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THE PHOTOGRAPHIC LENS

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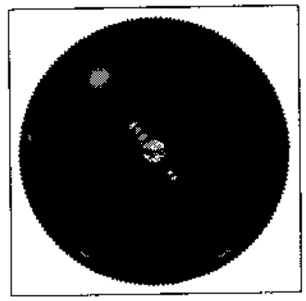
ARTICLES

DEPARTMENTS



THE COVER

The painting on the cover shows a summer landscape reflected in an ultra-wide-angle lens for a 35-millimeter camera. The antireflection coatings on the lens alter the normal colors in the outdoor scene. Thus the sky has a purplish cast and the reflection of the sky in the water is greenish. The sun is reflected several times by the lens's interior elements, of which there are 11 in all. If the lens were used to make a picture of the reflected scene, the image on the film would cover a 180-degree field of view, measured diagonally on the standard 24-by-36-mm. frame of a 35-mm. camera. Because of the lens's extremely wide angle of view and also because it makes the lines of rectilinear objects appear to be curved, it is known to photographers as a fish-eye lens. Made by the Minolta Corporation, it has a focal length of 16 mm. and a maximum aperture of $f/2.8$. The technology of creating such high-performance lenses is described by William H. Price in his article "The Photographic Lens" (page 72).

THE ILLUSTRATIONS

Cover painting by Ted Lodigensky

Page	Source
19–23	Total Communications Industries, Ltd.
25–29	Alan D. Iselin
30–31	Philip E. L. Smith, University of Montreal
32	EROS Data Center, U.S. Geological Survey
33–37	Adolph E. Brotman
47	EROS Data Center, U.S. Geological Survey
48–56	George V. Kelvin
57	EROS Data Center, U.S. Geological Survey
60	Charles Lane, Medical Research Council Laboratories, London
62–70	Bunji Tagawa
73	Norman Goldberg, courtesy of *Popular Photography*
74–82	Dan Todd
85–87	Tom Prentiss
88	Tom Prentiss (*top*); Rolf Schumacher, University of Bonn (*bottom*)
91	The Bettmann Archive, Inc.
92–98	Andrew Christie
99	Maurits C. Escher
100–105	Andrew Christie
106	Andrew Christie (*top*), Fritz Goro (*bottom*)
107–108	Andrew Christie
111	Morton Salt Company
112	Humberto Fernandez-Moran, University of Chicago
113	*Black Holes, Quasars, and the Universe.* © 1976, Houghton Mifflin Company
114	Crown Copyright. The Science Museum, London

The Photographic Lens

New optical materials (both glasses and plastics), antireflection coatings, laborsaving computer programs and new production methods yield high-performance lenses at increasingly low cost

by William H. Price

Designing a lens can be compared to playing chess. In chess a player tries to trap his opponent's king in a series of moves. In creating a lens a lens designer attempts to "trap" light by forcing all the rays arising from a single point in the subject to converge on a single point in the image, as a consequence of their passing through a series of transparent elements with precisely curved surfaces. Since in both cases the ultimate goal and the means by which it can be attained are known, one is tempted to think there will be a single best decision at any point along the way. The number of possible consequences flowing from any one decision is so large, however, as to be virtually, if not actually, infinite. Therefore in lens design as in chess perfect solutions to a problem are beyond reach. Although this article will be concerned only with the design of photographic lenses, the same principles apply to all lenses.

The lens designer has one enormous advantage over the chess player: the designer is free to call on any available source of help to guide him through the staggering number of possibilities. Most of that help once came from mathematics and physics, but recently computer technology, information theory, chemistry, industrial engineering and psychophysics have all contributed to making the lens designer's job immeasurably more productive. Some of the lenses on the market today were inconceivable a decade ago. Others whose design is as much as a century old can now be mass-produced at low cost. With the development of automatic production methods lenses are made by the millions, both out of glass and out of plastics. Today's lenses are better than the best lenses used by the great photographers of the past. Moreover, their price may be lower, in spite of the fact that 19th-century craftsmen worked for only a few dollars a week and today's lenses are more complex. The lens designer cannot fail to be grateful for the science and technology that have made his work easier and his creations more widely available, but he is also humbled: it is no longer practical for a fine photographic lens to be designed from beginning to end by a single human mind.

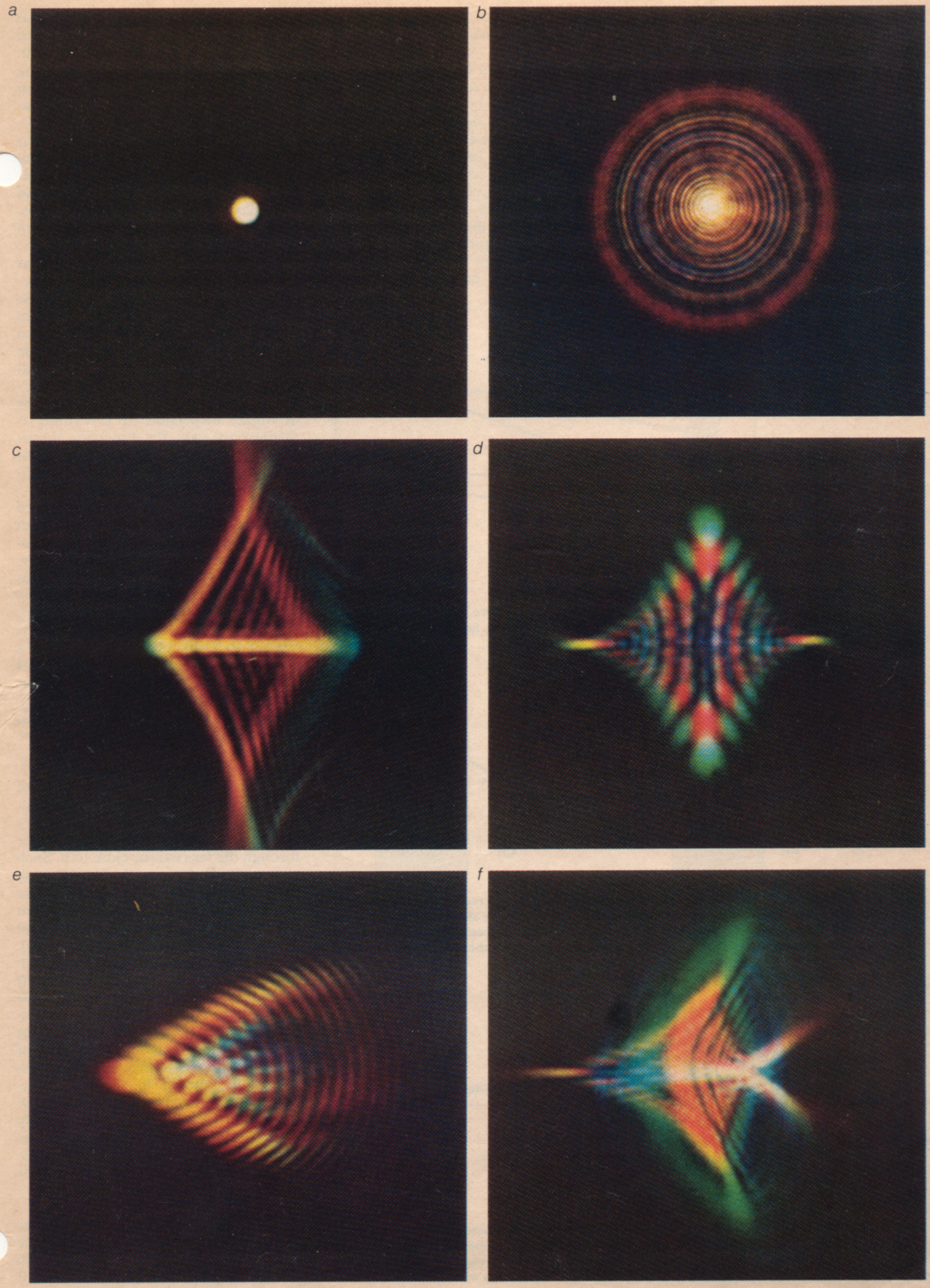
What kind of lens was the first to be used in photography is not known because the inventor of photography, Joseph Nicéphore Niepce, left no written record of his experiments. It is believed, however, that Niepce's first picture (which is lost to history) was made in 1822 with a meniscus lens in a camera obscura. "Meniscus" (from *meniskos*, the Greek diminutive for moon) describes the cross-sectional shape of the simplest practical photographic lens: a crescent moon, formed by two arcs of different radii. Simple eyeglasses for reading are meniscus lenses.

The camera obscura (the Latin for dark room) had been known from antiquity. Leonardo da Vinci described a simple form of camera obscura in which light entered the room through a small hole and formed a faint image on the opposite wall. In the 16th century the hole was replaced by a meniscus lens, which made the image many times brighter. The camera obscura was a popular tool of artists, who used it to trace the outlines of their subjects.

If Niepce made his first photographs with a camera obscura and a meniscus lens, he soon sought something better. It is reported that Charles Louis Chevalier, of a firm of engineers and instrument makers in Paris, provided him with a two-element achromatic lens. Such lenses, designed to minimize the chromatic aberration, or color fringes, produced by simple meniscus lenses, had been introduced to astronomy in 1758 by the English optician John Dollond, but they were still novelties early in the 19th century. At about the same time that Chevalier was adding an achromat to Niepce's camera, Joseph Jackson Lister and Giovanni Battista Amici introduced achromatic lenses to microscopy, thereby removing chromatic aberration from microscopes and for the first time making bacteria visible.

