century, had been forced to introduce a myriad of unfounded and sometimes contradictory hypotheses, rendering the theory incredibly complicated. In the experiment of two mirrors at an angle, Fresnel had obtained from a single light source two virtual sources that were always perfectly coherent. He tried to reproduce this device with the two rays obtained by double diffraction from a single incident beam, suitably compensating the optical path length difference between the two rays. No matter what, however, he could not obtain interference in the two polarised rays. In collaboration with Arago, he continued experimental studies on the possible interference of polarised light. The two scientists experimentally established that two rays of light polarised in parallel directions always interfere, while rays that are polarised in perpendicular directions never interfere (in the sense that they cannot cancel). How could one explain this, and on a larger scale, how could one explain all the other polarization phenomena that had nothing in common with acoustic ones? Because light polarised by reflection exhibits two orthogonal planes of symmetry passing through the ray, one could surmise that the vibrations of the ether occur in these planes, transverse to the ray. This idea had been suggested to Fresnel by André-Marie Ampère in 1815, but Fresnel had not thought it important. Young also thought of transverse vibrations when he heard of Fresnel and Arago's experiments on polarization, but, perhaps due to uncertainty or excessive prudence, spoke of *imaginary transverse motion*: even to the least conformist of scientists, transverse vibrations seemed mechanically absurd.

After using the language of transverse vibrations implicitly for several years, in 1821 Fresnel decided to make the leap and, having found no other avenue to explain polarization phenomena, embraced the theory of transverse vibrations.

"It has only been for a few months that," he wrote in 1821, "in meditating more attentively on this subject, I have recognized that it is very probable that the oscillatory movements of the light waves are executed solely according to the plane of these waves, for direct light as for polarised light… I will show that the hypothesis I present includes nothing that is physically impossible and that it can be used to explain the principal properties of polarised light."[10]

That the hypothesis could explain the principal properties of light, both polarised and non-polarised, was extensively demonstrated by Fresnel; but showing that the theory included nothing that was physically impossible was another task altogether. The transversality of the vibrations implied that the ether, despite being a very thin, imponderable fluid, had to also be a solid more rigid than iron, as only solids transmit transverse vibrations. Fresnel's hypothesis appeared very bold, and perhaps even foolhardy. Arago, a physicist who certainly did not let prejudices govern him and had been a friend, advisor, and defender of Fresnel in every occasion, did not want any responsibility for this strange hypothesis and refused to place his signature on the paper presented by Fresnel.

Starting in 1821, Fresnel therefore continued on his own path, encountering success after success. The hypothesis of transverse vibrations permitted him to formulate a mechanical model of light. At its basis was the ether that pervades the whole universe and permeates through bodies, shifting its mechanical properties in the presence of matter. Because of these modifications, when an elastic wave propagates from pure ether to ether mingled with matter, part of the wave is reflected at the separation

[10] Fresnel, *Œuvres complètes*, cit., Paris Vol. I, p. 630.

interface and the other part penetrates inside the matter: thus, the phenomenon of partial reflection, which had remained a mystery for a century, was mechanically explained. Fresnel gave the formulas that carry his name, unchanged since his time: among these we only reproduce here the one describing the reflection coefficient (the ratio between the intensities of the incident and reflected rays) for normal incidence. If n is the relative index of refraction between the second medium and the first, and r is the reflection coefficient, Fresnel's formula gives:

$$r = \left(\frac{n-1}{n+1}\right)^2$$

The propagation velocity of the vibrations that move through matter depends on wavelength and, keeping that constant, is slower in more refractive media: this leads to refraction and scattering of light. In isotropic media, waves are spherical and centred at the light source; in anisotropic media the wavefront is generally of fourth order. In this theory, all of the complicated polarization phenomena are explained in an impressively coherent picture consistent with experimental results, arising as special cases of the general laws of composition and decomposition of velocities.

The study of double diffraction led to research on the forces responsible for the microscopic molecular motion in elastic media. This research brought Fresnel to state a few theorems that formed the basis of a new branch of science, as Émile Verdet (1824-1866), the editor of Fresnel's works, observed. Thus, was born the general theory of elasticity, developing just after Fresnel with the works of Augustin-Louis Cauchy, George Green, Poisson, and Gabriel Lamé.

From 1815 to 1823, Fresnel erected his impressive scientific body of work which, as with all human constructions, was not free of inaccuracies. The young engineer approached and solved problems relying more on his powerful intuition than mathematical calculation, therefore he was often mistaken or only hinted at the true solution. Nevertheless, his ideas, despite the opposition of older physicists, quickly captured the support of young researchers, who admired the intuitiveness and simplicity of his theoretical model: Airy, Herschel, Franz Ernst Neumann (1798-1895) and a legion of other physicists corrected and organized the theory and studied its consequences.

From 1823 until his death, Fresnel dedicated himself to the study of lighthouses for his work. The latest lighthouses at the time were made up of four or five d'Argand lamps[11], whose light was directed in more or less a single direction by a metallic parabolic mirror in uniform rotational motion, such that the beam of light was successively emitted radially in all directions. This apparatus was not very efficient: barely half of the light produced was transmitted outwards by the reflector. Fresnel had the idea to substitute it with lenses to horizontally refract the light incident on their focus. An appreciable beam could only be obtained in this way using large lenses, which were very difficult to build at the time. Buffon had already proposed (1748) to build composite lenses, and Condorcet (1773) and Brewster (1811) had reconsidered the idea, but the project could not be practically carried out. Fresnel finally succeeded in making the idea concrete, separately building concentric rings of a small-diameter lens. In this way, he was able to obtain large lenses with a focal length of 92 cm. The composite lenses allowed for nine tenths of the incident light to be transmitted, massively advancing the capacity of lighthouses.

