Optics in the Nineteenth Century

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The nineteenth century laid the foundation for modern optics and for the establishment of The Optical Society in 1916. Optical science had come a long way from Newton's pioneering *Optiks*, but much remained to be learned. In 1800 Newton's particle theory of light still held sway, the interference of light had not been recognized, and the rest of the electromagnetic spectrum was undiscovered. Only the wealthy and elite used spectacles, poor glass quality limited the use of refractive optics, and the world's largest telescope was a 1.2-m reflector built by William Herschel in 1789 that required frequent repolishing.

Wave Nature of Light

A landmark experiment at the start of the nineteenth century shaped the course of optical science. Thomas Young showed that light passing through two parallel slits interfered to produce regularly spaced dark and light zones. In 1803, he told the Royal Society that the light was made of waves, not particles, as Newton had written in *Optiks* more than a century earlier.

Another new discovery came in 1808, when Etienne-Louis Malus found that turning a birefringent calcite crystal changed the reflection he saw from nearby windows. Malus called the effect polarization but thought he could explain it by considering light as particles. David Brewster studied polarized reflection in more detail and showed its connection to a material's refractive index, but he did not think wave theory was needed.

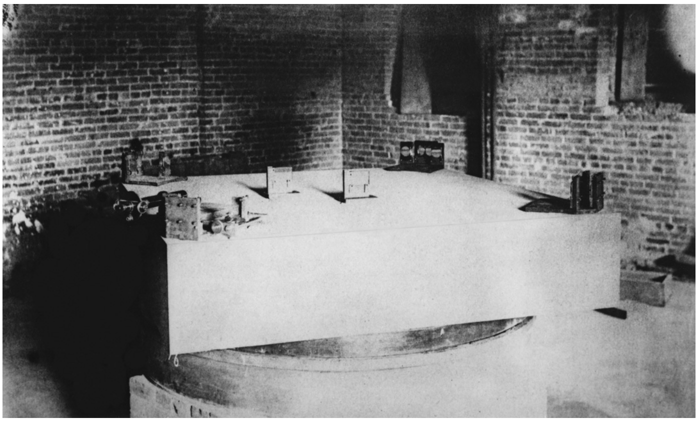
Acceptance of wave theory took time. In 1818, Augustin-Jean Fresnel used diffraction theory to explain interference as a wave phenomenon. A few years later, Fresnel showed that polarization could be explained only if light consisted of transverse waves. Other research bolstered the case for waves, which became the standard theory of light. But a big question remained: how could light waves travel through space?

Nineteenth century physicists thought the logical answer was through an invisible medium called the ether, which permeated space. Christiaan Huygens had proposed it as part of his wave theory, before Newton published *Optiks*. Waves in the ether fit with Fresnel's theory of diffraction. In 1820, Fresnel showed that transverse waves in the ether could explain polarization. But the nature of the ether was hard to fathom and would become a major debate for the rest of the century as physicists continued discovering new effects.

A series of experiments in the early 1800s showed that electricity and magnetism were closely related effects. In 1845, Michael Faraday found that magnetic fields could affect light passing through certain materials. He later suggested that light was a transverse vibration of electric- and magnetic-field lines.

James Clerk Maxwell built on those observations when he developed his theory of electromagnetism in 1860. Noting that light seemed to travel at the same speed as the forces of electricity and magnetism, Maxwell concluded that all three propagated in the same medium at a fixed velocity—the speed of light. That made light a form of electromagnetic radiation, which Heinrich Hertz confirmed experimentally in 1887 and 1888.

However, a nagging problem had emerged with Maxwell's assumption that the ether was a fixed reference frame for the universe. If that was the case, the Earth had to be moving relative to the ether, and that motion should be detectable as an "ether wind" by measuring the speed of light in two orthogonal directions at the same time. Optical techniques were the most sensitive probes available. Yet no one could measure any difference.



▲**Fig. 1.** Milestone Michelson–Morely experiment was conducted in a basement at what was then the Case Institute of Technology. Courtesy of Special Collections and Archives Department, Nimitz Library, U.S. Naval Academy.

In 1887, Albert Michelson teamed with Edward Morley using an extraordinarily sensitive interferometer in which a beamsplitter divided light between its two orthogonal arms (Fig. 1). In theory, it was sensitive enough to spot the "ether wind" if an absolute reference frame existed. But they could not measure any difference in the speed of light in the two directions. That inability to confirm an absolute reference frame would leave physicists scratching their heads for many years.