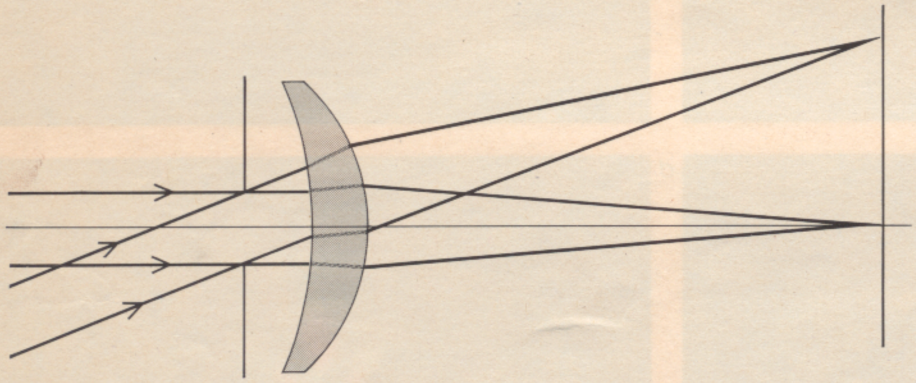
Chromatic aberration results from the phenomenon in which a prism disperses white light into a spectrum of colors. In a vacuum all colors, or wavelengths, of light travel at the same velocity. In a material medium the velocity of light is always reduced, and the velocity of the shorter wavelengths is reduced more than that of the longer ones. Thus when light leaves one medium and enters another at an angle, its path is sharply refracted, or bent, either toward or away from a line perpendicular to the interface between the two mediums, depending on whether its velocity in the second medium is lower or higher.

LENS ABERRATIONS can be studied by magnifying the images formed at the focal plane when a point light source is beamed at the lens. In the micrographs on the opposite page, made by Norman Goldberg, technical director of *Popular Photography*, the images are magnified 600 diameters. Ideally the image should itself be a point (*a*), but the ideal is usually achieved, as in this case, only when the light source is in line with the axis of the lens. Image *b* exhibits one of the most common lens defects, spherical aberration. (The sources of the various aberrations are illustrated schematically on page 75.) Another common defect, astigmatism, accounts for the strong horizontal line in image *c*, which also exhibits coma and chromatic aberration. Astigmatism shows up in purer form in image *d*. If the focus of the lens were moved slightly either forward or back, the astigmatism would produce either a sharp horizontal line or a sharp vertical line. Coma, a familiar type of aberration that arises when the light source is off axis, is depicted in image *e*. The final image (*f*), which combines a complex mixture of coma, astigmatism and chromatic aberration, is typical of the off-axis images produced when fast, modern lenses are used at full aperture. After allowance has been made for the great magnification of the image, however, it is evident that the lens focuses most of the light energy within a very small "blur disk," which in this particular case is a circle with a diameter of .03 millimeter.

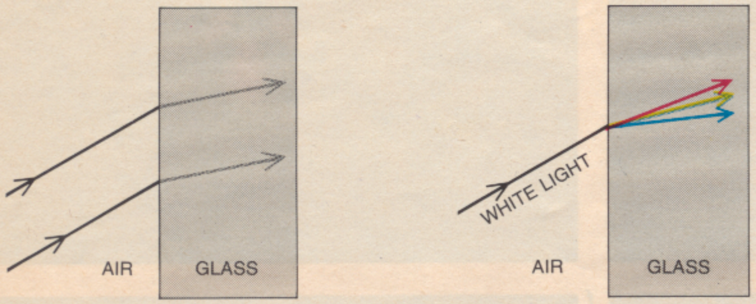

a
b
c
d
e
f

The susceptibility of light to refraction is the cornerstone of refractive optics, or the theory of lenses. Some 60 years before Isaac Newton took up the study of optics the phenomenon of refraction was described and graphically depicted by the Dutch mathematician Willebrord Snell van Royen. Thereafter René Descartes formulated the precise law of refraction, which became known as Snell's law: the sine of the angle of incidence times the index of refraction of the first medium is equal to the sine of the angle of the refraction times the index of refraction of the second medium. Snell's law is still the lens designer's single most useful formula. It tells him how to bend light to his will.

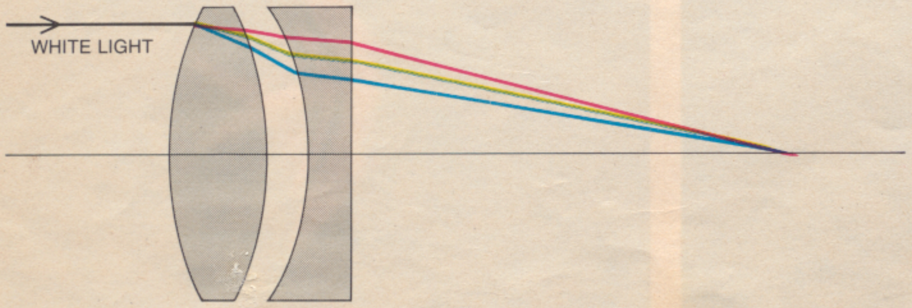
When a beam of white light strikes glass at an angle, the blue-violet wavelengths are bent the most and the red wavelengths the least. It is for this reason that the edges of the emerging beam appear to be fringed with color. From his work with prisms Newton was the first to perceive that white light is a mixture of colors. His first proposition in *Opticks* states that "Lights which differ in Colour differ also in Refrangibility." He was swept too far, however, by the force of his perception. He incorrectly jumped to the conclusion that since chromatic aberration is inherent in lenses, nothing can be done about it. (Whereupon he invented the reflecting telescope, which does away with lenses and the troublesome problem of refrangibility.)



SIMPLE MENISCUS LENS, a crescent-sectioned element with two spherical surfaces, was probably in camera with which Joseph Nicéphore Niepce took the first photograph in 1822.



LIGHT IS REFRACTED, or bent, when its velocity is changed as a result of passing from one medium to another. Because short wavelengths of light travel more slowly in glass than long wavelengths, white light is dispersed into its spectral colors. The degree of dispersion differs according to the composition of the glass (or composition of some other transparent medium).



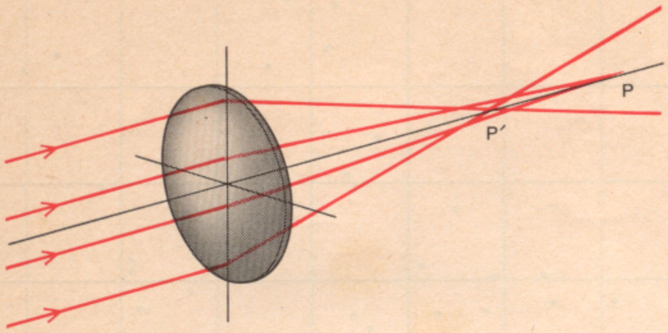
CHROMATIC ABERRATION can be corrected by combining glasses with different dispersions. In this example of a simple two-element lens first element is made from low-dispersion glass. The second element, of opposing power but weaker, is made from high-dispersion glass. Dispersion is canceled out but focusing power remains. Dispersion of colors is exaggerated.

What Newton failed to observe is that in passing through glasses of different compositions colors exhibit different degrees of refrangibility, or, as we would say today, glasses can have different dispersions. This is the weapon with which the lens designer can combat chromatic aberration. The trick is to make a lens with at least two elements. The first element is a convex lens made of a glass that disperses the colors to a minimum degree. The second is a concave lens made of a glass that disperses the colors to a maximum degree. In optical terminology a positive lens of lower dispersion is combined with a negative lens of higher dispersion. If everything is planned just right, the dispersion almost cancels out but the compound lens can still refract substantially [*see bottom illustration at left*].

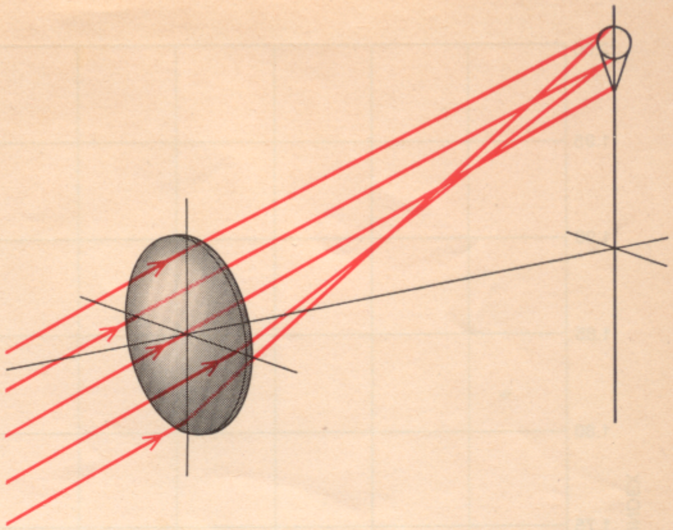
That roughly describes the standard landscape photographic lens of the 19th century. In fact, the two-element photographic lens is still in production today, both as a low-cost lens for simple cameras and as a fairly expensive telescopic lens for nature and sports photography. In such lenses a long focal length is needed to bring objects closer, and a small field of view is acceptable. Good as the original two-element recipe was, it was still only a recipe. The early achromats were empirical lenses. There was no exact theory of how to match up the variables.

