PRE–1940

1941–1959

1960–1974

1975–1990

1991–PRESENT

OSA® | 100

Introduction: Early Technology

Carlos Stroud

This section of our centennial history of optics addresses two tasks: setting the stage by describing the situation at the beginning of our highlighted period, and then summarizing the changes that occurred. The beginning and end of our period are both quite special years in political and economic history. The United States was just entering the Great War, as World War I was called in 1916; and in 1940 it was on the inevitable path leading to its entry into World War II. It is not an exaggeration to say that the course of civilization was dramatically altered by each of these events, and the course of optical research and technology was no less altered.

In a very real sense modern instrumental optics began in a series of developments in Germany led by Carl Zeiss, Ernst Abbe, and Otto Schott. In his essay Jeff Hecht reviews these and other earlier developments that formed the basis for the rapid developments in our field in the first half of the twentieth century. The dawn of the new century found Germany recently unified and growing quickly in industrial output, Great Britain at the peak of her imperial era, and the United States, fresh from its victory in the Spanish–American War, rapidly becoming the world's leading industrial power. Technical inventions such as a practical light bulb, the telegraph and telephone, phonograph, motion picture camera, and projector changed the way people lived. There was a great deal of optimism looking forward to the new century of continued progress. There were a series of world's fairs and exhibitions in which the latest inventions were touted. Perley G. Nutting, the prime mover in the founding of The Optical Society, apparently constructed the very first neon sign and exhibited it at the Louisiana Purchase Exhibition in 1904, proudly proclaiming "NEON" in glowing light.

It was in this heady environment that optics entered the twentieth century. Optics was centrally involved in two scientific revolutions that shook confidence in the foundations of the old Newtonian science that had served the science and industry of the nineteenth century so well: Einstein's relativity and quantum mechanics. Patricia Daukantas reviews the advances in spectroscopy up to 1940 and their importance to the development of quantum theory and astronomy. Today it is difficult to imagine carrying out precision spectroscopic measurements without a laser, a computer, or a photomultiplier or photodiode. Photographic plates had to suffice, unless you used Albert Michelson's technique of calibrating dark-adapted students. That proved adequate for him to resolve the 1.7 GHz ground state hyperfine splitting of sodium by measuring the drop-off of the visibility of the fringes in his interferometer illuminated by fluorescence from sodium. By 1940 the new quantum theory was in place, and Paul Dirac and Erwin Schrödinger had developed a quantum version of electrodynamics. The basic ideas underlying modern quantum optics were in place awaiting the development of optical technology that would allow controlled experiments one atom and one photon at a time. As we will see in later chapters in this volume, these technological developments followed in the second half of the twentieth century following the development of the laser.

Prior to the twentieth century, science and engineering were carried out mostly by university professors and amateur scientists working mostly alone with only their own funds or perhaps a rich patron's munificent interest. This changed completely in the new century, first by the establishment of a number of industrial and governmental research laboratories, and then by governmental science and engineering funding agencies following World War II. I review the founding of these laboratories and their central importance to twentieth century optics.

A very important optical industry has a history that almost exactly spans the first century of the existence of The Optical Society: film-based photography. Todd Gustavson recounts the history of photography, concentrating particularly on the first 40 years of the twentieth century. A lot of optical instrumentation is fairly specialized in its application, with but a few thousand to a few tens of thousands of units sold. With the introduction of George Eastman's Brownie camera in 1900, optics became "mass market" with sales of hundreds of thousands to millions. The economics of optics was completely changed, and with that technology changed equally rapidly.

A second mass-market development in optics was the production of affordable eyeglasses. Bausch and Lomb sold 20 million in 1903, and American Optical was not far behind. This supported rapid progress in vision research, which Patricia Daukantas reviews. From the founding of OSA to today this has remained a central concern of the Society and its members. As the average human lifespan increased due to improvements in sanitation, nutrition, and medical science, age-related vision problems became more important, and this field of optics responded with rapid developments.

The development of color photography and color printing as mass industries required standardization of color measurements and the development of a better understanding of color vision. Roy Berns recounts these developments with particular emphasis on the role of OSA and its committees.

This series of essays takes us up to the beginning of World War II, after which the climate for research and development in optics changed dramatically into something approximating its current form.

Optics in the Nineteenth Century

Jeff Hecht

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.

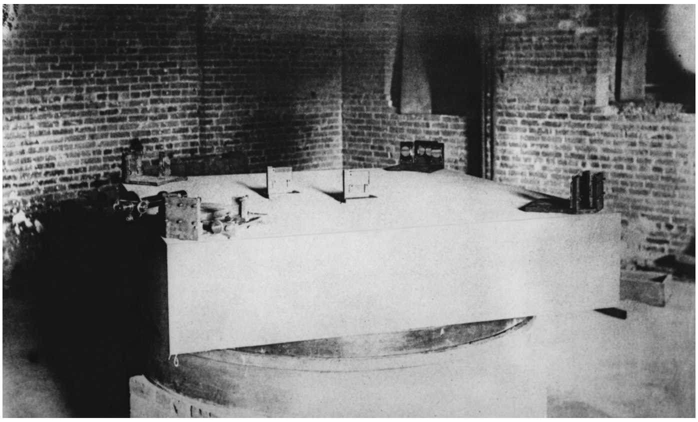
Acceptance of wave theory took time. In 1818, Augustin-Jean Fresnel used diffraction theory to explain interference as a wave phenomenon. A few years later, Fresnel showed that polarization could be explained only if light consisted of transverse waves. Other research bolstered the case for waves, which 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



▲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.

orthogonal directions at the same time. Optical techniques were the most sensitive probes available. Yet no one could measure any difference.

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.

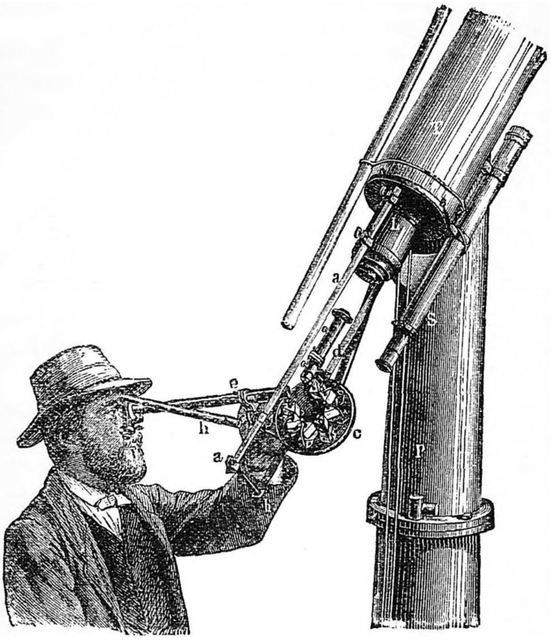
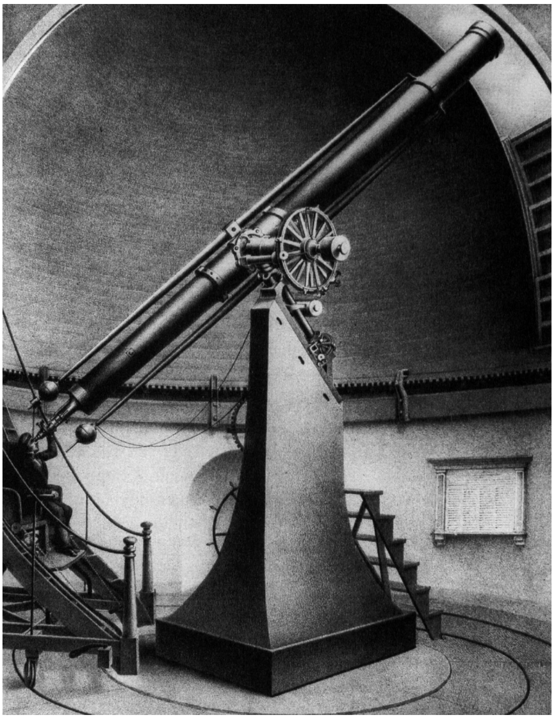


Fig. 3. Astronomical spectroscopy in the nineteenth century required attaching a spectrometer to the telescope and viewing the dispersed spectrum with the eye [14].

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

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.

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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PRE-1940

Spectroscopy from 1916 to 1940

Patricia Daukantas

During the first quarter century of The Optical Society (OSA), spectroscopy led to major insights into atomic and molecular physics and paved the way for important practical applications. Optical spectroscopy existed for decades before the formation of OSA, but it was empirical and descriptive in its nature. Spectroscopists had carefully measured the wavelengths of spectral lines associated with various elements, but the subatomic mechanisms that created these lines were not yet fully understood.

Twenty-four years later, as the world lurched toward the second all-encompassing war of the twentieth century, the spectroscopic fingerprints of atoms and molecules had provided vital evidence for the emerging quantum theory. Experimentalists refined their techniques and discovered previously unknown phenomena.

Spectroscopy and Quantum Mechanics

A few years before OSA was formed, Niels Bohr had proposed his model of the hydrogen atom, which explained the empirical Rydberg formula for the spectral lines of atomic hydrogen, at least to a first approximation. Theodore Lyman completed his investigations of the ultraviolet emission lines of hydrogen, beginning at 1216 Å in 1914.

Little happened in spectroscopy during World War I, but the field came raging back shortly after the armistice. In 1919, Arnold Sommerfeld, doctoral adviser to multiple Nobel Laureates, published *Atombau und Spektralinien* (*Atomic Structure and Spectral Lines*). William F. Meggers, who would become the 1949–1950 OSA president, opined that "spectroscopists were amazed that our meager knowledge of atomic structure and the origin of spectra could be expanded into such a big book" [1].

The same year, Sommerfeld and another German physicist, Walther Kossel, formulated the displacement law now named after them [1]. The law states that the singly ionized spectrum of an element resembles the neutral spectrum of the element preceding it in the periodic table. Likewise, the doubly ionized spectrum of an element resembles the singly ionized spark spectrum of the element preceding it, or the neutral spectrum of the element with atomic number two less than the designated element. The neutral spectrum was usually obtained by running an arc of current through a vapor; ionized spectra came from the light of an electric spark in a gas or vapor.