Hertz's experiments also found something unexpected: metal electrodes emitted sparks more easily if ultraviolet light illuminated the metal. That began looking odder after J. J. Thomson discovered the electron in 1897 and found that ultraviolet light was helping evaporate electrons from the metal surface, the photoelectric effect that Hertz had seen. But the sparks were not flying as expected. If light waves gradually deposited energy until the electrons soaked up enough to escape, any wavelength should suffice. But experiments showed that the electrons were freed only if the wavelength was shorter than a value that depended on the metal—as if light was made up of particles carrying an amount of energy inversely dependent on the wavelength.

Yet another complication emerged when Lord Rayleigh used classical physics to analyze blackbody radiation in 1900 and found that energy emissions should increase toward infinity as the wavelength decreased toward zero. Max Planck empirically resolved that "ultraviolet catastrophe" the following year by assuming that light could be emitted or absorbed only in discrete quanta. But not even Planck himself knew at the time what that meant.

Albert Einstein found the answers in his "annus mirabilis" papers of 1905. To explain the photoelectric effect, he proposed that light could be absorbed or emitted only as quanta, or chunks of energy, as Planck had proposed to account for blackbody emission. That paper led to the wave-particle duality of light and earned Einstein the 1921 Nobel Prize in Physics. His theory of special relativity explained the failure of the Michelson–Morley experiment by stating that the speed of light was the same in all inertial reference frames. Later, Einstein wrote that the experiment resulted in "a verdict of 'death' to the theory of a calm ether-sea through which all matter moves" [1]. The Michelson interferometer remains a remarkably sensitive instrument and today is at the heart of the Advanced LIGO (Laser Interferometer Gravitational-wave Observatory), which was to begin a new search for gravity waves in 2015.

Spectroscopy and Atomic Physics

Fresnel's use of wave theory to calculate the diffraction of light gave physicists the first direct way to measure wavelength. Prisms had long been used to display the spectrum, and in 1814 Joseph von Fraunhofer incorporated one into a spectroscope to measure light absorption and emission lines (Fig. 2). In 1821, he assembled a diffraction grating made of many parallel wires and found that diffraction from the regularly spaced lines could be used to measure the wavelengths of light directly.

Spectroscopy brought new ways to identify atoms and molecules by looking at emission lines from bright flames or at the dark absorption lines from cool gases. In 1853 Anders Ångström showed that hot gases emitted at the same lines that they absorbed when cold. In the 1860s, Gustav Robert Kirchhoff and

▲Fig. 2. Joseph von Fraunhofer demonstrates the spectroscope [13].

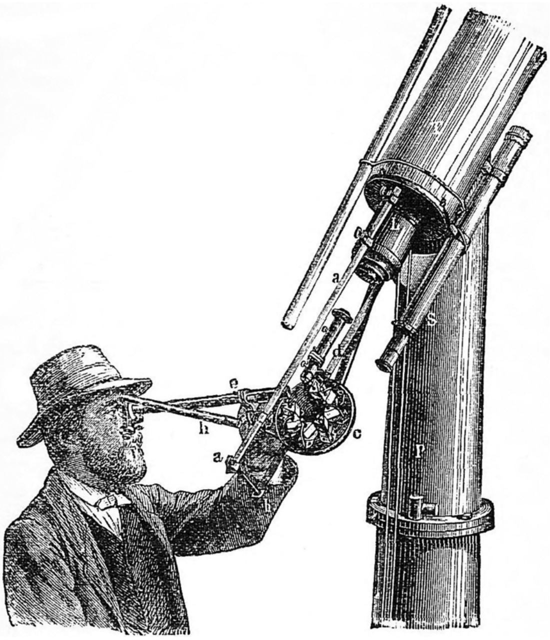
Robert Bunsen matched wavelengths that they measured in the lab with solar lines (Fig. 3). Astronomers William and Margaret Huggins then showed that stellar spectra included lines found in sunlight, and they measured the Doppler shift of Sirius, the first stellar motion detected on Earth.

