

4-STEP CHART TEST

- While not wearing glasses, hold the test chart 14" away from your eyes and begin reading the words.
- Stop at the word where reading becomes difficult.
- Try on a pair of DR. DEAN EDELL READERS marked with the magnification power shown above the word where you stopped reading.
- The strength of the glasses is right for you if you can clearly read the remainder of the words on the chart.

TEST CHART

+3.25 12		+3.25 +3.00 +2.75 12-14
YOUR		EYES
+2.75 +2.50 14-16	+2.50 +2.25 16-18	+2.25 +2.00 18-20
ARE	PRECIOUS.	GIVE
+2.00 +1.75 20-22	+1.75 +1.50 22-26	+1.50 +1.25 26-32
THEM	ONLY	BEST

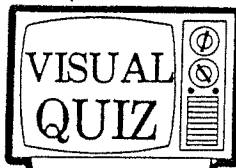


Dr. Dean Edell
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ASK???

Dr. Dean Edell



- When reaching the age of 50 or older, what percentage of people who never required glasses now need reading glass assistance?
 - 20%
 - 40%
 - 70%
 - Almost all
- When a 40 to 50 year old person with previously normal vision cannot see close, it is called:
 - Myopia
 - Tapioca
 - No eye focus
 - Presbyopia
- High pressure in the eye is called:
 - Cataracts
 - Glaucoma
 - Ceryuirticulis
 - Eyeoma
- What is a good lens color when purchasing sunglasses?
 - Green
 - Neutral Gray
 - Brown
 - All of the above

YOUR EYES ARE
PRECIOUS!
GIVE THEM ONLY
THE BEST



IF YOU HAVE TROUBLE READING THE
ANSWERS TO MY VISUAL QUIZ FROM 14"
AWAY FROM YOUR EYES - TRY ON A PAIR OF
DR. DEAN EDELL OPTICAL READERS

THE ANSWER IS "D"

ALMOST ALL

As we grow older, the lens of the eye becomes less elastic, so that the muscles which adjust the lens have more and more trouble focusing properly. Therefore, people past forty years of age who have never worn glasses previously may be required to wear lenses to focus on ordinary print.

THE ANSWER IS "D"

PRESBYOPIA

Presbyopia is caused by a hardening of the crystalline lens that robs the lens of its ability to properly focus light passing through the eye.

THE ANSWER IS "B"

GLAUCOMA

In this condition pressure within the eyeball brings about loss of sight. Interference occurs with the circulation of the fluid that comes into the eye. The accumulation of this fluid causes pressure.

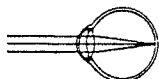
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ALL OF THE ABOVE

Green, neutral gray and brown lens shades are soothing to the eye while providing protection.

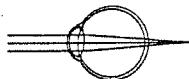
WHY DO YOU NEED READING GLASSES?

After the age of 35, blurred close-up vision is an almost universal problem. This is a perfectly normal condition called PRESBYOPIA (a Greek wording meaning "old sight").



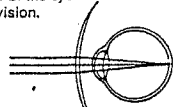
NORMAL EYE

Lens of the eye focuses light directly on the retina - at the back of the eye - producing focused clear vision.



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Lens of the eye focuses in back of the retina - causing blurred vision.



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By the use of simple and safe magnification - the light is bent in the lens itself and directed to the retina - IN FOCUS.

CORRECT PRESBYOPIA WITH DR. DEAN EDELL MAGNIFYING READERS

The solution is surprisingly easy and economical - DR. DEAN EDELL MAGNIFYING READERS. Available in 10 powers of magnification in optical quality frames.

THE ADVANTAGES OF DR. DEAN EDELL MAGNIFYING READERS

- Optically correct lenses provide the sharpest vision possible.
- Lens centering - places the optical center directly along the line of sight.
- Durable fashion frames - optical quality materials assures durability and long life.
- 10 powers of magnification to choose from in every style - makes it easy to select the right frame and power of magnification for you.
- Dr. Dean Edell magnifying readers represent high quality with value at reasonable prices.