In 1922, the English physicist Alfred Fowler and the German team of Friedrich Paschen and Richard Goetze published tables of observational data on spectral singlets, doublets, and triplets without interpreting them according to the fledgling quantum theory. Later the same year, Miguel A. Catalán of Spain published his finding that the arc spectra of complex atoms have lines that occur in groups with certain numerical regularities [1]. He called these groups multiplets, and their discovery sparked a productive era of description and interpretation of the optical spectra of most complex atoms, except those of the rare-earth elements.

The following year, Sommerfeld [1] posited the "inner-quantum number," now known as the azimuthal quantum number, represented by the script letter ℓ and the familiar subshells s, p, d, and f. In OSA's journal, Sommerfeld also proposed a model for the neutral helium atom, which had perplexed scientists since Bohr explained the hydrogen atom [2].

Then in 1925, Americans Henry Norris Russell and Frederick A. Saunders examined the spectrum of calcium and discovered the type of spin-orbit coupling now known as LS coupling [3]. This breakthrough led to, in short order, an outburst of important theories of atomic structure and atomic spectra. Meggers [1] listed the astonishing output of a single year, 1925:

- Wolfgang Pauli's rule for equivalent electrons and his exclusion principle;
- Friedrich Hund's correlation of spectral terms with electron configurations and his correlation of multiplet components to series limits; and
- the determination by George Uhlenbeck and Samuel Goudsmit of the contribution of electron spin to the complexity of spectra, and their postulation of the half-integral quantum numbers of fermions.

Nearly simultaneously in 1925, Werner Heisenberg and Erwin Schrödinger formulated their matrix and wave mechanics formalisms, and quantum theory blossomed. Two years later, Heisenberg came up with his uncertainty principle, which partially explains spectral line broadening (but is certainly not the only cause of it).

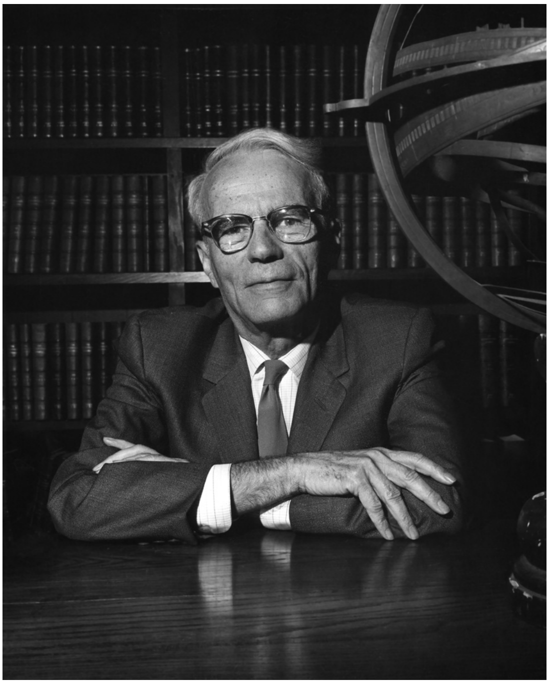
The Astronomical Connection

Some of the early spectroscopists, including Lyman, Russell, and Fowler, either worked as astrophysicists or had some background in the subject. The two specialties were synergistic: the discoveries of lines in the spectra of sunlight and starlight had motivated the birth of spectroscopy in the first place, and, as more atoms yielded their secrets in earthbound laboratories, astronomers learned about the chemical composition of the universe.

For instance, as a young man Frederick Sumner Brackett observed infrared radiation from the Sun at the Mount Wilson Observatory in California; in 1922, he discovered the series of infrared spectral lines, which bear his name, by studying the light from a hydrogen discharge tube [4]. In 1924, Ira S. Bowen (see Fig. 1) and OSA Honorary Member Robert A. Millikan modified their vacuum spectrograph to make it easier to record the extreme ultraviolet spectra of atoms heated by sparks [5]. Their work extended the range of spectroscopy into many light neutral atoms and multiply ionized heavier atoms. In turn, the lab work enabled Bowen to solve, in 1928, the mystery of the postulated element "nebulium."

Nineteenth-century astronomers had observed bright green emission lines in the object known as NGC 6543, popularly called the Cat's Eye Nebula. Since the lines matched those of no known element on Earth, they were attributed to a new substance named after the nebula. With his knowledge of both astronomy and spectroscopy, Bowen demonstrated that the emitting element was not nebulium at all, but doubly ionized oxygen giving off forbidden lines—spectral lines not normally permitted by the selection rules of quantum mechanics, but spontaneously occurring in the hard vacuum of a tenuous astrophysical gas cloud [6].

A decade later, astronomer–spectroscopists Walter Grotrian and Bengt Edlén identified the



▲ **Fig. 1.** Ira S. Bowen. (Courtesy of AIP Emilio Segre Visual Archives, W. F. Meggers Collection.)

true nature of “coronium,” another would-be element found in the solar corona 70 years earlier. Coronium turned out to be highly ionized iron, nickel, and calcium [7]. Every place astrophysicists have since looked, the rest of the universe consists of the same chemical elements that are found on Earth.

Advances in Molecular Spectroscopy

While some physicists occupied themselves with subatomic structures, other physicists and chemists investigated new spectroscopic phenomena in molecules. The nineteenth-century observations of fluorescence by G. G. Stokes led to the American R. W. Wood’s discovery of resonance radiation of vapors in 1918.

Wood (see Fig. 2), for whom an OSA award is named, began his career with detailed investigations of the spectra of iodine, mercury, and other elements in gaseous form. As a biographer wrote, Wood “discovered resonance radiation and studied its many puzzling features with great thoroughness and amazing experimental ingenuity” [8].

By far the biggest boost to molecular spectroscopy during this time period was C. V. Raman’s discovery of the inelastic scattering of light—the effect that came to bear his name. During his European trip in 1921, Raman (see Fig. 3), a native of India, spied the “wonderful blue opalescence” of the Mediterranean Sea and, as a result, was inspired to study the scattering of light through liquids [9]. In 1928, he and a colleague, K. S. Krishnan, discovered the inelastic scattering of photons now known as the Raman effect.

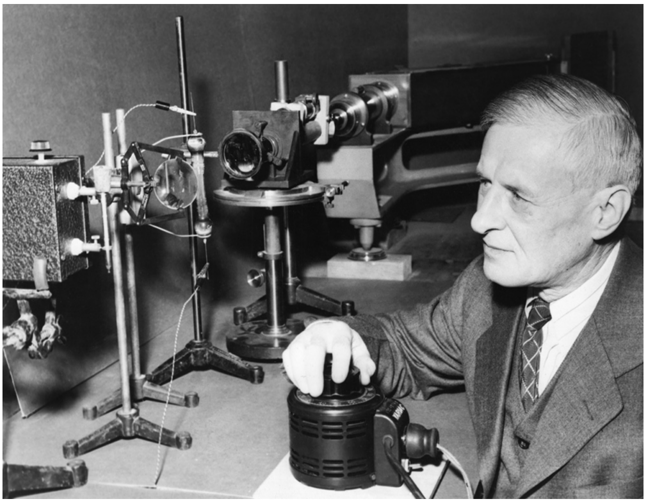
Lacking lasers, Raman and Krishnan had to use sunlight passed through a narrow-band photographic filter as a monochromatic light source. Early scientists who studied Raman scattering used mercury arc lamps or gas-discharge lamps as their sources. Nevertheless, in the 1930s scientists used Raman spectroscopy to develop the first catalog of molecular vibrational frequencies. The technique, however, would not reach its full flowering until the development of the laser in the 1960s.

Optical spectroscopy also played an important role in the understanding of nuclear structure. Although A. A. Michelson had observed hyperfine structure as far back as 1881, it lacked an interpretation until 1924, when Pauli proposed that it

▲ **Fig. 2.** R. W. Wood. (Courtesy of The Observatories of the Carnegie Institution for Science Collection at the Huntington Library, San Marino, California.)

▲ **Fig. 3.** Chandrasekhara Venkata Raman. (Massachusetts Institute of Technology, courtesy AIP Emilio Segre Visual Archives.)

resulted from a small nuclear magnetic moment. In a 1927 article on the hyperfine structures of the spectral lines of lanthanum, Meggers and Keivan Burns pointed out the association between wide hyperfine splitting and spectral terms that arise when a single *s*-type electron manages to penetrate the atom's core [10]. "These penetrating electrons, so to speak, spy upon atomic nuclei and reveal in the hyperfine structure of spectral lines certain properties of the nuclei," Meggers wrote in 1946 [1]. "These properties are mechanical, magnetic, and quadrupole moments."



▲ **Fig. 4.** William F. Meggers with his laboratory equipment. (Courtesy of AIP Emilio Segre Visual Archives, W. F. Meggers Collection.)

▲ **Fig. 5.** George R. Harrison working with laboratory equipment. (Photograph by A. Bortzells Tryckeri, AIP Emilio Segre Visual Archives, W. F. Meggers Gallery of Nobel Laureates.)

Spectral Analysis and Instrumentation

In parallel with the investigations into atomic and molecular structure, scientists of the 1920s and 1930s still had much to learn about the spectra of the various elements. They also made improvements to spectroscopic instruments and measurement techniques.

Before 1922, according to Meggers (see Fig. 4), scientists had only three ways to make quantitative spectrochemical analyses: the length-of-line method, the residual spectrum method, and the intensity-comparison with standards method [1]. During the following two decades, at least three dozen new techniques were published in the literature, although some were simply modifications of other procedures. Meggers and two of his colleagues at the U.S. National Bureau of Standards, C. C. Kiess and F. J. Stimson, published a 1922 monograph to bridge the gap between semiquantitative and quantitative spectroscopic analysis [11]. In 1926, Bowen published a detailed how-to article on vacuum ultraviolet spectroscopy [12], which David MacAdam later deemed one of the milestone articles in the history of the *Journal of The Optical Society of America* (JOSA) [13].

In a major advance for pre-laser applied spectroscopy, Henrik Lundegårdh in 1929 developed a new flame-emission spectroscopy technique, which used a pneumatic nebulizer to spray a vaporized sample into an air-acetylene flame. This method made it easier for scientists to process many samples in a single day [14].