Part of the solution came in 1841, when Carl Friedrich Gauss published his theory of lenses. The theory conceptually simplified a lens to ignore all rays except those that lie in a plane either through the lens axis or close to it. Such rays are called paraxial. Even though the Gauss model is simplified, it includes focal length (the distance from the optical center of the lens to the plane in which the rays are brought to a focus), magnification, the location of the principal points of the lens and the location of the image. Gauss's theory was to lens design what trigonometry was to navigation. Paraxial ray tracing served for several decades as the principal tool of photographic lens designers. The simplification implicit in Gauss's procedures does, however, exact a penalty: the plane of the sharpest image usually does not coincide precisely with the plane defined by the Gaussian rules. Nevertheless, as a first cut the analysis comes very close to the bone.

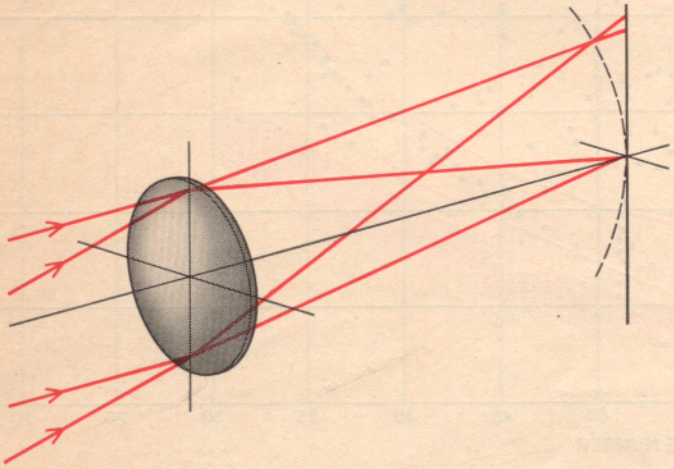
The Gaussian image plane also serves as a benchmark for measuring the entire range of aberrations with which the lens designer must contend, even if



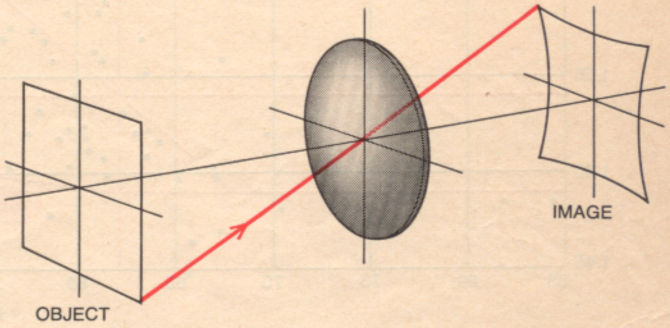
SPHERICAL ABERRATION is an inherent characteristic of any lens whose surface is a section of a sphere. Light originating from the same object point comes to a focus at slightly different points (*P* and *P′*), depending on whether the rays pass through the center of lens or the periphery. Distance separating *P* from *P′* varies with aperture.



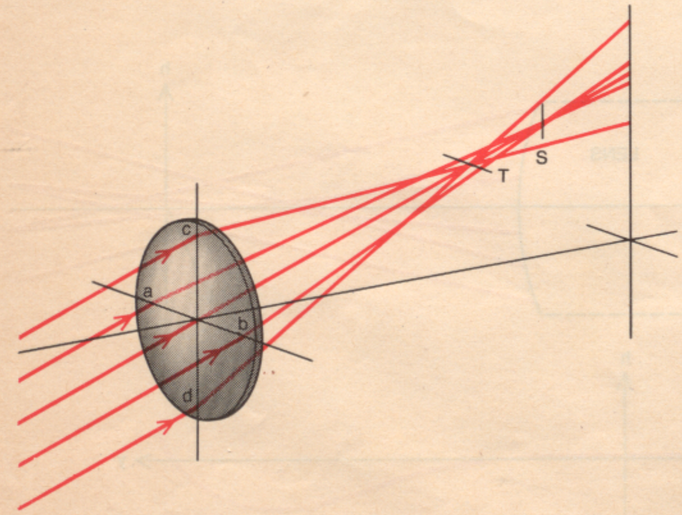
COMA is produced when light from a point off the axis of the lens passes through the perimeter of the lens and comes to a focus in a ring displaced radially from the focus of light that has passed through the lens center. Coma appears as a bright core of light with a spreading tail. Word is derived from the Greek for flowing hair.



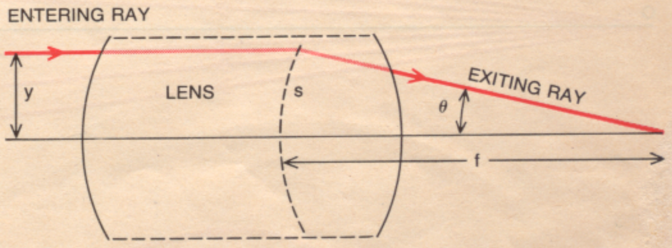
CURVATURE OF FIELD results when an oblique beam of light is brought to a focus closer to the lens than an axial beam of light is. This type of aberration gives rise to an image surface that is curved.



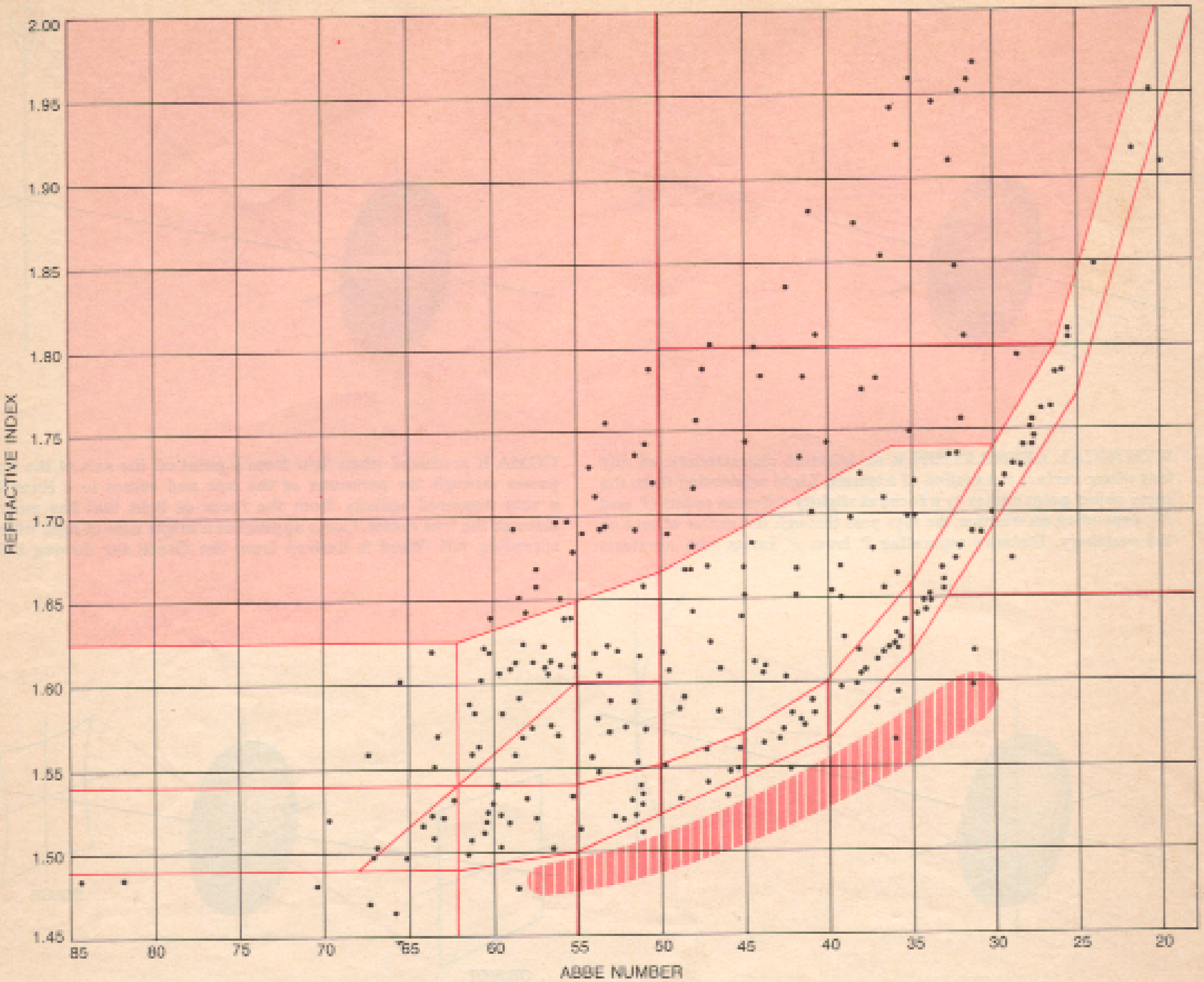
DISTORTION is a lens aberration in which the magnification of the image varies with the obliquity of the entering rays. The consequence of this aberration is that straight lines appear curved in image.



