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(*b*. Eisenach, Germany, 23 January 1840; *d*. Jena, Germany, 14 January 1905)

physics.

Abbe's importance for the development of scientific and practical optics can be comprehended only in connection with the founding and rise of the Zeiss Works.

In 1846 Carl Zeiss, a thirty-year-old mechanic, established his shop in Jena; in 1866, he began a technical and scientific collaboration with Abbe, who was then a lecturer at the university there. Abbe's fortunes grew with those of the Zeiss company; he had become a partner in 1876 and held a professorship at the university. Within ten years, the once small Zeiss workshop developed into an internationally famous industrial enterprise. The company's apochromatic lens was the greatest advance in technical optics made to that date. At the same period, Abbe began to manifest that interest in social welfare that soon led to the creation of the Carl Zeiss Foundation.

Abbe, according to Jena University curator M. Seebeck, "was born of lowly station, but with predestined claim to scientific fame." His father, Adam Abbe, a spinning-mill worker, would never have been able to send his son through high school and university if his employers had not provided a scholarship for the intelligent and industrious youth.

Upon graduating from the Eisenach Gymnasium in 1857, Abbe studied physics in Jena and subsequently in Göttingen, where he received the doctorate on 23 March 1861. Among the Göttingen professors who exerted a lasting influence on him were the mathematician Riemann, the famous exponent of the theory of functions, and the physicist Wilhelm Weber, former assistant to Gauss and one of the "Göttingen Seven," who had been temporarily suspended because of their protest against the king of Hannover's violation of the constitution.

Abbe's decision to apply for the position of lecturer at Jena University must not have been an easy one to make, since there would be a two-year interval, with its inevitable economic hardships, between his doctorate and his inauguration. He managed to make ends meet by accepting a poorly paid teaching position with the Physikalischer Verein in Frankfurt am Main, a group founded by local citizens for the propagation of the natural sciences. He also did some private tutoring. On 8 August 1863, at the age of twenty-three, Abbe finally achieved his ambition and was admitted to the faculty of Jena University as lecturer in mathematics, physics, and astronomy.

Abbe's straitened circumstances did not improve until he was made associate professor in 1870. On 24 September 1871 he married Elise Snell, the daughter of Karl Snell, head of the physics department at the University of Jena. The marriage was an extremely happy one from the start. The couple had two daughters. In 1876 Abbe's economic difficulties were resolved when Zeiss offered him a partnership. During the preceding ten years Abbe had con tributed eminently to the phenomenal rise of Zeiss's company; he now shared in the quite considerable profits.

Zeiss had early begun experiments to convert the production of his microscope, consisting of an objective and an ocular lens, into a scientific process; whereas formerly he had relied on trial and error to find the best lenses, he now wished to use scientific methods. In this effort, Zeiss had met with as little success as his teacher Friedrich Körner; he had also attempted to use the knowledge of the mathematician Friedrich Barfuss. After the latter's death, Zeiss remained unable to solve this problem because of his limited scientific training. He therefore turned to Abbe in 1866 and succeeded in interesting the young physicist in the systematic production of microscopes. During the following decade they constructed the machinery required for industrial production and turned out many commercially marketed instruments (illuminating apparatus for the microscope, known in England as "the Abbe," the Abbe refractometer, and others). Abbe also solved their main problem so completely and ingeniously that his theoretical findings became the basis for the further development of practical optics for decades to come. For example, in 1934 Frits Zernike derived from these findings the phase-contrast process, for which he was awarded the Nobel Prize in physics (1953). Somewhat earlier, Hans Busch, on the basis of Abbe's theory, had seen the possibility of developing electron microscopes.

Abbe's two most important scientific achievements were in radiation optics (the "sine condition") and undulatory optics ("Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung," 1873). The latter led Helmholtz to offer Abbe a professorship at the University of Berlin, but Abbe declined, mainly because of his ties to Zeiss.

The sine condition is easily derived with the aid of Figure 1. By imaging object point *O* in the image point *O′* through the decentered lens L, we obtain the image scale

which, in accordance with the known image formula, equals the quotient of the image distance *l′* divided by the real distance *l*. The relation

can also be derived from Figure 1. If the decentered lens *L* is regarded as the zone of a microscope objective at distance *h* from the optical axis, then it follows from the above equations that in the case of

the image scale *M* is constant for any zone of the lens, that is, over the entire aperture of the objective. Abbe applied the term "aplanatic" to optical systems where the spherical aberration has been corrected, i.e., the axis point *O* is accurately refracted in the axis point *O′* and the sine condition (3) has been fulfilled, so that the surface element around *O* is imaged by all lens zones on the surface element at the image point *O′* at the same scale. These two corrective conditions can be simultaneously fulfilled only for a single object and image distance; therefore, in the case of the microscope we are limited to a tube of a certain length.