Since each chemical element can emit as many different spectra as it has electrons, the 92 naturally occurring elements can produce a total of 4278 spectra, according to Meggers [1]. Yet by 1939, according to a report by Allen G. Shenstone, only 400 or so had been analyzed in any great detail [15]. Scientists still kept plugging away at their analyses. George R. Harrison (see Fig. 5), OSA president in 1945 and 1946, once said that Meggers "determined the origins in atoms and ions of more spectrum lines than any other person," though Harrison himself may have been a close second in that race [16].

With the data they did have, though, scientists vigorously advanced the field of spectrochemical analysis of mixed or complex substances. Meggers credited Harrison with spurring progress in this area by organizing 10 annual conferences on spectroscopy and applications, beginning in 1933. Researchers and technicians improved both prism spectrographs, which were favored in Europe, and grating spectrographs, by far the choice of Americans.

In 1938, Harrison invented a high-speed automatic comparator to record the intensities and wavelengths of spectral lines, and the following year he published the *MIT Wavelength Tables*, which listed the precise wavelengths of more than 100,000 individual spectral lines. Thanks to the economic circumstances of the era, Harrison procured funds from the U.S. Works Progress Administration to hire 143 workers to assist with the measurement of all those spectral lines. (A second edition, revised 30 years after its initial publication, is still in print.)

Toward the Future

During the first quarter-century of OSA's existence, spectroscopy helped scientists consolidate the understanding of the structure of atoms and molecules, led to a greater understanding of the universe, and paved the way for many new practical applications.

As 1940 dawned, the laser—and the many new spectroscopy techniques it would spawn—was still two decades in the future. From a kindling pile of quantum-related hypotheses, however, scientists on three continents had assembled a coherent quantum theory largely resting on the evidence from optical spectroscopy, and this quantum knowledge would in turn spawn the optical revolution of the last 60 years.

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Government and Industrial Research Laboratories

Carlos Stroud

A common impression is that each of the many types of lasers was invented in an industrial research laboratory. While one can dispute the accuracy of that statement in a few cases, there is no argument that industrial and governmental research laboratories were the locations of much of the development of optics in the twentieth century.

The concept of an industrial research laboratory emerged just before the beginning of the twentieth century. The first industrial optics research laboratory was Carl-Zeiss Stiftung, founded in 1889, in Jena, Germany, by Ernst Abbe. It grew out of earlier collaboration by Abbe, Otto Schott, and Carl Zeiss, and quickly became the source of optical glass and precision optical instruments for most of the world [1]. This German success did not go unnoticed and helped to stimulate the founding of other laboratories. The contributions of industrial and governmental laboratories in the twentieth century were truly incredible, and this essay briefly reviews how these various laboratories came to be; but it will leave, for the most part, their enormous range of inventions and discoveries to be described in the later essays in this volume.

Several factors led to the rise of industrial and government research laboratories at the beginning of the twentieth century. The harnessing of steam power, and then electricity, led to mass-consumer-product industries that had sufficient resources to support basic research laboratories. In 1903 Bausch & Lomb sold 20 million spectacle lenses and 500,000 photographic lenses per year; Eastman Kodak sold 150,000 Brownie cameras in 1900, the first year it was sold; and by 1914 General Electric sold 88.5 million lamps in the United States alone [2]. The general public saw the night lit up by electric lights; radio, telephone, and motion pictures changed the way people lived and perceived the future. Thomas Edison, George Westinghouse, and Nikola Tesla captured the popular imagination as scientific geniuses who would develop new technologies that would revolutionize industry. Everything was aligned to enable and encourage large investments in basic research. Small laboratories for quality and process control existed before, but not industrial and governmental research laboratories whose task was to develop whole new technologies and products that had never existed.

Following the Civil War, industry grew rapidly in the United States. The new companies were receptive to change and optimistic about future technologies, so much of the early development of industrial laboratories occurred in the United States. In 1900 General Electric (GE) established the first industrial basic research laboratory in Schenectady, New York, an outgrowth of Edison's earlier laboratories.

General Electric characterizes the nature of this laboratory:

> The lab was the first industrial research lab of its kind. Prior to the formation of the GE Research Lab the only industrial research labs were German pharmaceutical labs. In the German labs like Bayer scientists and researchers worked independently and competed with one another. At General Electric in Schenectady, New York engineers and scientists were encouraged to share information and assist with problem solving. They were given great financial support to buy materials. The best machinists and craftsmen were employed to help build prototypes. From the tungsten light bulb to the computerized hybrid car it is no wonder that the Schenectady lab produced a great proportion of our world's technology [3].

While the General Electric laboratory was not focused on conventional optics, it did work on illumination and the development of x-ray sources. William Coolidge's x-ray tube designs were instrumental in leading to the development of radiology, and his discovery of a method to make tungsten ductile provided a long-life filament for incandescent light bulbs. Soon GE was selling them by the millions, and Irving Langmuir's studies of monatomic films on filaments led to GE's first Nobel Prize. Most important, the GE Research Lab set the standard that other industrial labs used as a model.

In 1918 the Westinghouse Research Laboratory was established with goals and organization much like those of the earlier General Electric laboratory. In particular, this research laboratory was separate from any manufacturing facility. Again, the early work in this laboratory was not devoted to optics, although it was soon working in optical spectroscopy, a pursuit that it maintained for most of the century. One notable contribution to optics from this Pittsburgh laboratory was that it provided the first job for Brian O'Brien, who was the first permanent director of the University of Rochester's Institute of Optics. O'Brien, working with Joseph Slepian, developed the first lightening arrestors, which are commonly used today [4].

In 1915 the Eastman Kodak Research Laboratory was founded, and before World War I (WWI) broke out, laboratories were established at Dupont, Standard Oil (Indiana), U.S. Rubber, and Corning Glass. Bausch & Lomb did not have a formal research laboratory at that time but were soon central to the United States' efforts in optical research and development. After WWI Major Fred E. Wright wrote the following in a *Journal of the Optical Society of America* article [5]:

> Before this country entered the war, it was realized that the making of optical glass might prove to be a serious problem. Prior to 1914, practically all of the optical glass used in the United States had been imported from abroad; manufacturers followed the line of least resistance and preferred to procure certain commodities, such as optical glass, chemical dyes, and other materials difficult to produce, direct from Europe, rather than to undertake their manufacture here. The war stopped this source of supply abruptly, and in 1915 experiments on the making optical glass were underway at five different plants: The Bausch & Lomb Optical Co. at Rochester, N.Y.; the Bureau of Standards at Pittsburgh, Pa.; the Keuffel & Esser Company at Hoboken, N.J.; the Pittsburgh Plate Glass Company at Charloi, Pa.; the Spencer Lens Company at Hamburg, Buffalo, N.Y. By April, 1917, the situation had become acute; some optical glass of fair quality had been produced, but nowhere had its manufacture in adequate quantities been placed on an assured basis. The glass-making processes were not adequately known. Without optical glass, fire-control instruments could not be produced; optical glass is a thing of high precision, and its manufacture, accurate control is required over all the factory processes. In this emergency the Government appealed to the Geophysical Laboratory of the Carnegie Institution of Washington for assistance. This laboratory had been engaged for many years in the study of solutions, such as optical glass, at high temperatures, and had a corps of scientists trained along the lines essential to the successful production of optical glass; it was the only group in the country with a personnel adequate and competent to undertake a manufacturing problem of this character and magnitude. A group of their scientists, with writer [Major Wright] in charge, was accordingly placed in April 1917, at the Bausch & Lomb Optical Company, and took over virtual direction of the plant.

The effort succeeded, and the United States became a serious player in optics and optical instrumentation, no longer depending on European supplies and technology.

The military importance of precision optics in WWI was enormously enhanced by two technological developments: (1) machining of artillery barrels was much more precise than ever before so that shells could be directed much more accurately—if you knew with enough accuracy where your target was located; and (2) military aircraft, which required bomb sights and aerial cameras for the airplanes and ground-based binoculars and telescopes for the anti-aircraft artillery. Another development that one does not usually associate with optics was the invention of camouflage to hide ships, airplanes, and land-based targets from the improved optics. Abstract artists were brought in to design the patterns, and the company cafeteria building at Eastman Kodak was turned over to the military to develop camouflage, while other parts of the company developed aerial cameras.

These people and industries involved in American optics in WWI played a further enormous role in the development of optics. A group of them including representatives from Eastman Kodak and Bausch & Lomb met in the physics library at the University of Rochester in November 1915 to found the Rochester Optical Society, with an explicit intention of also founding a national optical society, which they did when they led the founding of The Optical Society at a meeting the following February in Washington. Perley G. Nutting (Fig. 1) of the Eastman Kodak Research Laboratory was the first society president, and the second president was the same Frederick E. Wright who led the glass effort at Bausch & Lomb. Adolph Lomb was the first treasurer of the society, and personally wrote checks to cover the budget deficits in the initial years. This connection between the early industrial research laboratories and the founding of professional societies and scientific journals was no coincidence. C. E. K. Mees, the founding head of the Eastman Kodak Research Laboratories, wrote in his history of the labs [6] that he and George Eastman discussed the nature of the industrial research laboratory that they planned to establish, and decided that if they wanted to have the best scientists on their staff they would have to encourage them to publish and to interact with other scientists. Good scientists need this interaction to be happy and productive. Furthermore, there needed to be professional societies and journals to support their efforts. The whole development of the optical research establishment owes a debt to this industrial initiative. Their contribution goes further. Mees and Eastman also decided that there needed to be an academic department to train optical engineers and scientists and to carry out basic optics research. They, along with Edward Bausch, approached the President of the University of Rochester about founding such a department. In 1929 the Institute of Optics was founded with a promise of an initial $20,000 grant for equipment and continuing support of $20,000 per year for five years, renewable for five more. Mees himself (Fig. 2) taught courses in photographic theory for many years in the Institute [7].

▲ **Fig. 1.** Perley G. Nutting unceasingly campaigned for the establishment of a United States national optical society. He started the campaign while working as one of the first employees of the National Bureau of Standards and later as one of the first employees of the Eastman Kodak Research Laboratories. He led the successful effort to found The Optical Society and served as its first President. Courtesy of The Optical Society (OSA).