DO I NEED TO SEE THE DOCTOR?

It should be emphasized that ready-to-wear glasses are not intended to replace examinations by an eye doctor. Continuous eye checkups, especially after the age of 35, will maintain the health of your eyes.

USES FOR DR. DEAN EDELL MAGNIFYING READERS

READING - Books, road maps, prescriptions, dictionaries, menus, want ads and telephone books.

FOCUSING ON - Hobbies, crafts and close work.

IT'S EASY TO SELECT THE POWER THAT IS RIGHT FOR YOU

	POWER OF MAGNIFICATION	DIOPTERS
MILD POWER	40	+1.00
	32	+1.25
	26	+1.50
MEDIUM POWER	22	+1.75
	20	+2.00
	18	+2.25
	16	+2.50
HIGH POWER	14	+2.75
	13	+3.00
	12	+3.25

SEE THE TEST CHART ON BACK

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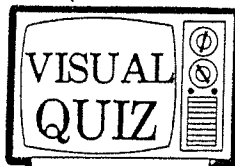
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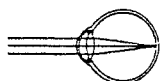
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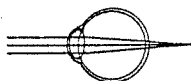
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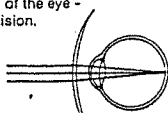
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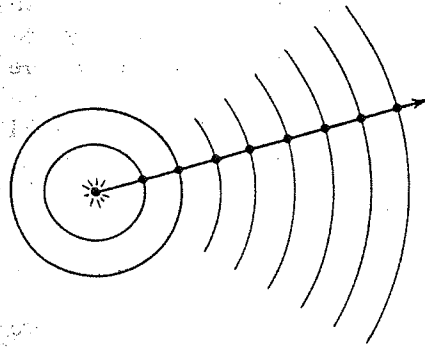


Figure 1.3 Light waves radiating from a point source in an isotropic medium take a spherical form; the radius of curvature of the wave front is equal to the distance from the point source. The path of a point on the wave front is called a light ray, and in an isotropic medium is a straight line. Note also that the ray is normal to the wave front.

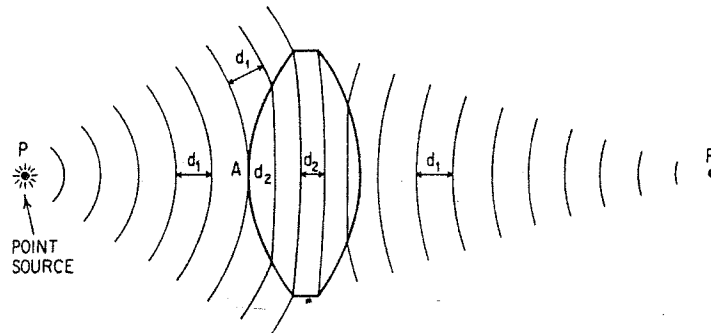


Figure 1.8 The passage of a wave front through a converging, or positive, lens element.

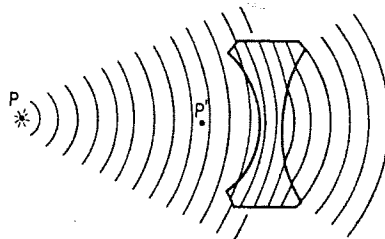


Figure 1.9 The passage of a wave front through a diverging, or negative, lens element.

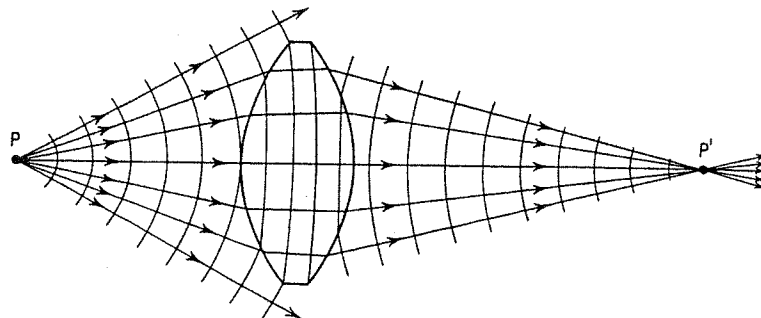


Figure 1.10 Showing the relationship between light rays and the wave front in passing through a positive lens element.