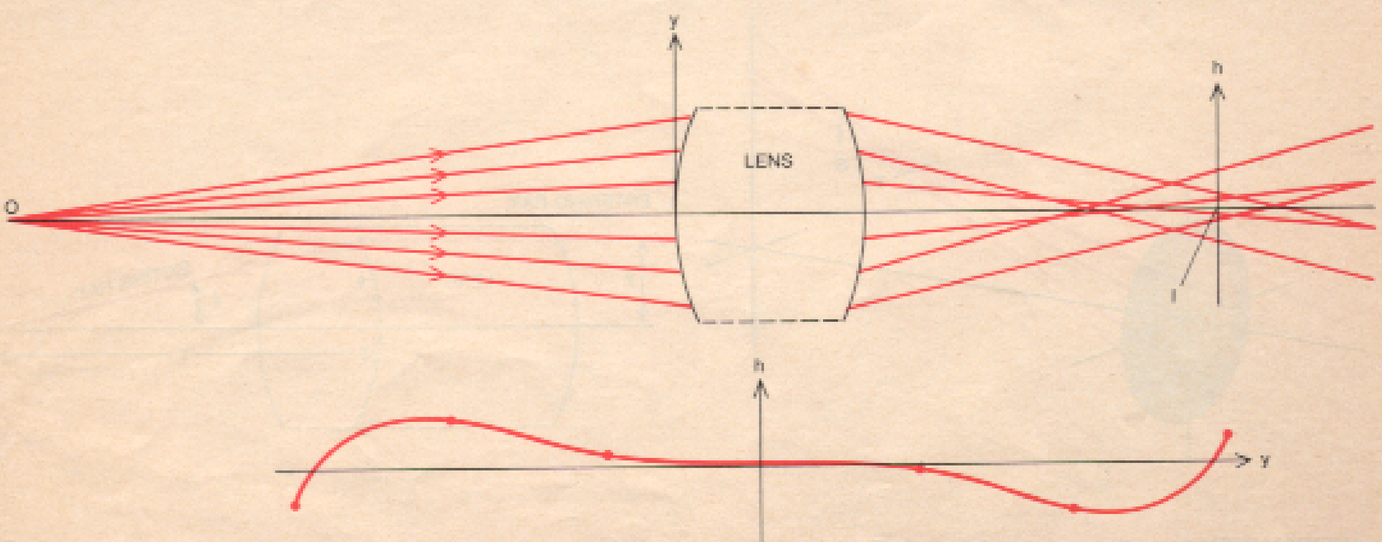
ASTIGMATISM is another common defect of off-axis images created by lenses. Light from an off-axis point that passes through the lens along the axis *a,b* is focused at *S*, whereas light from the same object point that passes through the lens along axis *c,d* is focused at *T*. *S*, which is known as the sagittal, or radial, focus, is a line image that is perpendicular to the optical axis; *T*, the tangential focus, is a line image that is tangent to a circle centered on the optical axis.



ABBE SINE CONDITION, formulated by Ernst Abbe, specifies the condition for simultaneous correction of spherical aberration and coma. When the rays entering the lens and the rays leaving the lens are extended, they intersect at a surface, *S*, defined as the locus of the points at which all rays from an infinitely distant point source on the axis of the lens appear to be refracted. The dual correction is achieved when y is equal to $f \cdot \sin\theta$; therefore surface *S* is spherical.



PROPERTIES OF OPTICAL GLASSES are commonly characterized by their refractive index, n, which measures the light-bending power of the glass, and by their Abbe number, ν, which measures the extent to which the glass disperses white light into its spectral colors. The lower the Abbe number, the greater the dispersion. Each point on the chart represents a different optical glass. The rare-earth glasses (*area tinted in color*) combine high refractive index with low dispersion. Optical plastics lie in hatched area below optical glasses.



TRANSVERSE SPHERICAL ABERRATION, h, of a given lens, L, is a measure of the failure of light rays originating at O to converge at the Gaussian image point, I. The aberration varies with lens aperture y in a manner described by a series expansion, $h = ay^3 + by^5 + cy^7 + \dots$. Plotted curve of h against y shows such an equation fitted to a few traced rays. The aberrations of other rays passing through lens may be interpolated from curve or calculated from equation, after solving for a, b, c..., without further ray tracing.

his lens is to be used only for photography in light of one color. The primary monochromatic aberrations, which were defined mathematically by Ludwig Seidel in 1856, are spherical aberration, coma, astigmatism, curvature of field and distortion.

Spherical aberration arises because lens surfaces are sections of spheres, and light passing through the edge of a lens comes to a focus at a point different from that for light passing through the center of the lens. Coma also involves the spherical nature of lens surfaces: images formed off the central axis of the system tend to be asymmetrical. "Coma" has the same root as "comet": the Greek for flowing hair. Because of coma the point of focus seems to have a cometlike tail.

Astigmatism means not coming to a point; it is from the Greek *a*-, not, and *stigma*, mark or spot. It is also due to the asymmetry of off-axis images, but its effect is to cause light to be spread along a line either in a plane through the image point and the lens axis or at right angles to that plane. It has the curious effect of blurring horizontal lines and sharpening vertical lines, or vice versa.

Curvature of field arises if the locus of the sharpest points in the image lies on a curved surface instead of on a plane. It is this aberration that accounts for photographs that are sharp in the center and blurred around the edges. In certain types of large telescopes the aberration is left uncorrected and the photographic plate is curved to compensate for it. The last of the principal aberrations, distortion, gives the appearance of a curved object projected onto a flat surface, or vice versa. It is analogous to the effect that makes Greenland so large in a map made on Mercator's projection.

The early 1840's saw not only the genesis of scientific lens design based on Gaussian principles but also the birth of two men who were to make the next great contributions to the lens-design problem: Ernst Abbe and John William Strutt, later Lord Rayleigh. Born in 1840, Abbe became the chief physicist and lens designer for the famous optical firm of Carl Zeiss. Among his many contributions were the Abbe number, which is used in the classification of optical glasses, and the Abbe sine condition, which defines a lens that is free of coma. The Abbe number is the reciprocal of the degree of dispersion; it incorporates the difference in refraction of two wavelengths that are widely separated in the spectrum. Guided by the Abbe number, the lens designer can cancel out chromatic aberrations for any two wavelengths of light. The Abbe number was the lens designer's answer to Newton.

In selecting glasses for a new lens the designer consults a chart of glass properties in which the horizontal axis is marked off in Abbe numbers [*see top illustration on opposite page*]. The scale on the vertical axis shows the index of refraction for light of a specified color in the middle region of the spectrum. With the chart the designer can see at a glance the interaction between the available glasses and light of the primary colors.

The Abbe sine condition states that coma is eliminated when the distance from the axis of the lens to the point where a ray enters the lens, traveling parallel to the axis, is equal to the focal length of the lens times the sine of the angle the ray makes with the axis at the point of focus [*see illustration at bottom right on page 75*]. Today nearly every fine camera lens meets the Abbe sine condition.

Lord Rayleigh, two years younger than Abbe, presented lens designers with the ultimate challenge by stating the conditions that must be met by a perfect lens. He showed mathematically that an image formed by an optical system will not differ sensibly from a perfect image only if all the rays travel over optical paths of equal length. Rayleigh found that in practice the perfect image is attained if the difference between the shortest path and the longest does not exceed a quarter of a wavelength of light. Such a lens is said to be diffraction-limited. Ideally a lens should be at the Rayleigh limit for light of all wavelengths. If this goal is to be closely approached, the glasses in the lens must all have the same partial dispersion even though their individual dispersions may vary. (Partial dispersion is the rate of change of dispersion with wavelength. Dispersion proper is the rate of change of the index of refraction with wavelength.)

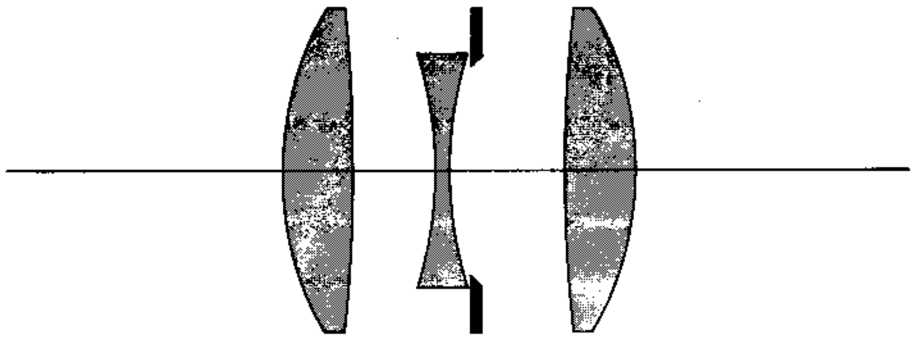
During the 19th century and early in the 20th Józef Miksa Petzval, Henry Coddington and A. E. Conrady, among others, derived mathematical relations and developed techniques for evaluating the magnitude of specific aberrations on the basis of the smallest possible amount of data, in order to reduce the crushing burden of calculation. Petzval, the inventor of the Petzval portrait lens, discovered that the curvature of field of a lens, in the absence of astigmatism, is a relatively simple function of the index of refraction of the lens elements and their radii of curvature. Coddington is credited with the derivation of simple formulas for the calculation of astigmatism for small lens apertures. Conrady is considered by many to be the father of modern optical design, through his application of the concept of optical-path difference to the primary aberrations, both monochromatic and chromatic.