In 1925, Western Electric Research Laboratories and part of the engineering department of the American Telephone & Telegraph Company joined to form Bell Telephone Laboratories, Inc., as a separate entity. It was tasked to plan, design, and support the equipment that Western Electric built for Bell System operating companies. A few workers were assigned to basic research, and the results were rather spectacular, as essays later in this volume attest, and include 14 Nobel Laureates for work carried out in part or full at Bell Labs.

Another monopoly that led to the founding of an important industrial research laboratory was for radio communications. During WWI the Western Allies cut the German transatlantic telegraph cables and the Central Powers maintained contact with neutral countries in the Americas via long-distance radio communications. In 1917 the government of the United States took charge of the patents owned by the major companies involved in radio manufacture to devote radio technology to military needs. After the war, the War and Navy departments sought to maintain a federal monopoly of all uses of radio technology. Congress did not agree to continue this monopoly after the war, but the Army and the Navy negotiated with GE that if they bought assets of the confiscated American Marconi Company and founded a publicly held company in which they managed to retain controlling interest, that company, the Radio Corporation of America (RCA), would be granted a monopoly on radio communication. Westinghouse and AT&T joined in the forming of the company. So, by 1920 AT&T had a monopoly on long-distance telephone systems, and GE and Westinghouse, through RCA, had a monopoly on long-distance radio communication. By the mid-1920s short waves had replaced radio waves for long distance communication, the federal government broke up the monopoly controlled by GE and Westinghouse, and RCA became a separate and successful company. RCA made major optics contributions in photomultipliers, LEDs, CMOS devices, and liquid crystals, as well as in the development of sound recording, radio, and television [8].

▲ **Fig. 2** C. E. Kenneth Mees. George Eastman wanted C. E. Kenneth Mees so much to be the founding head of the Eastman Kodak Research Laboratory that he bought the English company for which Mees was a part owner, Wratten and Wainright, and moved Mees and the company to Rochester, where he led the laboratories until his retirement after World War II (WWII). (AIP Emilio Segre Visual Archives.)

If WWI greatly changed industrial research, and industrial optics research in particular, WWII completely redefined it and made it and governmental research a central component in the American economy. United States involvement in this war was more protracted than in WWI, and science and technology, particularly in the areas of radar and atomic bombs, were central to the nation's effort. This short essay cannot cover all of the important developments lab by lab even within optics. Happily, many of the contributions of these labs are detailed in the chapters on individual technologies later in this volume. Therefore this essay will be limited to general trends and national initiatives. While the concept of industrial research laboratories grew out of nineteenth-century Germany, most of the major developments in the first half of the twentieth century were in the United States. After recovery from the devastation of WWII, Europe joined in with its own important industrial research laboratories. World War II not only was the genitor of many new industrial research laboratories, but it also led to a proliferation of governmental research labs. Their origins will be reviewed before the evolution of all of these labs during the second half of the century is discussed.

The Royal Observatory in Greenwich, England, was founded by Charles II in 1675. The United States got into the governmental laboratory business somewhat later with the establishment of the Depot of Charts and Instruments, the predecessor of the U.S. Naval Observatory, in 1830. But, it was in 1900 that Congress passed an act establishing the National Bureau of Standards (NBS), the direct predecessor of National Institute of Standards and Technology (NIST), whose scientists have received four recent Nobel Prizes in optics. These were among 13 Nobel Prizes awarded employees of governmental research laboratories in the United States. The climate that led to the forming of this laboratory is mentioned at the beginning of this essay and is nicely stated in the official history of NIST [9]:

> The idea of a national bureau of standards was presented at an auspicious hour. America in the year 1900 thought well of itself. The hard times of 1893–95 were all but forgotten in the aura of prosperity and sense of achievement that energized the Nation. Industry and invention boomed and business flourished as never before. The prophets at the turn of the century unanimously agreed on the good years to come.

At the recommendation of the Secretary of the Treasury, Congress passed a bill, which the president signed, to form NBS, which was to aid "manufacturing, commerce, the matters of scientific apparatus, the scientific work of the Government, of schools, colleges, and universities." It was not just in the United States that the need for such a government laboratory was felt; in England the National Physical Laboratory was founded in the very same year for these same purposes.

The staff of NBS in 1904 included in the Section on Light and Optical Instruments: Samuel W. Stratton, Perley G. Nutting, and Frederick J. Bates. This same Perley G. Nutting was already working to found a national optical society before he was lured away to the newly formed Eastman Kodak Research Laboratory, where he led the effort to found the local Rochester society, and then OSA, of which he was the first president.

We return our narrative to the onset of WWII when industrial and governmental optics research had a true phase transition in its development. As war broke out in Europe in 1939 a group of leading scientists and academic administrators including Vannevar Bush, President of the Carnegie Institution of Washington; James B. Conant, President of Harvard University; Frank B. Jewett, President of the National Academy of Sciences and President of Bell Laboratories; Karl Compton, President of MIT; and Richard C. Tolman, Dean of the Graduate School at California Institute of Technology, were concerned with the lack of technological preparedness of the U.S. for its likely entry in the war. They suggested a plan for the establishment of the National Defense Research Committee (NRDC), which Vannevar Bush described in four paragraphs that he submitted to President Roosevelt. At the end of ten minutes he had an approval from the President, and an order creating NDRC was issued on 27 June 1940. Some 30 years later in his biographical memoirs Bush describes the reasons for this initiative [10]:

> There were those who protested that the action of setting up NDRC was an end run, a grab by which a small company of scientists and engineers, acting outside established channels, got hold of the authority and money for the program of developing new weapons. That, in fact, is exactly what it was. Moreover, it was the only way in which a broad program could be launched rapidly and on an adequate scale. To operate through established channels would have involved delays—and the hazard that independence might have been lost, that independence which was the central feature of the organization's success.

Bush was appointed chairman, and the organization was established and expanded in 1942 to become the Office of Scientific Research and Development (OSRD), with Bush as director (Fig. 3). The OSRD had three principal subdivisions at that time: the NDRC, with Conant as chairman; the Committee on Medical Research (CMR), with A. Newton Richards as chairman; and the advisory Council, with Bush as chairman. The latter included the chairmen of the National Advisory Committee on Aeronautics (NACA), NDRC, and CMR, as well as representatives from the Army and Navy as a coordinating group. In addition, Bush was chairman of the Joint New Weapons Committee of the Joint Chiefs of Staff and, when the Manhattan District was created, chairman of its Military Policy Committee, which served as its board of directors [11].

Perhaps one might be tempted to say that the power grab was by Bush himself, but he had the confidence of the President and Congress so that he was able to coordinate and to smooth the inevitable friction between these varied groups remarkably well. Weisner summarizes quite nicely the organization that Bush set up:

> The organization was a remarkable invention, but the most significant innovation was the plan by which, instead of building large government laboratories, contracts were made with universities and industrial laboratories for research appropriate to their capabilities. OSRD responded to requests from military agencies for work on specific problems, but it maintained its independence and in many cases pursued research objectives about which military leaders were skeptical. Military tradition was that a way had to be fought with weapons that existed at its beginning. Bush believed that World War II could be won only through advances in technology, and he proved to be correct. In some instances, the armed forces were enthusiastically cooperative. In others, resistance to innovation had to be overcome. Bush, himself, went to Europe to make sure that the proximity fuse was introduced to the battlefield and used effectively.

▲ **Fig. 3** Vannevar Bush watches as President Truman presents James Conant with the Medal of Merit and Bronze Oak Leaf Cluster in May, 1948. The nation was greatly appreciative of the leadership of Bush and Conant and other scientists during the war, allowing Bush and Conant to build a structure to continue government support of research after the war through governmental laboratories and research grants for university basic research.

> The major exception to the policy of avoiding the building of government laboratories was in the development of the atomic bomb. After preliminary studies by NDRC and OSRD, it became clear that a colossal program would be needed, and Bush recommended to Secretary Stimson that the Army take over the responsibility. The result was the formation of Manhattan Engineering District by the Corps of Engineers. Bush with Conant as his deputy, maintained an active scrutiny of the enterprise.

This was the foundation of science and engineering administration in the U.S. as it exists up until now. All of the developments in optics in the second half of the century grew up in this environment. Optics during the war was overseen by Division 16, Optics and Camouflage of the NDRC. It was led by George Harrison. Paul Kelley describes elsewhere in this volume the optical developments during this period. Well before the war was over, Bush started to plan how the momentum of research could be sustained with new peacetime goals. President Roosevelt asked him to make recommendations on government policies for combating disease, supporting research, developing scientific talent, and diffusing scientific information. Four committees were set up to generate recommendations. On the basis of these recommendations Bush submitted a report titled “Science—The Endless Frontier,” which laid out the proposals for organizing post-war science and technology. The argument for the government to continue supporting research after the war was summed up in the report: “To create more jobs we must make new and better and cheaper products. We want plenty of new, vigorous enterprises. But new products and processes are not born full-grown. They are founded on new principles and new conceptions which in turn result from basic scientific research. Basic scientific research is scientific capital.”

The National Science Foundation was proposed, and a bill was introduced in Congress by Senator Warren Magnuson from Washington. After much argument in Congress and a veto by President Truman, a modified version was signed by President Truman in 1947. Vannevar Bush asked that Truman not name him to the board of the new foundation, suggesting that people were tired of his running things. Even before the NSF was launched, the Office of Naval Research was established in 1946 with the stated mission of "planning, fostering, and encouraging scientific research in recognition of its paramount importance as related to the maintenance of future naval power and the preservation of national security." The Air Force Office Scientific Research would be formed in 1951 and the Army Research Office in 1957, and the Defense Advanced Research Projects Agency (DARPA) was signed into existence by President Eisenhower in 1958. Figure 4 shows the Laser Guide Star Adaptive Optics project, one of the technologies that came from the funding provided by those agencies. The National Aeronautics and Space Administration (NASA) grew out of the old NACA during the administration of President Eisenhower. At present the Navy operates one laboratory and seventeen Warfare Centers. The Army operates eleven labs, and the Air Force operates one laboratory and ten Technical Directorates.