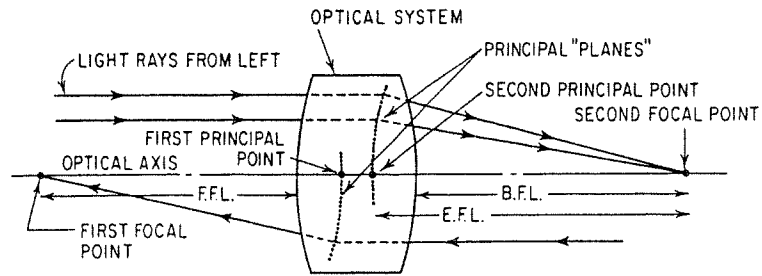


Figure 2.1 Illustrating the location of the focal points and principal points of a generalized optical system.

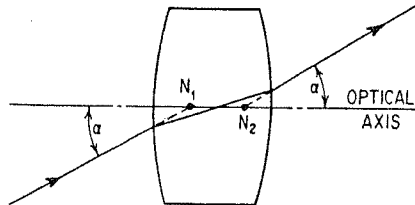


Figure 2.2 A ray directed toward the first nodal point (N_1) of an optical system emerges from the system without angular deviation and appears to come from the second nodal point (N_2).

Stops and Apertures

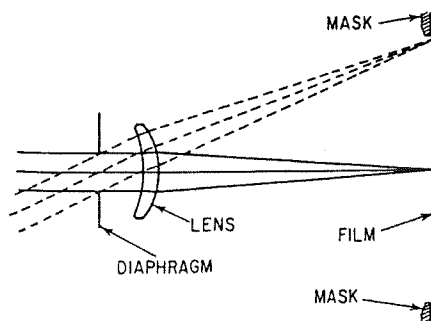


Figure 6.1 The elements of a simple box camera illustrate the functions of elementary aperture and field stops (the diaphragm and mask, respectively).

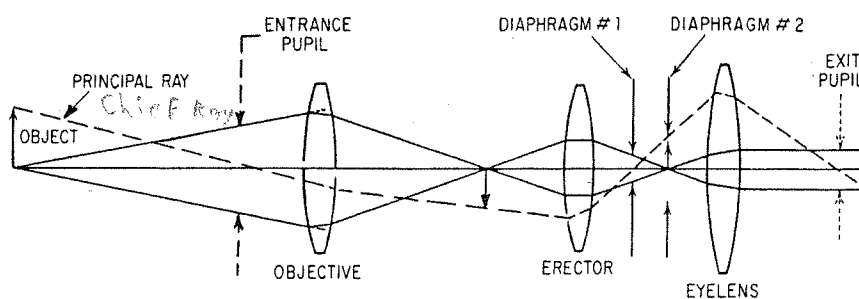


Figure 6.2 Schematic sketch of an optical system to illustrate the relationships between pupils, stops, and fields.

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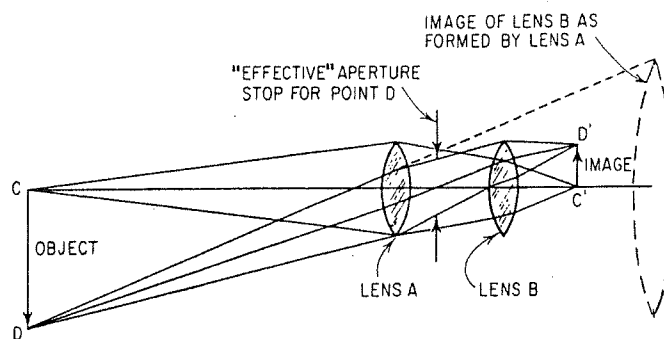


Figure 6.3 Vignetting in a system of separated components. The cone of rays from point D is limited by the lower rim of lens A and the upper rim of B , and is smaller than the cone accepted from point C . Note that the upper ray from D just passes through the image of lens B which is formed by lens A .