Fresnel's brief life paralleled his scientific work, which remained limited to theoretical and practical optics. He was born on 10 May 1788 in Broglie, near Bernay in the Eure region. Having been judged a boy of modest intellectual capacities, though very ingenious and skilled in manual tasks, at age sixteen he enrolled in the École polytechnique of Paris, where his teacher Adrien-Marie Legendre immediately noticed his uncommon mathematical talent. Having obtained the title of engineer of bridges and roads, he immediately began working as a civil engineer for the state and remained in this line of work, with a few interruptions for study or illness, until his death by tuberculosis on 14 July 1827 in Ville-d'Avray, near Paris. He was a member of the Académie des sciences of Paris and the Royal Society of London, but he was never able to obtain a position at a university, which could have alleviated the suffering caused by his constant ill health and the disease that afflicted him in his last years, which at the time was always fatal. Even then the university system, perhaps unknowingly, followed rules that could be detrimental to scientific research, not to mention unforgiving.

1.4 Hamilton-Jacobi optics

William Rowan Hamilton, born in Dublin on 4 August 1805 and died on 2 September 1865, was still a second year student at Trinity College when he read his paper on caustics to the Royal Irish Academy. Further expanding

[11] § 7.15 of M. Gliozzi: *A History of Physics from Antiquity to the Enlightenment*, Cambridge Scholars Publ. 2022.

this idea, he was led a few years later to predict the phenomenon of "conical refraction": when a ray of light is incident on a rectangular sheet cut by a biaxial crystal perpendicular to an optical axis, and the angle of incidence is parallel to the optical axis, the ray is refracted into a cone of light whose radius depends on the thickness of the sheet. In 1837, on Hamilton's suggestion, Humphrey Lloyd (1800-1845) experimentally verified this phenomenon in an aragonite sheet.

With this theoretical discovery began Hamilton's brilliant career as a mathematician, although his interests extended beyond science to philosophy, humanism, and poetry.

In the first years of Hamilton's career, wave theory was not unanimously accepted, as we saw earlier. Poisson was still a supporter of Newton's corpuscular theory; Biot, the most conservative of the great 19th century physicists, maintained his convictions until his death in 1862; Brewster did not accept the wave theory because he could not think "the Creator guilty of so clumsy a contrivance as the filling of space with ether in order to produce light," and, incredible as it may seem, he claimed that he could not follow Fresnel when he spoke of transverse vibrations as if it was a point in his favour.

In light of this general attitude among the prominent scientists of the time, Hamilton set out to construct a formal theory of known optical phenomena that could be interpreted both from an undulatory point of view and from a corpuscular point of view, through the principle of least action. His stated aim was to construct a formal theory of optics that had the same "power, beauty, and harmony" of Lagrangian mechanics. According to Hamilton, the laws of ray propagation could be considered in and of themselves, independently of the theories that interpreted them, to arrive at a "mathematical optics". Indeed, following this approach, he deduced a doctrine of scientific philosophy. Hamilton distinguished two phases in the development of science: in the first, the scientist generalizes individual facts into laws through induction and analysis; in the second, the scientist goes from general laws to their specific consequences through deduction and synthesis. In short, according to Hamilton, humans gather and group observations until the scientific imagination discovers the inner laws governing them, creating unity out of variety. Then, humans re-obtain variety from unity by using the discovered laws to make predictions about the future.

This was the method with which Hamilton worked. He observed that the principle of least action, while deduced from the metaphysical concept of the "economy of nature", was more properly a principle of extremal action, as there were several known cases in which it was the maximum in action that described phenomena. He thus spoke of *stationary* or *varied* action, depending on whether the endpoints of the rays and trajectories were taken to be fixed or variable. In this way, Hamilton arrived at the formulation of the principle that carries his name, according to which there is a certain optical quantity, defined in a mathematical way, that is stationary in the propagation of light. Through this approach, geometric optics was converted into a formal theory that could explain experimental results without requiring a choice of either the corpuscular hypothesis or wave hypothesis of light.

In 1834-35, Hamilton extended his optical theory to dynamics and systematically developed it. In his framework, the solution of a general dynamical problem depends on a system of two partial differential equations.

Hamilton's work was an admirable synthesis of optical and dynamical problems, which Louis De Broglie would rediscover and Erwin Schrödinger would use as inspiration (§ 8.5): it is interesting to see that the most powerful mathematical instruments of quantum mechanics were provided by analytical mechanics, which was developed within the framework of classical physics.

It was Carl Gustav Jacobi (1804-1851), however, who with his famous works, beginning in 1842, gave the broadest application of Hamilton's theory, simplifying it and at the same time generalizing it to a now-classic form: for this reason, the theory is often called Hamilton-Jacobi mechanics.

Before moving on, we must also relate another great merit of Hamilton, his introduction of a new mathematical technique involving what he called "quaternions" (a system of four numbers that extends complex numbers). He announced this novel approach in 1843, and developed in in a lengthy treatise (of 872 pages) published in 1853, which appeared incomprehensible to his contemporaries. The theory started from the consideration that the imaginary unit can be thought of as an operator that indicates a 90 degrees rotation, much like a factor of -1 indicates a 180° rotation. The extensive applications of quaternions to many branches of physics are well known, but in the first decades following the introduction of Hamilton's number system it seemed that physicists did not take the new algebra into consideration (the first example of a non-commutative algebra and the algebraic beginnings of linear algebra), and neither was its study encouraged by Mathematics Departments.