▲ **Fig. 4** The Air Force Starfire Optical Range for lidar and laser guide star experiments is tuned to the sodium D2a line and used to excite sodium atoms in the upper atmosphere. This provides what is essentially a point source of light in the mesosphere to use for adaptive optics to remove blurring of ground based imaging due to atmospheric turbulence.

The old Army-controlled Manhattan Project during the course of the war developed a number of secret sites including Los Alamos, Hanford, and Oak Ridge. There was also the reactor research lab at the University of Chicago that spawned Argonne National Laboratory. After the war the Atomic Energy Commission took over the wartime laboratories, extending their lives indefinitely, and funding was obtained to establish a number of new laboratories for classified as well as basic research. Each of the new laboratories was generally centered around some particle accelerators or nuclear reactors. At present, the organization in charge is the Department of Energy (DOE), and it administers 19 different national laboratories and provides more than 40% of the total national funding for physics, chemistry, and materials science. While the DOE directs most of its attention to nuclear, particle, and plasma physics, it supports major efforts in optics as well, especially through its high-energy laser fusion programs and its x-ray light sources.

Another important source of funding for optics research is the independent research and development funds that are provided by indirect cost charges to military contracts, allowing military contractors to carry out internal research programs and keep their scientists and engineers busy between contracts developing new technology. This supports long-term research efforts at many industrial laboratories.

This enormous research and development system that grew out of WWII is not without its detractors; many point to the address of Dwight David Eisenhower just three days before he left office. The President, who signed into existence many of the agencies that support this system warned, "In the councils of government, we must guard against the acquisition of unwarranted influence, whether sought or unsought, by the military–industrial complex. The potential for the disastrous rise of misplaced power exists and will persist." As you look over the essays in this volume that review the progress in optical science and technology, particularly over the past half century in which optics has become an indispensable enabler in essentially every industry, it is hard to fault the model, given its evident success. But even today, some 50 years after this speech, many would argue that we need to keep our guard up to see that this enormously beneficial system of research and development is not corrupted.

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Camera History 1900 to 1940

Todd Gustavson

Introduction

The photographic process, announced in 1839 by the Frenchman Louis Jacques Mandé Daguerre, captured and fixed the images that were viewed through a camera obscura. This was accomplished through a combination of mechanics (the camera), optics (to improve the image), and chemistry (to sensitize and process the image). Over the next forty years, improvements made to all aspects of the process—cameras, shutters, lenses, and chemistry—led to cheaper and simpler image making, generating a growing interest for the nonprofessional photographer.

The technicalities of early photography required the photographer to sensitize media shortly before exposure and then process the image immediately afterward. Although this system was fine for the professional, it was generally too cumbersome and time-consuming for most amateurs. On 13 April 1880, George Eastman of Rochester, New York, patented a machine for coating gelatin dry plates. The following January, with the financial backing of Rochester businessman Henry Strong, he formed the Eastman Dry Plate Company, one of the first commercial producers of light-sensitive photographic emulsions. With reliable plates now available, companies worldwide began manufacturing cameras designed specifically to use them.

Eastman's business expanded five years later with the introduction of his American Film, a paper-supported stripping film intended for the professional market. It was not well received by the professionals, who considered it to be rather difficult to process. Undeterred, Eastman instead used it in a new small box camera he named the Kodak. Introduced in 1888, the Kodak was an easy-to-use "detective camera," a box-style, point-and-shoot camera meant for the novice photographer. Eastman's camera required no adjustments, which was atypical of the time, but the real innovation was after exposing the film: the camera was shipped back to the company for processing and reloading, marking the beginning of the professional photo-finishing industry. This novel feature was marketed with the advertising slogan "You press the button, we do the rest," which established the company's business model: the promotion of cameras as the means to selling highly profitable film and processing. Twelve years later, the Brownie camera was added to the camera line; its $1.00 selling price made photography available to just about everyone.

Brownie

Introduced by Eastman Kodak Company in 1900, the Brownie camera was an immediate public sensation due to its simple-to-use design and inexpensive price. (See Fig. 1.) Now nearly anybody, regardless of age, gender, or race, could afford to be a photographer without the specialized knowledge or cost once associated with the capture and processing of images. An important aspect of the Brownie camera's rapid ascendancy in popular culture as a must-have possession was Eastman Kodak Company's innovative marketing via print advertising. The company took the unusual step of advertising the Brownie in popular magazines instead of specialty photography or trade magazines with limited readership. George Eastman derived the camera's name from a literary character in popular children's books by the Canadian author Palmer Cox. Eastman's astute union of product naming, with a built-in youth appeal, and inventive advertising placement had great consequence for the rise of modern marketing practices and mass consumerism in the twentieth century.

The Brownie was designed and manufactured by Frank A. Brownell, who had produced all of Eastman Kodak's cameras from the beginning. The use of inexpensive materials in the camera's construction and George Eastman's insistence that all distributors sell the camera on consignment enabled the company to control the camera's $1 price tag and keep it within easy reach of consumers' pocketbooks. More than 150,000 Brownies were shipped in the first year of production alone, a staggering success for a company whose largest single-year production to date had been 55,000 cameras (the No. 2 Bullet, in 1896). The Brownie launched a family of nearly 200 camera models and related accessories, which over the next 60 years helped to make Kodak a household name.

▲ **Fig. 1.** Brownie camera. Eastman Kodak Company, Rochester, New York, ca. 1901. Gift of Ansel Adams, 1974.0037.1963.

▲ **Fig. 2.** No. 3A Folding Pocket Kodak Model B-4, w/ Zeiss Tessar Lens. Eastman Kodak Company, Rochester, New York, ca. 1908. Gift of Eastman Kodak Company, 2001.1559.0012.

Folding Pocket Kodak

The Kodak marketing plan was to sell new customers interested in photography an affordable Brownie camera, then move them up to better, more expensive models. The company catalogs were full of such model lines priced in incremental steps. From the basic box camera, the next logical step was the Folding Pocket Kodak. (See Fig. 2.) Introduced in 1897 (at the time it was an upgrade from the Pocket Kodak, the model replaced by the Brownie), the FPK, as it was commonly known, became the first of a long line of folding bellows cameras in common use for the next half century. These cameras were a popular travel accessory because they produced the large negative desired by photographers, yet upon folding became small enough to fit into a carrying case or coat pocket. At that time of undependable light sources and a cumbersome enlargement process, the physical size of the camera usually determined the finished picture size. The 3A (3A is a Kodak camera format introduced in 1903 with the No. 3A Folding Pocket Kodak; it produced 3¼ × 5½-in. images on No. 122 film) was especially appealing, as it was available at many price points. Largely determined by its various lens and shutter combinations, the 3A functioned both as a more serious entry-level camera, and also as the company's flagship amateur product. Due to its prominent position in the company product line and long production run, the 3A received numerous upgrades throughout its history.

In its early years, most 3A cameras were fitted with Bausch & Lomb (B&L) lenses and shutters. Eastman had first turned to B&L as the supplier of lenses for his original Kodak camera back in 1888, a year after B&L produced its first photographic objective. However, Eastman Kodak offered other options to the more serious photographer, as the 3A was available with the best lenses from Europe, including England's Cooke Anastigmat (1907–1912) and Germany's Georz Dagor (1903–1908), or Zeiss Tessar (1908–1910). Bausch & Lomb signed a licensing agreement with Zeiss to produce the Tessar in Rochester, and of course the 3A was available with those lenses (1906–1912). Eastman Kodak entered into its own agreement with Zeiss, and the 3A was produced with the Zeiss Kodak Anastigmat (1909–1912). Eastman Kodak Company began producing lenses of its own design in 1913; the 3A received the first version of the Kodak Anastigmat in 1914. The 3A was the first production camera to be fitted with the coupled rangefinder, which put Kodak about 15 years ahead of most other manufacturers. Beginning in the 1930s, high-end cameras such as the Contax (by Zeiss Ikon) and the Leica (by E. Leitz) were fitted with coupled rangefinders. Even today, most higher-end digital cameras use a form of this technology.

Institute of Optics

World War I changed the optical landscape in the United States. The industry relied on German manufacturers for the supply of high quality optical glass, optics, and engineers. A number of steps were taken to remedy the situation, the first being establishing The Optical Society (OSA) in 1916. Under the leadership of Perley G. Nutting, and with the support of optical scientists in Rochester, the optical center of the United States, the OSA's mission was to promote and disseminate knowledge of optics and photonics. This was accomplished with published journals and by holding conferences, thus establishing a network of information exchange. The University of Rochester, with financial support from B&L and Eastman Kodak Company, established the Institute of Applied Optics (now known as the Institute of Optics) in 1929. The president of the University, Reverend Benjamin Rush Rhees, hired Rudolf Kingslake, graduate of the Imperial College of Science and Technology in London, where he studied under Alexander Eugen Conrady, to teach at the new school. Kingslake became the head of Eastman Kodak Company's Optical Design Department in 1937, a position he held until retiring in 1968. Kingslake continued to teach at the University of Rochester during his "Kodak years"; he continued teaching at the university into the 1980s.

Kodak Research Labs/Color Photography

The advancement of photography is about more than cameras and lenses; improvements in sensitized materials has always played an extremely important role. The founding of the Kodak Research Laboratories may be George Eastman's greatest contribution to photography. Established expressly for the empirical study of sensitized materials, the Kodak Labs were among the first of their kind in the United States. Impressed with the laboratories he saw while visiting Germany in 1911, Eastman realized that the future of the industry would be color photography. He knew from his own early experimentation in emulsion making that it would take more than lone individuals experimenting on their own in home-brew labs to facilitate the future. For the founding director of the Kodak Labs, Eastman hired C. E. K. (Charles Edward Kenneth) Mees, managing director and a partner at Wratten & Wainwright, a dry plate manufacturer in England best known for introducing panchromatic dry plates. To acquire Mees's services, Eastman bought his employer.

Of the many developments by the Kodak Labs, the most important was color film. The search for color in photography dates back to the medium's earliest days. For the most part, colored photographs were exactly that, photographs with hand-applied color. There was a so-called color version of the daguerreotype known as the Hillotype, though it is up for debate as to whether these plates had color or not. Color photography largely remained a hand-applied art or rather complicated "laboratory experiment" based on James Clerk Maxwell's three-color experiments until 1903 with the introduction of Autochrome plates by France's Lumière brothers. Autochrome used the additive color process, with the plates first coated with a mosaic screen made of microscopic potato starch grains, randomly dyed red, green, and blue; the empty spaces between the starch grains were filled with black and then coated with a panchromatic photographic emulsion. This rather odd-sounding system did work, but due to the filtering nature of the plates, exposure times were quite long.