At the end of a century of photographic-lens development, say by the mid-1920's, the creation of lenses was no longer a cookbook operation, but lens design still remained more of an art than a science. Confronted with a lens-design problem, a few men with a genius or a knack could sense the direction to take. Then it was a matter of the laborious application of Snell's law over and over again as designs were checked out by tracing the paths that rays of light might take from the object to the image. Few outside the profession could comprehend the magnitude of the task. The only tools available were a six-place table of common logarithms and by the 1930's a desk-top mechanical calculator. A difficult lens could absorb several man-years of computation. The key to a successful outcome was persistence.

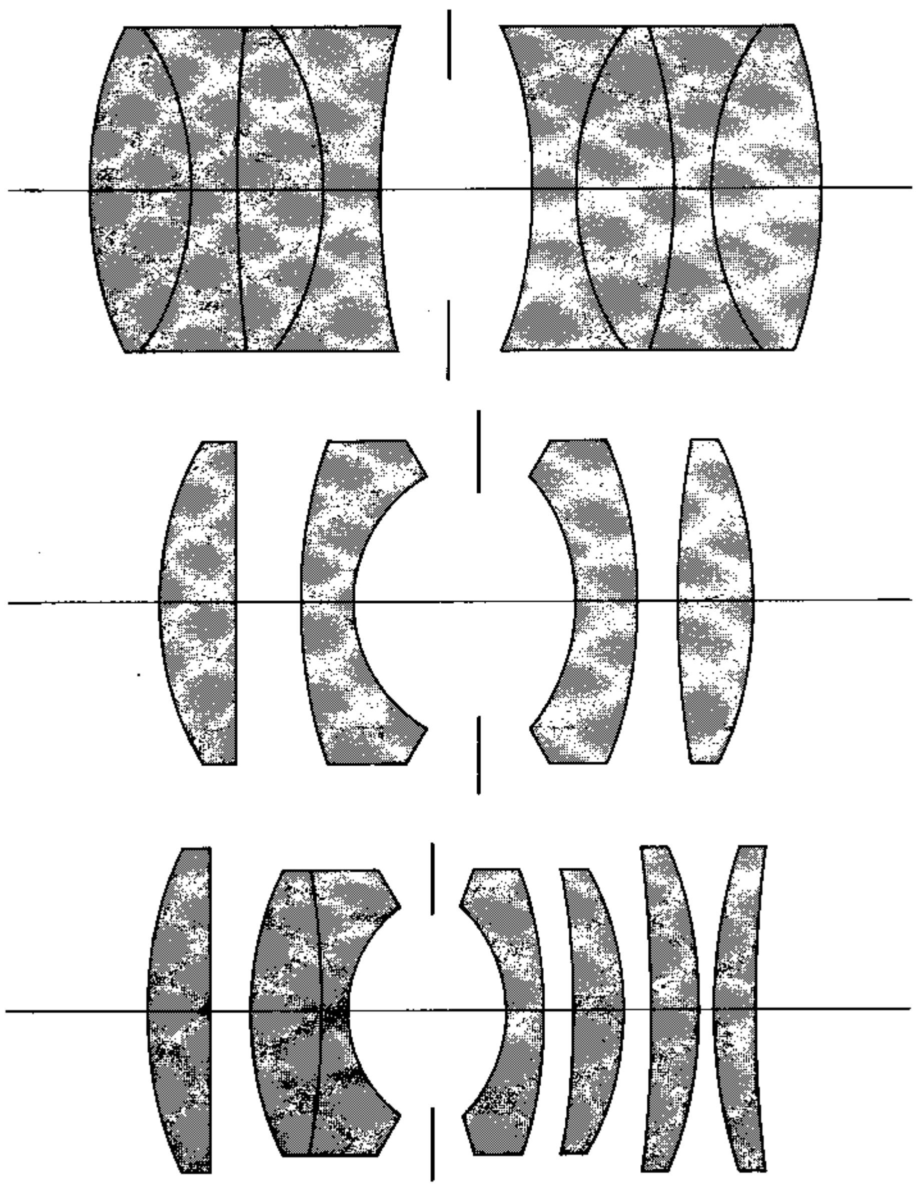
For all the inelegance of such brute-force methods, nearly all the fundamental types of lenses on the market today were pioneered during that period. Some of them, such as the Zeiss Sonnar $f/1.5$, were impressive for their speed. Others, such as the Cooke triplets, were remarkable for their simplicity. (The designation $f/1.5$ means that the focal length of the lens is 1.5 times the maximum aperture of the lens. The smaller the f ratio is, the more light a lens can gather in a given time. Light-gathering power, or speed, is inversely proportional to the f number squared.)

A brief excursion into geometric optics will help to explain the unique position of the Cooke design, first described in 1893 by H. Dennis Taylor of the British optical house of Cooke and Sons. Geometric optics, unlike the more general field of physical optics, ignores all the known facts about light except those affecting the path of its propagation. Consider the spherical aberration of the hypothetical lens depicted at the bottom of the opposite page. The designer would like the lens (L) to bring all the rays from a point of origin (O) to a point of focus (I). One can see that lens L fails badly in this respect. Although some of the rays do converge at I, most of them do not.

Any failure of a ray to strike point I can be measured in the same way a miss in target practice can be measured, by finding the distance from the bull's-eye to the striking point. In optics such a deviation is called a transverse aberration, a distance measured perpendicular to the path of the light ray. In the diagram for lens L the transverse aberration from the aiming point I is designated as the magnitude h (for height above or below the axis). Inspection of the diagram tells us that h is a function solely of the point where the ray enters the lens; that point will be designated as a magnitude along dimension y. In other words, the transverse spherical aberration of rays from any point is a function of the aperture of the lens. This is a general characteristic of lenses, which is why most of them achieve their maximum sharpness when they are used at less



COOKE TRIPLET LENS, originally conceived in 1893 by H. Dennis Taylor, is probably the most studied and refined type of photographic lens in service today. Its three elements provide the simplest arrangement that enables the lens designer to eliminate all seven basic aberrations out to third order. Terms of higher order tend to be small. The seven are spherical aberration, coma, astigmatism, distortion, curvature of field and chromatic aberration along two axes.



REFLECTIONS FROM LENS SURFACES hampered lens design before the development of antireflection coatings in the late 1930's. When many elements were desirable for high performance, designers were limited to systems in which several of the elements were cemented together (*top*) to eliminate the reflections that normally occur at air-to-glass surfaces. Because the cemented surfaces had to have the same curvature, the designer had fewer degrees of freedom with which to reduce aberrations. The lenses were also costly to manufacture. For many purposes Gaussian designs with fewer elements (*middle*) were nearly as satisfactory. Today antireflection coatings make air-spaced systems of many elements feasible (*bottom*), so that highly corrected, large-aperture (fast) photographic lenses are available at moderate cost.

than their full aperture. Spherical aberration applies only to the images of object points lying on the optical axis of a lens. It may vary with the distance from the lens of the object point *O*.

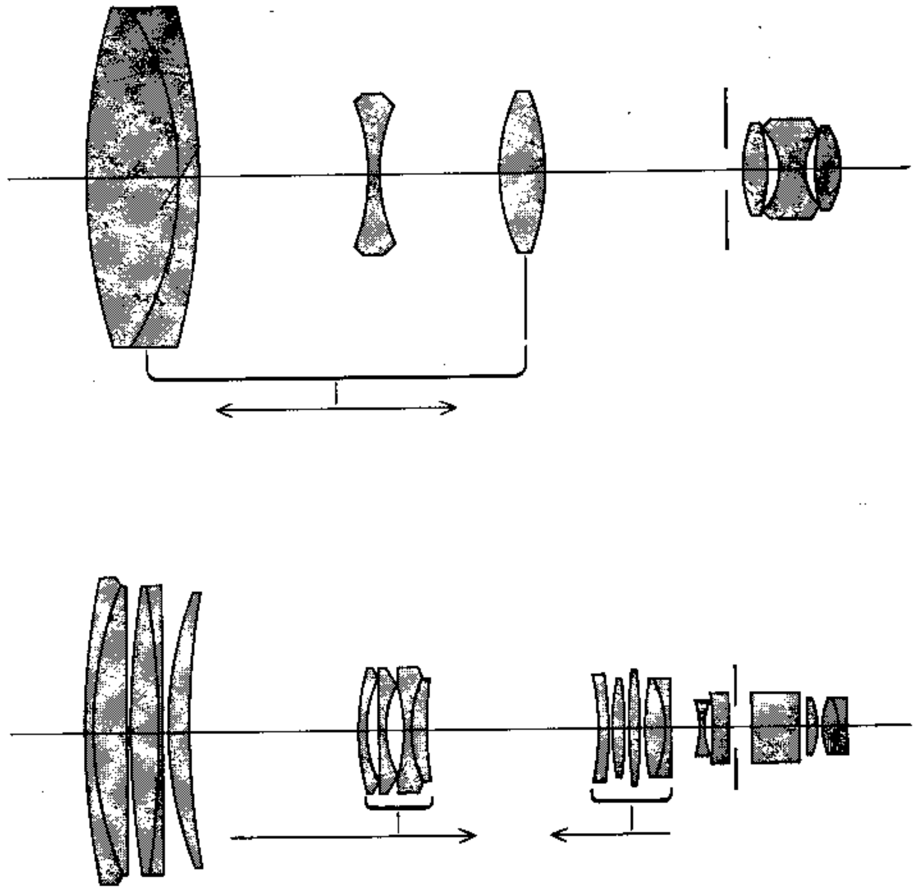
The exact position of any of the infinite number of possible aberrant rays on dimension h is found by solving the equation $h = ay^3 + by^5 + cy^7 \ldots$ The coefficients $a, b, c \ldots$ are found by tracing several rays at various apertures, y, to calculate the specific values of h, then solving the resulting simultaneous equations in $a, b, c \ldots$ The values differ with each lens design. Once the values are derived for a few magnitudes of y, they hold for all intermediate magnitudes of y, and therefore they comprehensively describe all the aberrant light in the image.