Spectroscopy also opened a new window on atomic physics. In 1885, Swiss mathematician Johann Balmer discovered a numerical pattern in a series of visible hydrogen wavelengths measured by Ångström. The wavelengths were equal to a constant multiplied by the quantity $n^2/(n^2 - 2^2)$ where n was an integer. Balmer used the formula to predict additional wavelengths in the ultraviolet, which William Huggins and Hermann Wilhelm Vogel confirmed in the spectra of white stars. Later, Johannes Rydberg developed a more general formula that explained other series of lines.

Those patterns remained a mystery until Niels Bohr recognized them as transitions between a limited number of electron orbits in the hydrogen atom and then developed the Bohr model of hydrogen in 1913, a major step on the road to quantum theory.

Optical Instruments

The poor quality of optical glass limited optical instruments at the start of the nineteenth century. In 1757, John Dollond had combined crown and flint glass to make the first achromatic lens, but he lacked high-quality glass and accurate dispersion measurements. Eighteenth century astronomers had turned to reflectors for a better view of the sky. The world's largest telescope in 1800 was a reflector with a 1.26-m mirror and 12-m focal

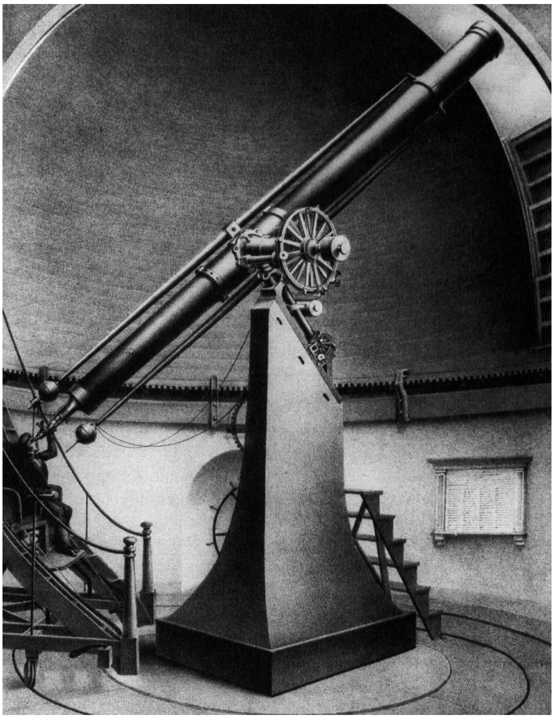


▲Fig. 3. Astronomical spectroscopy in the nineteenth century required attaching a spectrometer to the telescope and viewing the dispersed spectrum with the eye [14].

length built by William Herschel. But the telescope's huge size and the poor reflectivity of its easily tarnished speculum mirror limited its use.

Glass quality improved in the early nineteenth century after Swiss craftsman Pierre Louis Guinand tried stirring molten glass with clay rods rather than wood to remove bubbles. Fraunhofer used such glass to build a 24-cm telescope for the Dorpat Observatory in 1824. It was the first modern achromatic refractor, and Wilhelm Struve used it to survey over 120,000 stars [4].

Astronomers came to prefer the high optical quality of refractors. William Parsons built the largest telescope of the century at his estate in Ireland around a three-ton, 1.8-m mirror, and the "Leviathan" was used from 1845 to about 1890 [5]. But refractors were more productive.



▲**Fig. 4.** Harvard 15-in. refractor installed in 1847 was the world's largest refractor for two decades. Courtesy of the Harvard College Observatory.

In 1847 the Harvard College Observatory installed a 15-in. (38 cm) refractor built by Mehr and Mahler of Munich (Fig. 4). It was a twin to one built in 1839 for the Pulkovo Observatory that Struve had just established in Russia, and the pair were the world's largest refractors for some 20 years. The Harvard "great refractor" remains in the observatory on the Harvard campus, where it is used for public observing nights. Later in the century, Alvan Clark and Sons in the U.S. was famed for big refractors. They built the 36-in. (91-cm) Lick Telescope, which was the world's largest refractor in 1887 when it was installed on Mount Hamilton, near Santa Cruz, California. The Clarks also made the 40-in. (1.02-m) lens for the Yerkes Observatory in Lake Geneva, Wisconsin, finished in 1897, which was among the first telescopes used primarily for photography and spectroscopy.

Better glass and achromatic lenses also revolutionized microscopy. Joseph Jackson Lister, father of the Joseph Lister who pioneered antiseptic surgery, redesigned the microscope with achromatic optics in 1830, and his design was used widely for many years.