Kodachrome is usually considered to be the first practical color film. Two musician-scientists, Leopold Godowsky, Jr., and Leopold Mannes, began investigating color photography, filing their first patent application in 1921. (Godowsky and Mannes were boyhood friends who shared a common interest in music and photography. Mannes earned a bachelor's degree in physics at Harvard College but worked as a musical composer at the New York Institute of Art. Godowsky studied physics and chemistry as well as the violin at the University of California at Los Angeles. He was a soloist and first violinist with the Los Angeles and the San Francisco Symphony Orchestras.) C. E. K. Mees was informed of their research by a friend, Robert Wood, the next year, prompting Mees to travel to meet with Mannes at New York City's Chemist's Club. Impressed with Mannes, Mees decided to assist the two young scientists in their work, first by supplying them with evenly coated plates, and then as ad hoc members of the Kodak Research Labs. By 1930, Godowsky and Mannes had become regular members of the company and moved to Rochester. The result was Kodachrome film, first introduced in 1935 as a 16-mm ciné film and the next year for still photography as a 35-mm transparency film. The first multi-layered film, Kodachrome consisted of three separate black-and-white layers (with a yellow filtering layer), for recording cyan, yellow, magenta, the subtractive color primary colors. When exposed, these black-and-white layers acted as "placeholders" to which color dyes were added during processing. Kodachome is still considered to be the most permanent color film.

35-mm Precision Cameras

George Eastman's easy-to-use Kodak camera, introduced in 1888, marks the beginning of point-and-shoot photography. Since using it required no special knowledge, it was an ideal camera for the newly conceived market of amateur novice photographers. Thomas Edison used film from the Kodak, slit to 35 mm and then perforated on both edges, in his 1890s experiments perfecting the Kinetoscope, the first motion picture film viewer. 35-mm film became the standard film size of the motion picture industry. As film quality improved over the next couple of decades, a number of companies around the world began to experiment with the format for still photography. The Multi Speed Shutter Company of New York City (a company that also manufactured motion picture projectors) introduced the Simplex camera in 1914, the first still camera to use the now standard 24 × 36-mm image size on 35-mm-wide film; this was twice that used for motion picture's 18 × 24 mm. Soon after, other companies—such as Jules Richard of Paris, France, with the Homéos (the first 35-mm stereo camera) and New Ideas Manufacturing of New York City with the Tourist Multiple—would market cameras using 35-mm film. These cameras used film acquired as leftover ends from the motion picture industry. It was a novel idea, but none were very successful, as most snapshot photographers preferred using the well-established box or folding cameras. Still, a successful precision 35-mm camera was on the horizon.

Leica A

Starting about 1905, when he worked at the firm of Carl Zeiss in Jena, Germany, Oskar Barnack (1879–1936), an asthmatic who hiked to improve his health, tried to create a small pocketable camera to take on his outings. At the time, cameras using the most common format of 13 × 18 cm (5 × 7 in.) were quite large and not well suited for hiking. Around 1913, Barnack, by then an employee in charge of the experimental department of the microscope maker Ernst Leitz Optical Works in Wetzlar, designed and hand built several prototypes of a small precision camera that produced 24 × 36-mm images on leftover ends of 35-mm motion picture film. Three of these prototypes survive. The most complete one has been dubbed the "Ur-Leica," meaning the first or "Original Leica," and is in the museum of today's firm of Leica Camera AG in Solms, Germany.

Barnack used one of his cameras in 1914 to take reportage-type pictures of a local flood and of the mobilization for World War I. That same year, his boss, Ernst Leitz II, used one on a trip to the United States. However, no further development of the small camera took place until 1924, when Leitz decided to make a pilot run of 25 cameras, serial numbered 101 through 125. Still referred to as the Barnack camera, these prototypes were loaned to Leitz managers, distributors, and professional photographers for field testing. Interestingly, the evaluations were not enthusiastic, as the testers thought the format too small and the controls too fiddly, which they were. For instance, the shutter speeds were listed as the various distances between the curtains, instead of the fraction of a second it would allow light to pass. In spite of its reviews, Leitz authorized the camera's production, basing his decision largely on a desire to keep his workers employed during the post-World-War-I economic depression. An improved version of the "O-Series Leica," the Leica I, or Model A, with a non-interchangeable lens was introduced to the market at the 1925 Spring Fair in Leipzig, Germany. (See Fig. 3.) The name "Leica," which derives from Leitz Camera, appeared only on the lens cap.

▲ **Fig. 3.** O-Series Leica. Ernst Leitz GmbH, Wetzlar, Germany, 1923. George Eastman House collection, 1974.0084.0111.

Contax I (540/24)

The successful introduction of the Leica camera was not lost on Zeiss Ikon AG of Dresden, Germany. Formed in 1926 as the merger of Contessa-Nettel, Goerz, Ernemann and Ica, Zeiss Ikon was the largest camera manufacturer in Europe. Zeiss was one of the leading manufacturers of optical devices, with its roots dating back to optician Carl Zeiss. Zeiss began as a lens and microscope manufacturer in 1847. He hired physicist Ernst Abbe in 1866 as research director; Abbe designed the first refractometer in 1868, a device used to measure the index of refraction of optical glass. Abbe hired Otto Schott in 1883 to develop new types of glass necessary for reducing reflection in microscope objectives, then hired Paul Rudolph to design photographic lenses with glass developed by Schott. After the passing of Carl Zeiss in 1888, Abbe bought out Zeiss's son Roderich and established the Carl Zeiss Foundation. Unusual in its day, the Zeiss foundation was partially owned by its workers. Many of the classic lenses used in photography, such as the Anastigmat (1890), Planar (1895), Unar (1899), and Tessar (1902), originated at Zeiss, under the direction of Paul Rudolph.

The Zeiss Ikon catalog of 1927 listed over 100 camera models from the small pocket-sized Piccolette roll film camera to the Universal Jewel professional folding dry plate camera (Ansel Adams used one). Its camera line included the Deckrullo focal plane shutter models and the Miroflex reflex. And like Eastman Kodak Company, along with cameras Zeiss Ikon sold a complete line of photography equipment for darkroom and motion picture projection. With the introduction and success of the Leica from one of its smaller competitors, Zeiss—considered to be the gold standard of camera makers—needed to come up with a better version of the precision 35-mm camera. The answer was the Contax, introduced in 1932. (See Fig. 4.) On paper it was exactly that, a better Leica. The Contax used a built-in coupled rangefinder, with a longer base than the Leica's, for more accurate focusing, vertical-traveling focal plane shutter, with speeds to 1/1250 s, which was more than twice as fast as the Leica's 1/500. The Contax had a removable back for easy loading, in contrast to the Leica, which rather awkwardly loaded through its removable bottom plate. And most important, the Contax used Zeiss lenses, which were far superior to those used by the Leica. But there was one problem: the Contax was an unreliable picture taker, with most of the problems relating to its shutter.

Over the years Zeiss tried to remedy this, but it could never match the durability of the Leica's rubberized cloth shutter.

▲ **Fig. 4.** Contax I (f). Zeiss Ikon AG, Dresden, Germany, ca. 1932. Gift of 3M; ex-collection Louis Walton Sipley. 1977.0415.0004.

Kodak Retina

August Nagel, of Contessa Nettel, dissatisfied with his company's merger with Zeiss Ikon, left and formed a new company, Nagel Werke in 1928. Eastman Kodak Company purchased Nagel Werke in 1932, becoming Kodak AG, the company's German manufacturing arm. In 1934, Eastman Kodak Company introduced the Retina, its first precision 35-mm camera, designed to compete with the Leica. Unlike the Leica and Contax, the Retina was a folding 35-mm camera with a permanently mounted lens. Introduced with the Retina was the Kodak 35-mm daylight loading film magazine, which became the standard used on just about every 35-mm camera. The Kodak film magazine used a built-in heat-sealed velvet light trap still in use today. Prior to this, the other 35-mm cameras used their own unique film magazines, fitted with some type of light trap mechanism connected in some way to the bottom of the camera (Leica) or with separate supply and take-up housing (Contax).

Kodak AG went on to produce some 50 different models of the Retina camera through the mid-1960s.

▲ **Fig. 5.** Super Kodak Six-20 Eastman Kodak Company, Rochester, New York, 1938. Gift of Eastman Kodak Company, 001.0636.0001.

Super Kodak Six-20

The Super Kodak Six-20 was the first production camera to feature automatic exposure (AE) control. (See Fig. 5.) Aimed at removing the exposure guesswork for photographers, the camera's shutter-preferred AE control meant that the photographer chose the shutter speed and the camera would then "choose" the correct lens opening. Kodak's engineers accomplished this feat by mechanically coupling a selenium photocell light meter, located just above the lens, to the lens aperture.

This advancement, though groundbreaking, was not picked up by most camera manufacturers for some 20 years after the debut of the Super Six-20. These days, automatic exposure is a standard feature on almost all cameras, so it is not much of a stretch to call the Super Kodak Six-20 the first "smart camera."

But auto exposure was not the only cutting-edge feature of the Super Six-20. It was also the first Kodak camera to use a common window for both the rangefinder and the viewfinder. The film advances with a single-stroke lever, which also cocks the shutter at the end of the stroke, thus preventing double exposures. And like auto exposure, these features would not become common on cameras for many years. Features aside, the Super Kodak Six-20 is one of the most attractive cameras ever marketed. Its lovely clamshell exterior design was styled by legendary industrial designer Walter Dorwin Teague.

All this innovation came at a rather high cost, in both money and performance. The Super Kodak Six-20, which in 1938 retailed for $225 (more than $2,000 today), had a reputation for being somewhat unreliable—the built-in self-timer was known to lock up the shutter. Since few units were manufactured, just 719, it is one of the rarest of Kodak production cameras.