The reader may wonder why only odd-numbered exponents appear in the equation. The first-order exponent, y^1, is absent because it represents nonaberrant light that converges exactly at *I*. All even-numbered terms are absent because regardless of whether y is positive or negative, y^2, y^4 and so on would all be positive. Image formation, however, is symmetrical. Even-numbered terms drop out because they implicitly contradict symmetry.

For lenses of small aperture and small field the higher-order terms tend to be small. If the aberrations represented by the third power of the aperture and the field are corrected, most of the light energy is concentrated in the image point. The first practical formulas for calculating the third-order values of the primary aberrations were published by Seidel 120 years ago. Canceling out lower-order aberrations does not necessarily reduce aberrations of higher order, but they nonetheless tend to be reduced. And if they are reduced, a very good lens results.

The great virtue of the Cooke triplet is that it contains the smallest number of elements by means of which all seven of the third-order aberrations can be eliminated. The seven are spherical aberration, coma, astigmatism, distortion, curvature of field and two chromatic aberrations (along two axes, longitudinal and lateral). Besides controlling these aberrations the lens designer must deal with one more variable, the focal length of the lens, which determines the magnification.

Faced with eight dependent variables (seven aberrations and the focal length), the designer must have at least that many independent variables under his control or he is helpless to effect a solution. For a given selection of glasses the independent variables, or degrees of freedom, available to the designer of a three-element lens are as follows. There are two separations: the distance from the first element to the second and from



"ZOOM" LENSES, which can vary the magnification of the image over a considerable range, also became practical with the advent of antireflection coatings. The seven-element zoom lens at the top, designed in the early 1960's for eight-millimeter motion-picture cameras, has a relative aperture of *f*/1.9 and provides a continuous range in focal lengths from 10 to 30 mm. The first and third components move together to achieve the threefold change in focal length while simultaneously keeping the image focused on the film. The zoom lens at the bottom provides a 20-to-one range in focal length, a range widely used in television. The second and third groups of elements are moved in opposite directions nonlinearly to produce the zoom and maintain focus. Large number of elements are required to control lens aberrations over long zoom range.

the second to the third. For each of the three elements the designer can choose the power, or magnification. Finally, each lens element has one independent surface of curvature. (The other is fixed by the choice of the first curvature and the power.) Thus, given enough experience and time, the designer can in principle find some combination of the eight variables in a Cooke triplet that will eliminate all third-order aberrations.

The second century of the photographic lens has seen a different line of progress. In 1927 George W. Morey of the Geophysical Laboratory of the Carnegie Institution of Washington realized that the formulation of optical glass was a field dominated by tradition. He was convinced that many potentially interesting formulations remained to be explored, although he was not sure what new properties might be most useful. He approached Charles W. Frederick, the chief lens designer of the Eastman Kodak Company. Frederick was interested. To answer Morey's question Frederick's department designed a number of lenses incorporating hypothetical (and unobtainable) glasses. Morey and Frederick came to the conclusion that what was really needed was a glass with both low dispersion and a refractive index much higher than that of any glass then available.

Toward the end of 1932 Kodak signed a contract with Morey. He was to experiment in the basement of his home to try to make glass of the required type. Morey's samples showed that he was making progress in the right direction, but his glass was much too dark for lenses. Although he was unable to reduce the coloration, he did arrive at the sought-after values of refraction and dispersion. To make his all but opaque glass Morey used boric oxides and the rare-earth element lanthanum.

The Kodak Research Laboratories set up a small pilot plant to determine the cause of the coloration and to eliminate it. Analysis indicated that it was due to impurities, mostly metal oxides, introduced in the making of the glass. Using a platinum crucible to make the glass eventually reduced the coloration to yellow, which was bad for many lenses but was quite acceptable for the lenses used by the U.S. in aerial-reconnaissance cameras during World War II. The yellow eliminates some of the effects of atmospheric haze.

Continued research on chemical purification removed the last vestige of color by reducing the impurities in the glass to the level of less than one part per billion. For some glasses this required a gold crucible rather than a platinum one. These glasses came to be known as EK glasses after their prefixes in the Kodak catalogue. The hypothetical lens designs had been prophetic. Today all manufacturers of optical glass make rare-earth glasses. At least one lens element of such glass is employed in practically every high-performance photographic objective made in the world.

Almost predictably, the new rare-earth glass created a new problem even as it solved many old ones. Since internal reflection in a lens increases with the lens's refractive index, the new lenses were more susceptible to flare, or non-image light. Flare has more effect on photography than one might think. It destroys information and is therefore analogous to noise in a communications system.

It had been known since 1936 that a thin coating of transparent material on the surface of a lens could counteract flare, and that for any one wavelength such a coating could in fact eliminate flare entirely. The coating materials had to have a refractive index equal to the square root of the refractive index of the lens and had to be applied with a thickness of a quarter of the given wavelength. Such a coating not only cancels out reflection of that wavelength but also increases the transmission of light through the lens.

Repeated attempts to coat the surface of glass chemically with a thin film were inconsistent and unsatisfactory. The key was turned in 1936 when John D. Strong of the California Institute of Technology reported success in evaporating a film of fluorite (calcium fluoride) on glass in a vacuum. The first fluorite coatings did not adhere well, however. They were soft and rubbed off easily. The problem was solved by heating the lens during the deposition of the coating to drive off impurities. For virtually all applications fluorite has now been supplanted by more durable coatings of magnesium fluoride.

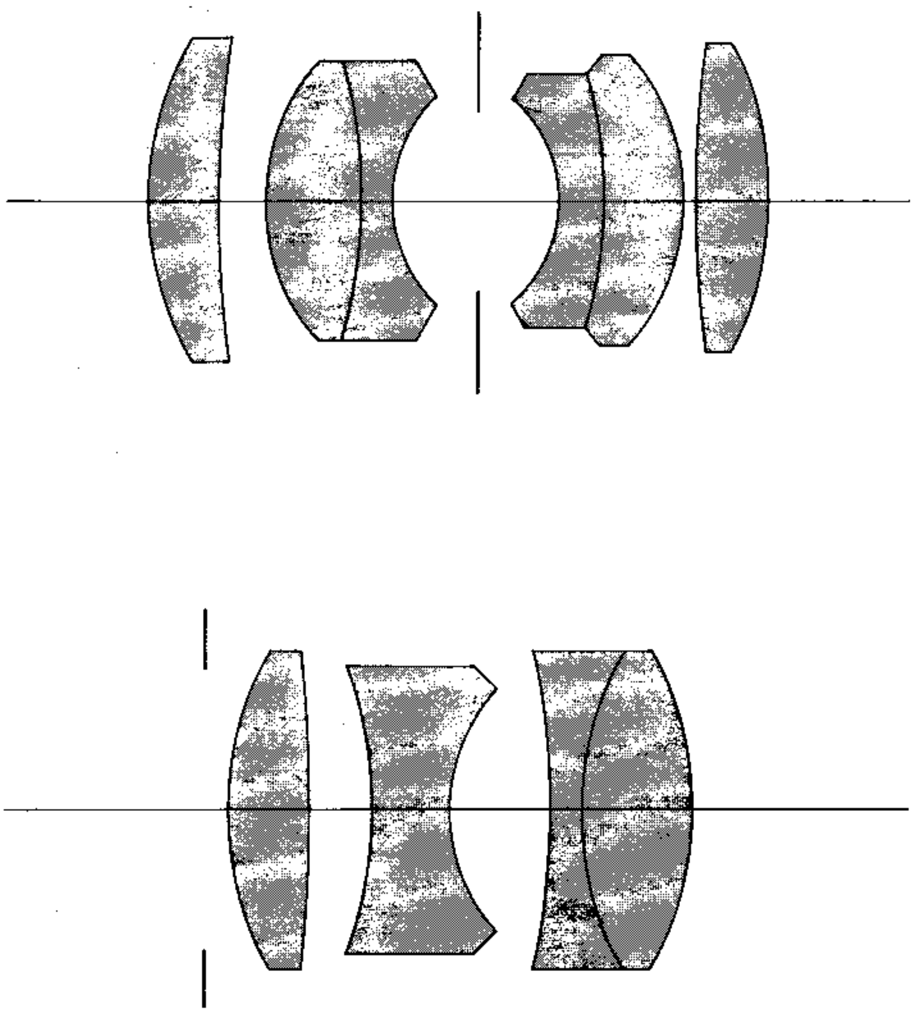
Among the lenses that lens coating and rare-earth glass made practical was the "zoom" lens, which had first appeared in the early 1930's. (The Busch Vario-Glaukar of 1931 was the first.) Zoom lenses have grown from the early seven-element configurations with a zoom ratio of three to one to today's 20-to-one lenses used in telecasts of sports events to carry the viewer from the tee to the green or from a close-up of the quarterback to a view of the entire play. These lenses contain 20 or more elements and are equipped with motor-driven zoom, focus and aperture controls.