The birth of modern optical microscopes came from the partnership formed in Jena, Germany, by Professor Ernst Abbe and instrument maker Carl Zeiss in 1866. They analyzed and refined the design of lenses, microscopes, and illumination systems for six years, leading to Abbe's publication of his theory of microscopic imaging, and Zeiss's later introduction of 17 microscope objectives based on that theory [6].

Finding that glass quality limited performance of those microscopes, Abbe teamed with Otto Schott in 1881 to develop new glasses and improve their uniformity. That led to the formation of Schott and Sons in Jena, which in 1886 introduced the "apochromat" objective, which reached Abbe's theoretical limit of resolution [7]. Schott's new glasses also enhanced the optical quality of Porro prisms, allowing production of the first high-performance modern binoculars in 1894.

Spread of Spectacles

Although Benjamin Franklin is famed for inventing—or at least popularizing—bifocals in 1784, few people of his time wore spectacles. They were expensive, and visual science was not advanced enough to give a precise correction.

Thomas Young has been called "the father of physiological optics" based on his 1801 paper "On the mechanism of the eye" [8,9]. He developed an optometer to measure visual accommodation, analyzed peripheral vision, and discovered astigmatism—previously unknown—in his own eyes. However, it took time to apply his insights. Only in 1827 were corrective lenses used to correct astigmatism in the eyes of George Airy, who measured his own eyes and had an optician make the lenses [10].

Spectacles spread slowly at first. In 1853, young German immigrant John Jacob Bausch found little business when he hung out his shingle as an "optician" in Rochester. In time, he took in a partner, Henry Lomb, and after Lomb returned from the Civil War, their company became Bausch and Lomb, Optician.

Business picked up after the war ended. German physicist and physiologist Hermann Helmholtz had advanced optical science by inventing the ophthalmoscope in 1851 and writing his three-volume *Handbook of Physiological Optics*, which The Optical Society had translated into English in the 1920s [11]. Furthermore, new technology was bringing down costs.

Bausch and Lomb introduced eyeglass frames made of vulcanite rubber, a material much less expensive than wire- or horn-rimmed glasses. Demand soared. The American Optical Company, founded in Southbridge, Massachusetts, by merging smaller companies dating back to 1833, specialized in steel eyeglass frames, first developed in 1843 by local jeweler William Beecher, who was frustrated by cheap imports.

The companies soon expanded. American Optical was one of the first U.S. spectacle firms to start making their own lenses in 1883. They started making other lenses a decade later [12]. Bausch and Lomb began making microscopes in 1876, photographic lenses in 1880 [13], shutters in 1888, and their own spectacle lenses in 1889. Meanwhile, Europe began importing American-made vulcanite frames.

By the waning years of the nineteenth century, photography also was emerging as an important consumer market for optics. Photography depends on light-sensitive materials, and early processes for exposing and developing such materials had been complex, requiring bulky cameras, heavy glass plates, and chemical processing. That changed after a Rochester bookkeeper named George Eastman took up photography as a hobby in 1878.

Eastman started with wet-process plates but became intrigued by a new dry process based on gelatin, and he went to London to learn more about it. That led him to invent a new plate-coating machine, and in 1880 he opened a business making dry plates. In 1884 he introduced a flexible light-sensitive film on an oiled-paper base. He opened the floodgates to popular photography by announcing the first Kodak camera in 1888, followed in 1889 by a new transparent film on a cellulose nitrate base that quickly supplanted his earlier film [14].

Film was also a crucial technology for the new field of motion pictures. Thomas Edison, the archetypical technology entrepreneur of the era, filed the first of his many patents in the field in 1888. Movie cameras and projectors required complex mechanical systems to move the film while it was exposed and projected. They also needed special camera and projection lenses. The real growth of the industry started after the turn of the century and led to new companies such as Bell and Howell, founded in 1907 by two projectionists.

By the turn of the century, optics had become a big business, especially in Rochester. In 1903, Bausch and Lomb reported making 20 million eyeglasses a year. Photography also was growing, with the company reporting total sales of 500,000 photographic lenses and 550,000 camera shutters since entering the business in the 1880s. Smaller optics companies were proliferating.

Precision optics and optical instruments remained a smaller field, dominated by German companies such as Zeiss and Schott. That would become an important factor in the formation of The Optical Society, as military agencies sought to develop American sources of military optics after the start of World War I cut off access to high-quality German glass and optics.

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