Conclusion

Camera research and development largely went on hold during World War II. Much of the German photo manufacturing industry was destroyed by the end of the war. The post-war era also saw the division of the Zeiss factories, split between East and West Germany. The low cost of post-World-War-II German labor had a direct impact on American manufacturing, causing most U.S. makers to concentrate on inexpensive point-and-shoot cameras only. And the U.S., in trying to strengthen Japan, helped re-establish the fledgling camera manufacturing there, laying the seeds for what became the premier camera manufacturing power for the rest of the century.

OSA and the Early Days of Vision Research

Patricia Daukantas

By the second decade of the twentieth century, scientists studying human vision had come a long way from the days of the ancient Greeks, who debated whether light rays shot themselves out of the eyeball or emanated from objects in the visual field [1]. Nevertheless, the whole area of vision, especially the retina's reaction to light, remained an important topic of research as The Optical Society (OSA) was organizing itself.

In the early days of the OSA, scientists had come to realize that vision sat at the intersection of three fields: physiology, for the anatomy of the eye; physics, for the action of stimuli on the eye; and psychology, governing how the conscious brain interprets the eye's sensations [2]. Reflecting the interdisciplinary nature of the subject, vision-related articles published in 1920 were distributed among 58 different journals from fields ranging from physics and engineering to zoology and pathology.

Between the two world wars, the scientists studying photochemistry—including two who would become OSA Honorary Members—progressed from the simple eyes of sea creatures to the complexities of the human visual system. Researchers learned that the retina contains vitamin A, leading to generations of parents telling their children, "Eat your carrots—they're good for your eyesight!" The new understanding of the eye paved the way for advances in vision correction and optical instruments.

Visual Reception and Photochemical Theory

In the very first issue of the *Journal of The Optical Society of America* (JOSA), two OSA presidents addressed some of the fundamental questions associated with human vision. Leonard Thompson Troland (1889–1932) published his theory of how the eye responds to light [3]. Perley G. Nutting (1873–1949) explored the status of a general photochemical theory that would apply to both the eye and photography and noted the similarities in the characteristic curves of photographic film and the eye's response to light [4] (see Fig. 1).

Nutting, who had tried to start an optical society several years before OSA's founding, served as the new organization's president through 1917. In his later years his focus shifted to geophysics. Troland (Fig. 2), who served as OSA president in 1922 and 1923, died in the prime of life when he fell off a cliff on Mount Wilson in California. Though he was never elected to the U.S. National Academy of Sciences, the academy gives an annual award in his name to young researchers who study the relationship between consciousness and the physical world. In photometry, the troland is a cgs unit for physical stimulation of the eye by light.

By 1919, OSA was becoming a leader in defining standards of visibility. That year, the Society's standards committee on visual sensitometry, led by Nutting, summarized [5] the extent of scientists' quantitative knowledge of the visibility of radiation, detection thresholds of intensity and contrast, color vision, rates of adaptation to changes in light, and "absolute sensibility," which takes into account the area of the retina exposed to light. For example, it was already well established that the human cone is most sensitive to light with a wavelength of 556 nm.

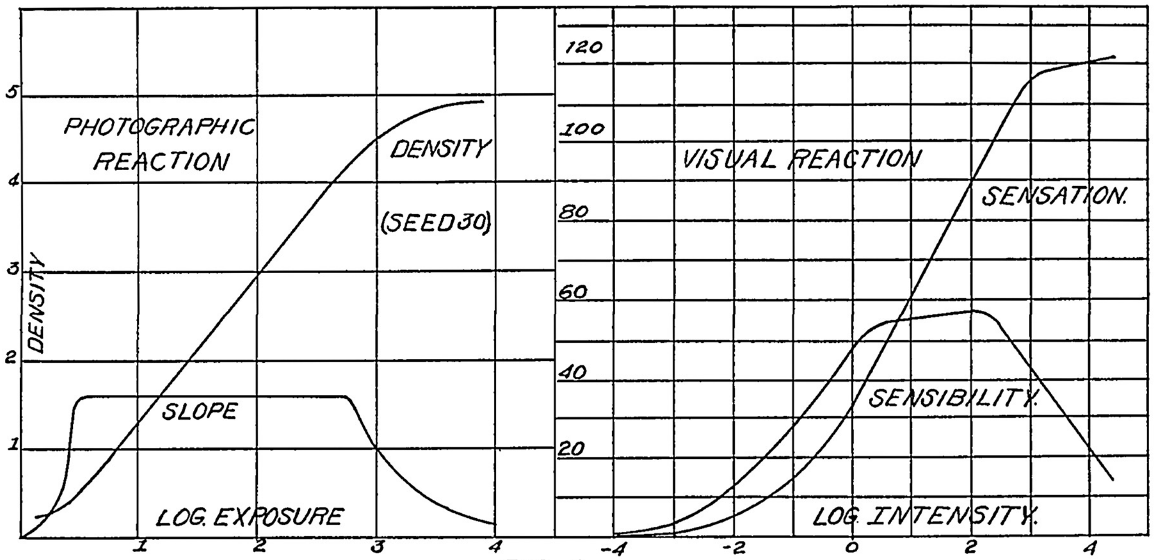


FIG 1

(Photographic and Visual Reaction)

▲ **Fig. 1.** P. G. Nutting's comparison of the sensitivity of photographic film (left) and human vision (right) to light [4]. For film, optical density is plotted against the logarithm of exposure; for vision, reaction is plotted against the logarithm of light intensity. The lower curve on the vision graph, "photometric sensibility," was determined experimentally, according to Nutting, whereas the upper curve, "sensation," was determined "by integration."

Photochemistry: Hecht, Hartline, and Wald

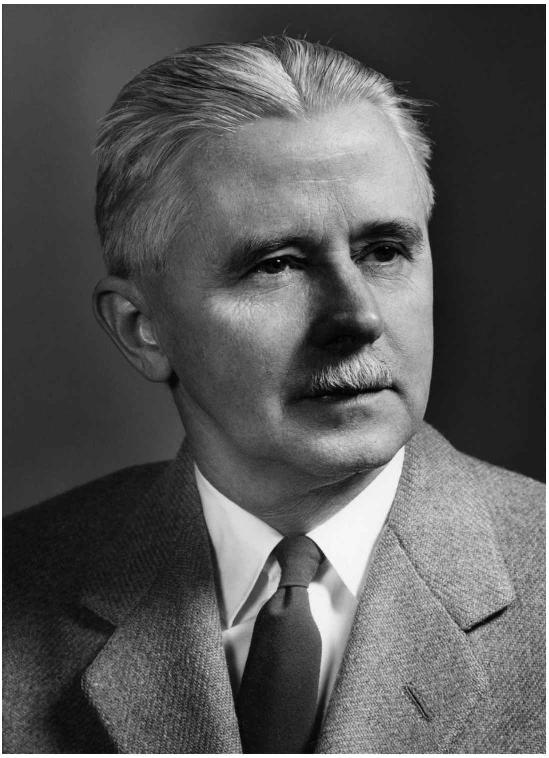
During the 1920s and 1930s, three scientists whose talents bridged the fields of physics, chemistry, and biology made invaluable contributions to our understanding of the molecules that react in the presence or absence of light.

Born in an Austrian town now part of Poland, but raised in the United States, Selig Hecht (1892–1947) (Fig. 3) explored the photochemistry of vision by studying animals whose visual systems are much simpler than those of humans: the worm *Ciona* and the clam *Mya*. Those organisms' reactions to light were slow enough that they could be measured without sophisticated apparatus [6].

Hecht began his studies of the photoreceptor process immediately after receiving his Ph.D., when he spent a summer at the facility now known as the Scripps Institution of Oceanography. There he investigated the sensitivity of *Ciona* to light. As he moved among several institutions in the United States and England, he studied the rate at which visual purple (now known as rhodopsin) decomposes upon exposure to light [7], the bleaching of rhodopsin in solution [6], and (with Robert E. Williams) the spectral sensitivity of human rod vision [8]. Hecht ended up at Columbia University, where, with his frequent collaborator Simon Shlaer, he built an instrument for

▲ **Fig. 2.** Leonard Thompson Troland, OSA president from 1922 to 1924. (AIP Emilio Segre Visual Archives.)

▲ **Fig. 3.** Selig Hecht. (AIP Emilio Segre Visual Archives, Physics Today Collection.)



▲ **Fig. 4.** Haldan Keffer Hartline. (Eugene N. Kone, Rockefeller Institute, courtesy AIP Emilio Segre Visual Archives, Physics Today Collection.)

measuring the dark adaptation of the human eye, leading to one of the classic experiments in eye sensitivity, still taught today [9].

Hecht considered himself a physiologist, but he served a term as an OSA director at large and another term on JOSA's editorial board [6]. In 1941, OSA awarded him the Frederic Ives Medal for overall distinction in optics.

Trained as a physician, Haldan Keffer Hartline (1903–1983) (Fig. 4) never practiced medicine. Indeed, after receiving his M.D. from Johns Hopkins, he spent a year Europe studying mathematics and physics under Arnold Sommerfeld and Werner Heisenberg. He was disappointed that he lacked the background to keep up with the pioneering physicists, but his quantitative bent served him well in his research career.

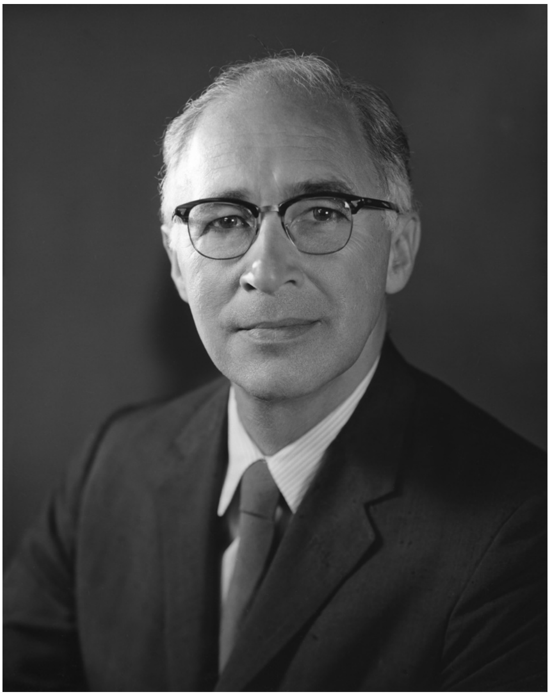
Hartline spent the 1930s as a medical physicist at the University of Pennsylvania, where he investigated the visual systems of the horseshoe crab (*Limulus polyphemus*). In 1932, he and colleague Clarence H. Graham made the first recording of the electrical activity of a single fiber taken from the optic nerve of a horseshoe crab. (Five years earlier, another team had studied the electrical pulses of the trunk of an eel's optic nerve, but could not separate the fibers.) Their work revealed that the intensity of the light falling on the photoreceptor is reflected in the rate of discharge of the nerve's electrical pulses [10,11].