Given relative freedom from flare, designers of high-performance lenses could abandon an expensive path they had long trod. To avoid flare they had been creating lenses with many elements and perfectly mated surfaces that were cemented together to minimize interfaces between glass and air. They could now design lenses of the Gauss type, which exploit glass-air interfaces. A Gauss lens may have as few as four elements but it has at least eight such interfaces. No mating is required because air conforms perfectly to any curved surface. Moreover, for every two elements separated the lens designer acquires another independent variable to work with. Today practically all the fastest camera lenses (of *f*/2 or lower) use air-spaced elements.

New process-control techniques have made it possible to deposit high-efficiency antireflection coatings consisting of multiple layers to minimize reflection over the entire visible spectrum. For several years devices and techniques developed by the Optical Coating Laboratory, a California company, have been widely used in Japan to make multiply coated camera lenses.

Once a water white rare-earth glass was achieved, attempts to make low-dispersion glasses with a high index of refraction were not forgotten. Whereas in the 1930's the aim was to get a low-dispersion glass with a refractive index of 1.75 (as compared with a value of 1.62 for high-index crown glass), in the 1970's optical-glass manufacturers succeeded in making experimental glass with a refractive index of 2.01 and relatively low dispersion.

The Kodak glass plant is now able to make economical production melts of water white, relatively low-dispersion glass with an index of 1.95 to 2.0. This unique material has given lens designers the freedom to create more effective lenses without incurring prohibitively high manufacturing costs. One application lies in increasing the aperture of a camera lens to make it possible to take color pictures at light levels that are lower than those currently practical without long exposures or flash. A lens aperture of *f*/1.9 is desirable. Heretofore *f*/1.9 lenses of suitable quality required at least six elements. The new glass makes it possible to produce an *f*/1.9 lens of the same quality with four elements [*see illustration on this page*]. Many more people should be able to afford the four-element lens when it reaches the market in the near future than can now afford a six- or seven-element lens.



NEW HIGH-INDEX GLASSES enable designers to reduce the number of elements needed to achieve a given level of freedom from aberration. The two lens configurations shown here are both *f*/1.9 and yield images of equivalent quality. In the six-element Gaussian lens the refractive index of the elements ranges from 1.6 to 1.75. In the four-element Tessar lens the refractive index of elements ranges from 1.9 to 1.95. An added benefit of the compact Tessar design is that the aperture stop, or the diaphragm, of the camera can be located in front of the lens, thus making it possible to align the four elements of the lens precisely in a single mount.

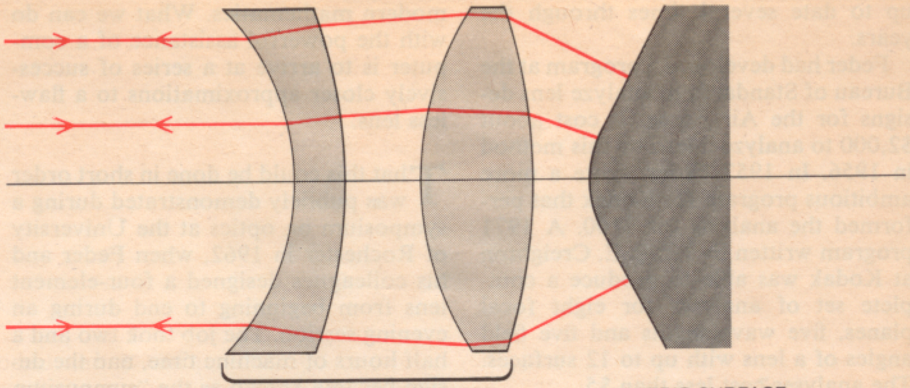
In an early effort to reduce costs camera-lens manufacturers experimented in the 1930's with lenses made of plastics. With the compression-molding techniques of that time it was not possible, however, to achieve the mirror-smooth surfaces required. Although satisfactory lenses could be made by casting, the process was too slow and expensive. Ultimately injection molding proved to be more promising than either of the other methods. In 1952 viewfinder lenses made of molded transparent plastic were introduced in box cameras. This success led by 1957 to the use of plastic for some of the simplest camera lenses, and by 1959 triplet lenses were being made by injection molding. That was no mean achievement, since several difficult problems had to be overcome.

One problem with plastic lenses is thermal change. The lenses are less dense and their index of refraction is lower in warm weather than it is in cold. At Kodak we puzzled over this for some time. We found we could design the lenses so that as one element changes with the heat to shift the focus to the rear, a compensating element changes with the heat to shift the focus forward by an exactly corresponding amount.

A more insidious problem was that of achieving a strain-free lens element. Strain in a lens has unwelcome optical properties. What is more, the strain in plastic is eventually relieved by thermal cycling (as happens, for example, in cold weather when a camera is moved from indoors to outdoors and back again). As the strain diminishes with many such cycles, the dimensions of the lens change enough to ultimately degrade its image.

We tried every kind of steel mold. None would yield a strain-free product. Finally we found a special ceramic that can be polished to the required high luster and has heat-transfer characteristics that make it possible to fabricate a lens element that is free of strain. This technique has also made it practical to coat plastic lenses to reduce reflections, just as is done with glass lenses.

Meanwhile we have continued to study the molding process and have modeled it mathematically with the intention of getting closer tolerances. We are now able to hold tolerances through the center of a lens of 1/1,000 inch and across the diameter of a lens of 1/10,000 inch. We can also hold surface-contour tolerances of 1/200,000 inch during 30,000 molding cycles. Since as many as 16 lenses are molded in each cycle, we can produce 500,000 lenses before a mold has to be reconditioned.



TESTING OF ASPHERIC SURFACES, recently introduced in some lenses, creates special problems. One testing scheme uses an optical null corrector, which converges an entering parallel beam of light (one with a plane wave front) into a beam with an aberrated wave front that conforms to the aspheric surface. Hence light reflected from the aspheric surface retraces the incoming path and emerges from the null corrector as a plane wave again. The unit is placed in one arm of an interferometer. Any departure of the aspheric surface from the desired shape shows up in the interferometer image as a deviation of the emerging wave front from a plane.

The spherical surface of a lens is only an approximation of the ideal surface. In a reflecting telescope the ideal mirror has a parabolic section. Perfect lenses would have a surface of rotation slightly more complex than that. Aspheric, or nonspherical, refraction optics have been in use since Bernhard Schmidt somewhat accidentally discovered in 1930 a manual technique for making an aspheric correcting lens to work in conjunction with a spherical telescope mirror. The process, still in service today, uses the surface tension of glass to retain a smooth polish when a plate is heated and allowed to sag into a mold. The surface that goes against the mold will be poor and is subsequently ground and polished flat, but the free surface retains its original high polish in its "sagged" contour. The result was the wide-field Schmidt telescope. Apart from this application, however, aspheric lens elements are available commercially only in certain professional motion-picture camera lenses and in some half a dozen lenses for 35-millimeter cameras. The 35-mm. camera lenses, one made in West Germany and the others in Japan, have speeds of up to *f*/1.2 and retail for about $1,000. High cost has put aspheric lenses out of reach for most nonprofessional photographic purposes.

Aspheric molds for plastic lenses promise to change that. We have now developed practical techniques of making aspheric molds for plastic lenses with the precision and repeatability required for photographic lenses. So far lenses with one aspheric surface on a plastic element are able to gather twice as much light (that is, they are one full *f* stop larger) as an all-spherical lens comparable in quality and number of elements. The testing of aspheric surfaces has required the development of new techniques. In one such technique a lens called an optical null corrector converts a parallel beam of light into an intentionally distorted, or aberrated, wave front that is directed at the aspheric lens surface to be tested. If the test surface has the proper aspheric curvature, it reflects the aberrated incident light in such a way that when the light passes through the optical null corrector, the parallel plane wave front is restored. Placed in an interferometer, the aspheric surface can now be tested in the same way that a spherical or plane surface is.

With injection molding we have found it possible, and sometimes preferable, to mold a plastic mount directly onto a ground, polished and coated glass lens element. Mounting problems present some of the severest trials of glass lens manufacture. Injection molding provides a degree of exactness and repeatability in lens assembly that is not otherwise economic.

As matters now stand, glass is superior to plastic in dimensional stability, elasticity, hardness and refractive index. Optical plastics are still limited to a few types of polymer, mainly acrylic, styrene and styrene-acrylonitrile. Plastic camera lenses, which we now confidently predict can be mass-produced with aspheric surfaces, will require fewer elements for the same results and will offer the possibility of higher-order correction.

An alternative to aspheric surfaces for correction of the limitations of spherical surfaces is gradient-index glass. As we have seen, spherical aberration is typical of these limitations. The spherical surface is too strong at the edge. This may be overcome by asphering one surface to make it weaker toward the edge, or alternatively lowering the refractive index toward the edge. Research on gradient-index glass is being actively pursued at the Institute of Optics of the University of Rochester in cooperation with Bausch & Lomb Inc. At the Kodak Research Laboratories gradient-index plastics are under development, and research on the mathematics required for the design of gradient-index lenses is in progress. Since light in a gradient-index medium does not travel in a straight line, the mathematical calculation of the light path and the wave-front contour becomes significantly more complex. Attending these developments is the need for specifications, tolerances, testing techniques and the manufacturing control of the gradients. Although this field is now in its infancy with respect to photographic lenses there seems to be room in the future for both aspheric surfaces and gradient refractive index.