In examining a number of hit-or-miss microscope objectives, Abbe found that in operational position they all fulfilled the sine condition, thus solving the mystery of the success of the hit-or-miss method.

Now Abbe was in a position—through application of the sine condition—to undertake accurate corrections of the aberrations of image systems that did not have too large a divergence. His pupil, Siegfried Czapski, remarked that despite the vastly superior ray union, the images of fine microscopic objects produced by these objectives were duller, showed fewer details, and had less resolving power than the old, poorly corrected systems with larger divergence. After many strenuous and often vain attempts—at tremendous expense to Zeiss—Abbe finally came upon the solution to the problem, as follows.

If—as shown in Figure 2—a graticule (heavy vertical lines in figure) is illuminated with, say, red filtered sunlight, then the light rays passing the edges of the graticule gap are deflected. Thus the lower ray in the figure, when it meets the upper ray in point Z' of the rear focal plane of the objective, has covered a distance longer by a fraction or multiple z of the wavelength λ than the upper ray has. Consequently, the two rays are out of phase by

The rays are optimally intensified when z is an integer, i.e., the wave crests coincide. The resulting images of the light source are designated as diffraction images of the order of $z = 0,1,2,....$ According to Abbe, the accuracy of the image reproduction is a function of the number of diffraction patterns received by the microscope. For the resolution of a graticule the diffraction image of the first order suffices.

If the space between object and objective is filled with a substance (immersion fluid) having the refracvive index *n*, the wavelength λ is reduced to λ/n. Accordingly, the diffraction equation is

limited to the diffraction maximum of the first order ($z = 1$). This renders possible calculation of the grating constants *d*, that is, the smallest still separable structures of the sample, provided the first-order diffraction maxima of the light source are recognizable in the microscope with the eyepiece. Abbe called the denominator of equation (5) "numerical aperture":

Thus it is possible to separate microscopically such structures as

which become finer as the wavelength of the rays used for illumination diminishes and the numerical aperture of the objective used increases. But even if the aperture of the microscope is too small to accommodate diffraction images of the first order, the grating constant can be calculated if, in addition to the diffraction image of 0 order of magnitude of the light source, at least one of the two diffraction images of the first order is accommodated in the microscope. In the extreme case, given oblique illumination. grating structures of the order

can still be calculated and thus resolved.

With the setting up of equations (3) and (7) or (8) the last difficulty was cleared and the reason found for the previously puzzling observation that a poorly corrected objective with large aperture revealed more details in the sample than did a well-corrected objective with small divergence. This peculiarity, derived from Abbe's theory of image resolution, had a powerful effect upon electron microscopy, which developed half a century later. According to (7), the extraordinarily short equivalent wavelength of the electrons should have made the resolution in the electron microscope 100,000 times greater than that in the light microscope. The numerical apertures (6) achieved to date, however, amount to only a fraction of a percent of those of the light microscope, resulting in a much smaller superiority—hardly 100 times—of the electron microscope in the resolution of the smallest objects.

Today it is difficult to realize the magnitude of the effect that the above theoretical considerations exerted on the optical production of the Jena workshop.

The effort to discover a better chromatic correction of the microobjective is also noteworthy. In his report on his visit to the South Kensington Exposition in London(1876), which had an excellent optical section, Abbe points out the causes for this shortcoming; the refusal of the glassworks to consider not only economic but also scientific interests in the application of glass smelting. Nevertheless, his report led one glass chemist, Otto Schott, to undertake this task. Joining forces with Zeiss and Abbe, Schott perfected production methods in the Jena glassworks of Schott & Associates by refining a great number of new optical glasses to high perfection. Ten years after the London Exposition, the Zeiss Works celebrated its greatest triumph to that date with the development of an apochromatic system in which not only the primary but also the secondary color spectrum had been eliminated.

Of no lesser importance is the change in Ernst Abbe's personal outlook that occurred at this time and turned the physicist into a social reformer of equal stature. Having become sole owner of the optical plant and its share in the glassworks after the death of Carl Zeiss in 1888 and the departure from the firm of the letter's son Roderich, in 1891 he created the Carl Zeiss Foundation, to which he bequeathed his perosnal fortune, wthi his wife's approval. In the foundation's charter—which in some respects later served the Prussian state as the model for its progressive social legislation (then generally admired) and turned over the larger part of the profits to the University of Jena—Abbe originated an economic system that unites socialism and capitalism. The economist Alfred Weber, in volume I of *Schriften der Heidelberger Aktionsgruppe zur Demokratie und zum foreien Sozialismus* (1947), proposed a voluntary socialization of German industry modeled after the Carl Zeiss foundation.

BIBLIOGRAPHY

Abbe's work is collected in the *Gesammelte Abhandlungen von Ernst Abbe*, 5 vols. (Jena, 1904–1940). Further bibliographical information may be obtained from Firma Carl Zeiss, Oberkochen, or Volkseigener Betrieb, Jena.

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