Subsequently, Hartline progressed to studies of single optic-nerve cells from vertebrate retinas and measured their varying responses to light: some signaled during steady illumination, whereas others responded to the initiation or cessation of light [10,12]. By 1940, he came to realize that the ganglion cells in the retina received exciting and inhibiting stimuli through various pathways from different photoreceptors, and the optic nerve fiber, attached to the ganglion, serves as the final pipeline to transmit the signals to the brain [13]. Finally, Hartline discovered the effect now known as lateral inhibition in the *Limulus* compound eye sometime during the late 1930s, although he did not publish a report on it until 1949 [10].

George Wald (1906–1997) (Fig. 5), one of Hecht's graduate students at Columbia University, took his mentor's work further. As a student, Wald worked on the visual functioning of the *Drosophila* fruit fly and participated in Hecht's photoreceptor research. After he completed his doctorate in 1932, Wald identified the substance known as vitamin A—which was itself discovered only in 1931—in the retina.

The German scientist Franz Christian Boll had discovered rhodopsin, the primary light-sensitive pigment in the retina's rod cells, back in 1876, but nobody before Wald knew the exact chemical mechanism that made the substance react to light. During postdoctoral research in the laboratory of German biochemist Otto Warburg, Wald took the absorption spectrum of rhodopsin and found that the pigment contains carotenoids, which he found intriguing, because physicians had already connected nutritional night blindness with vitamin A deficiency [14].

Working with a Swiss researcher, Paul Karrer, Wald extracted vitamin A from the retinas of cattle, sheep, and pigs, and then moved to the Heidelberg lab of another Nobel laureate, Otto Meyerhof. With the clock ticking down on his time in Europe—after Adolf Hitler came to power, the U.S. National Research Council recalled the young Jewish postdoc home—Wald used a shipment of frogs, delivered while everyone else was vacationing, to gain a revolutionary insight. Since dark-adapted retinas contained a carotenoid slightly different from the vitamin A found in light-adapted retinas, he reasoned that the carotenoid, which he initially called retinene, was bound to the protein in rhodopsin and was released upon exposure to light, then gradually recombined to the rhodopsin protein to reverse the process [14]. (Later scientists changed retinene's name to retinal.)


▲ **Fig. 5.** George Wald. (Photo by Bachrach.)

Wald moved to Harvard University in 1934 and continued studying the chemical reactions within the retina both at Harvard and the Marine Biological Laboratory at Woods Hole, Massachusetts. He began investigating pigment molecules in the retina's cone cells, but World War II duties interrupted that line of work, so the important research he and his co-workers conducted on the red-sensitive pigment of the cones was not completed until the mid-1950s.

Hartline and Wald, along with Finnish–Swedish scientist Ragnar Granit (1900–1991), shared the 1967 Nobel Prize in Physiology or Medicine for their studies of vision systems. Hartline's 1940 JOSA paper was cited as one of the works for which he won the Nobel [15]. Hartline and Wald also were named OSA Honorary Members, the former in 1980, the latter in 1992.

Lasting Consequences

Many of the discoveries about the eye as a visual system did not bear practical fruit until after the interwar (1916–1940) period. The studies of sensitivity performance and contrast thresholds of the human eye formed the basis of everything from television and computer displays to the design of highway signs, which must be read in mere milliseconds for safety's sake [16,17]. That early twentieth century work continues to enhance many aspects of our twenty-first century life.

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PRE–1940

Evolution of Color Science through the Lens of OSA

Roy S. Berns

The Optical Society (OSA) was the dominant professional society in the evolution of color science, both through its many technical committees and through the Journal. This chapter highlights some of the many significant activities and publications that occurred through the 1950s.

OSA established the Committee on Colorimetry in 1919 chaired by I. G. Priest from the National Bureau of Standards and during its first year circulated a preliminary draft [1]. The committee's first report was published in the Journal in 1922, authored by the current chairman and president of the Society, L. T. Troland [2]. This remarkable 64-page report outlined the basis of photometry and colorimetry, including visibility and color-matching function data (referred to as the OSA excitation curves), terminology for visual description, chromaticity diagrams, complementary wavelengths, standard illuminants, color temperature, optimal color filters for trichromatic color reproduction, visual colorimetry, and transformation of primaries. All of these concepts would be central to establishing the 1924 Vλ visibility curve and the 1931 CIE colorimetric system, XYZ and xyY. The Colorimetry Committee was a driving force in the evolution of modern colorimetry, culminating with the book *The Science of Color* published in 1953 [3]. The book indicates the breadth of expertise of the committee and that color science is multi-disciplinary as it includes physics, optics, physiology, psychophysics, and history beginning with our first use of colored materials hundreds of thousands of years ago.

The first color order system that was based on extensive psychophysics was the Munsell system. The Munsell Value scale quantified visual compression by establishing the relationship between incident light and perceived lightness [4]. It has been used to support Steven's exponential model of visual compression and relate luminance factor to CIE lightness, L*. An OSA committee performed extensive research leading to the current definition of the Munsell system [5]. These data were used by Adams to derive the precursor to CIELAB [6]. The Munsell system is a cylindrical system, and as a consequence, neighboring samples are not equidistant. In addition, samples of constant hue vary in either lightness or chroma, but not both simultaneously as occurs in common coloration. In the late 1940s an OSA committee, chaired by D. B. Judd from the National Bureau of Standards, was established to develop a new color order system where samples were equidistant in all three dimensions based on a regular rhombohedral crystal lattice structure to [7]. The OSA Uniform Color Scales were the result thirty years later. Both systems are still used to develop and evaluate colorimetric-based color spaces for visual uniformity.

Any quantitative color description of objects depends on measuring the spectral reflectance factor. A breakthrough occurred during the 1930s when A. C. Hardy, a professor at the Massachusetts Institute of Technology, developed the first recording spectrophotometer whose illumination geometry was optimized for measuring materials via an integrating sphere where the specular component could be included or excluded, the latter correlating with the appearance of glossy materials [8]. General Electric manufactured the Hardy spectrophotometer. By the late 1940s, it was possible to interface the instrument to an automatic tristimulus integrator [9], and as a result, color measurements were reported as a spectral graph and CIE tristimulus values. One drawback of this approach was the high cost. Hunter made color measurement much more accessible with the development of a color-difference meter using color filters and three photodetectors, first presented at an OSA Annual Meeting in 1948 [10].

When the CIE system was promulgated in 1931, there were three standard sources, A, B, and C, representing incandescent, sunlight, and daylight, respectively. Source C was produced by filtering incandescent lighting with bluish liquid filters. Such a light was very deficient in UV and short-wavelength visible radiation compared with natural daylight. Measurements of daylight, principal component analysis, and a very clever approach to calculate the eigenvector scalars for a specific correlated color temperature resulted in the CIE D series illuminants [11, 12]. Today, CIE illuminants D50 and D65 are used extensively in color reproduction and color manufacturing, respectively.

All specifications include tolerances, and as early as 1932 [13], the Journal began publishing research demonstrating the CIE system's lack of uniformity with respect to color discrimination, research proposing linear and nonlinear transformations that improved correlation, and psychophysical data from discrimination experiments. At the forefront of this research was D. L. MacAdam, a student of Hardy at MIT, who went on to have a distinguished career at the Eastman Kodak Research Laboratories. In the early 1940s, he built an apparatus to measure color-matching variance that resulted in the "MacAdam ellipses," still used as a discrimination dataset [14]. His research and leadership resulted in the 1960 uv and 1976 u′v′ uniform chromaticity scale diagrams and the 1976 L*a*b* and L*U*V* uniform color spaces.

An interesting research topic was designing color reproduction systems that could be related to colorimetry by linear transformation. During the late 1930s, Hardy and Wurzburg [15], MacAdam [16], and Yule [17] laid the groundwork for today's color management for both additive and subtractive imaging systems.

We all use manufactured products meeting a color specification. Predicting and controlling a recipe is invaluable for coloration systems where the colorants and media both absorb and scatter light. The theory proposed in 1931 by P. Kubelka and F. Munk and published in the Journal in 1948 [18] continues to be used successfully in textiles, plastics, and coatings. In 1942, J. L. Saunderson demonstrated its effectiveness for the coloring of plastics, particularly by accounting for refractive index discontinuities at the surface [19].

Today, color science has evolved from tristimulus XYZ, through L*a*b* and L*u*v*, to color-appearance spaces such as CIECAM97s and CIECAM02. A key requirement of such spaces is accounting for the effects of chromatic adaptation. Such research began in the 1950s and the seminal experiments by R. W. Burnham, R. M. Evans, and S. M. Newhall from Eastman Kodak remain reliable and viable data [20].

I will end my highlight tour with Ref. [21], which describes how MacAdam created separation plates for printing both the color gamut of a set of offset printing inks and a spectrum. A 19-page article appeared in the 3 July 1944 issue of *Life* magazine, titled "Color: it is the response of vision to wave lengths of light" [22]. This remarkable article includes colored images of a dispersed spectrum, additive and subtractive mixing, principles of selective absorption of colored filters, spectral reflectance curves of a lemon and a tomato, the Hardy recording spectrophotometer, the visible spectrum, the Munsell system, an afterimage demonstration using the American flag, and several other optical illusions. The 1931 CIE system was used to calibrate the color separations where dominant wavelength represented the spectral hues and, in turn, mixtures of the printing inks. Incredibly, I have MacAdam's copy of the article. The article summarizes color science and, indirectly, the tremendous impact the OSA has had on its evolution.

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