My predecessor as the manager of the Optical Design Department at Kodak, Rudolf Kingslake, has often remarked that lens designers may have benefited more than anyone else from the introduction of computing machinery. We certainly would be hard put to calculate our aspheric surfaces and zoom lenses without them.

By 1950 ray-tracing programs had been written for a number of computers, including the IBM card-programmed calculator, the National Bureau of Standards Eastern Automatic Computer and the Harvard Mark I. By 1954 work was under way on the automatic design of lenses at Harvard, at the University of Manchester and at the Bureau of Standards. In 1956 Kingslake hired Donald P. Feder to develop a practical automatic-design program for Kodak. In the beginning we shared the company's business computer, but in time the demand for scientific computing warranted separate facilities. These have been brought up to date several times through the years.

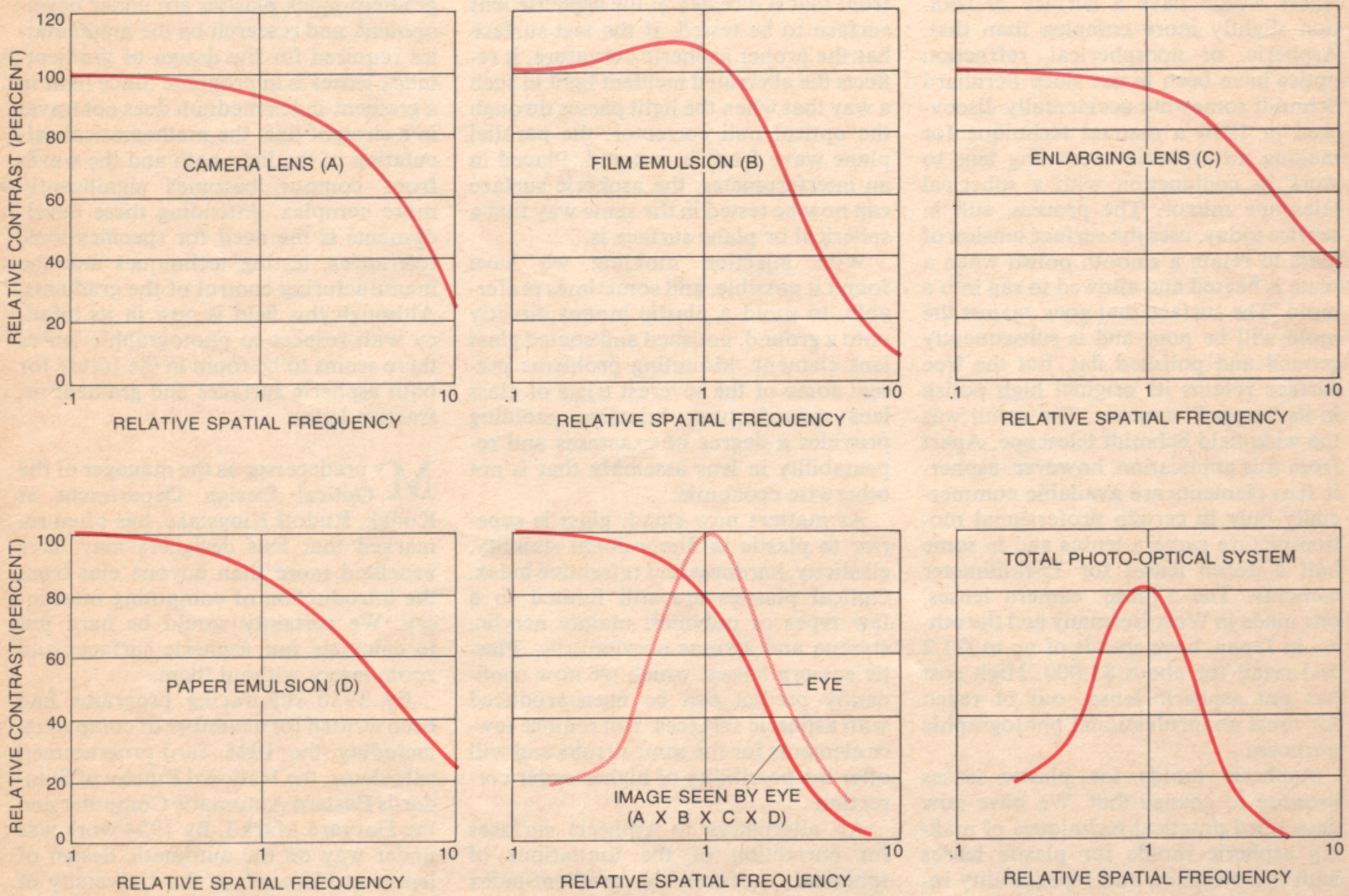
Feder had developed a program at the Bureau of Standards to analyze lens designs for the Air Force. It cost about $2,000 to analyze a lens by this method in 1956. In 1957 Feder wrote a more ambitious program for Kodak that performed the analysis for $100. A 1971 program written by Philip E. Creighton at Kodak was able to produce a complete set of analyses for eight focal planes, five wavelengths and five field angles of a lens with up to 12 surfaces. The analyses cost less than $5.

The real strength of the computer, however, lies not in analysis but in its ability to improve a lens design. The aim is to reduce lens errors to an acceptably small amount. We should like in fact to reduce the errors to their mathematical minimum, but that is not possible because to do so would require solving a large number of simultaneous nonlinear equations with a large number of unknowns. The task is beyond the reach of modern mathematics. What we can do with the powerful assistance of a computer is to arrive at a series of successively closer approximations to a flawless lens.

That this could be done in short order was publicly demonstrated during a symposium on optics at the University of Rochester in 1962, when Feder and his colleagues designed a four-element lens from beginning to end during an evening session. The job took two and a half hours of machine time, and the design became known as the "symposium lens." Feder estimates that present-day computers working with the same program would take a couple of minutes. When it was applied later that year to the improvement of a high-quality microfilm lens that had been designed by hand, the program provided a more precise optical system that was cheaper to manufacture. The day of automatic optical design had arrived.

Since the early 1960's lens-design computer programs have been developed at the University of Rochester and other universities, at lens-manufacturing companies throughout the world and by independent consulting firms such as David Grey Associates, Inc., of Waltham, Mass. There is no longer any doubt that the best of the computer programs will produce results superior to those that can be achieved by precomputer methods. It is estimated that the use of computers has increased the productivity of lens designers tenfold. Moreover, designers are now much more confident than they were in the reliability of their predictions regarding lens performance and manufacture. Part of this confidence stems from a Monte Carlo technique for analyzing the sensitivity of a lens design to cumulative manufacturing variations within the limits of normal process control. The technique makes it possible to decide whether or not a lens can be effectively manufactured.

Professional and advanced amateur



MODULATION TRANSFER FUNCTION of a complete photographic system involves the modulations, or losses, introduced at each step. In this analysis fine details in an image are regarded as variations in light intensity in space in the same way that variations in signal strength with time are regarded by a radio engineer when he is evaluating the performance of radio equipment. At each step in a photographic system fine details (high spatial frequencies) are reproduced with loss of contrast (that is, modulated). These curves are calibrated with the performance of the eye normalized to show peak response (100 percent relative contrast) at a relative spatial frequency of 1. Unlike a lens, the eye degrades the contrast of images that are both lower and higher than 1 in relative frequency. The image seen by the eye is the product of the first four modulation curves (lens times film emulsion times enlarging lens times paper emulsion). The quality of image transmitted to the brain is proportional to area under last curve, which is the product of modulation curves of all stages.

photographers used to argue vigorously over the merits of various lenses, particularly the high-performance lenses made for expensive 35-mm. cameras. Although lenses could be tested objectively with resolution charts, it was generally recognized that resolving power alone (defined as the number of high-contrast lines per millimeter that a lens can resolve in various parts of the image field at various apertures) is a surprisingly unreliable guide to the quality of pictures a lens might produce. Much of the mystery surrounding lens "quality" was cleared up in 1951 when Otto H. Schade, Sr., of the Radio Corporation of America described his investigations of the lenses used in the entire chain of information transmission represented by a television system. Schade was able to show that the recording of fine detail was not necessarily related to the general efficiency of information transfer. His most surprising result was that some highly rated lenses were not as good for television purposes as lenses that were thought to be inferior.

Schade's investigations added a dimension to the Rayleigh definition of image quality. The Rayleigh criterion is now seen as being a limiting case: it locates one end of the quality continuum. It tells us when a lens is approaching perfection but does not tell us which of two imperfect lenses is the better.

By regarding light-intensity variations in space across the image formed by a lens as the radio engineer regards signal-strength variations in time when he measures the performance of transmitters, receivers and amplifiers, Schade was able to apply information theory to lenses and to provide for them an "optical transfer function." The fact that the transfer function coincides rather well with criteria that lens designers have been using for generations is an indication of its validity. Even more important, the transfer function of a lens can be combined with the transfer function of film, of photographic printing devices, of projection lenses and so on. The transfer function can be computed for the lens design and also measured on the manufactured lens. Hence with the computer we can mathematically model the entire photographic system, beginning with the subject and ending with the transfer function of the viewer's eye.

The comparison of such objective calculations and measurements with people's subjective reactions to the corresponding photographic results tells us, in terms of design requirements, just what constitutes a better picture. Such conceptual models have greatly helped the photographic industry in deciding just where to concentrate its research-and-development efforts, thus improving the ratio of quality to cost for people who make pictures.