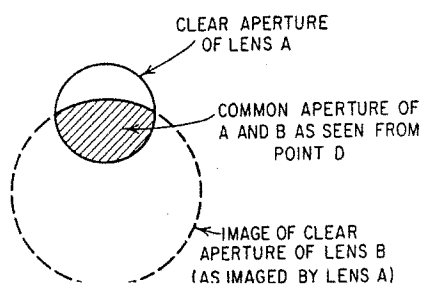


Figure 6.4 The apertures of the optical system of Fig. 6.3 as they are seen from point D .

Not all systems are as obvious as the box camera, however, and we will now consider more complex arrangements. Because the theory of stops is readily explained by the use of a concrete example, the following discussions will be with reference to Fig. 6.2, which is a highly exaggerated sketch of a telescopic system focused on an object at a finite distance. The system shown consists of an objective lens, erector lens, eyelens, and two internal diaphragms. The objective forms an inverted image of the object. This image is then reimaged by the erector lens at the first focal point of the eyelens, so that the eyelens forms the final image of the object at infinity.

6.2 The Aperture Stop

By following the path of the axial rays (designated by solid lines) in Fig. 6.2, it can be seen that diaphragm #1 is the aperture of the system which limits the size of the axial cone of energy from the object. All of the other elements of the system are large enough to accept a bigger cone. Thus, diaphragm #1 is the aperture stop of the system.

The oblique ray through the center of the aperture stop is called the *principal*, or *chief*, ray, and is shown in the figure as a dashed line. The *entrance* and *exit pupils* of the system are the images of the aperture stop in object and image space, respectively. That is, the entrance pupil is the image of the aperture stop as it would be seen if viewed from the axial point on the object; the exit pupil is the aperture stop image as it would be seen if viewed from the final image plane (in this case, at an infinite distance). In the system of Fig. 6.2, the entrance pupil lies near the objective lens and the exit pupil lies to the right of the eyelens. Notice that the initial and final intersections of the dashed principal ray with the axis locate the pupils, and that the diameter of the axial cone of rays at the pupils indicates their diameters. It can be seen that, for any point on the object, the amount of radiation accepted

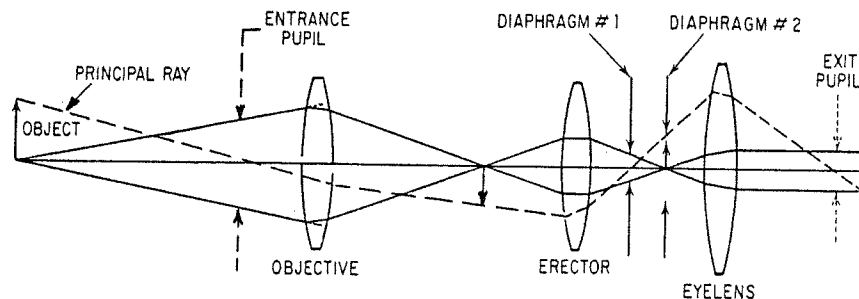


Figure 6.2 Schematic sketch of an optical system to illustrate the relationships between pupils, stops, and fields.

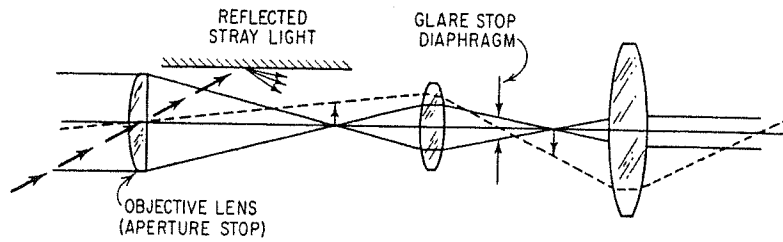


Figure 6.6 Stray light, reflected from an inside wall of the telescope, is intercepted by the glare stop, which is located at the internal image of the objective lens.

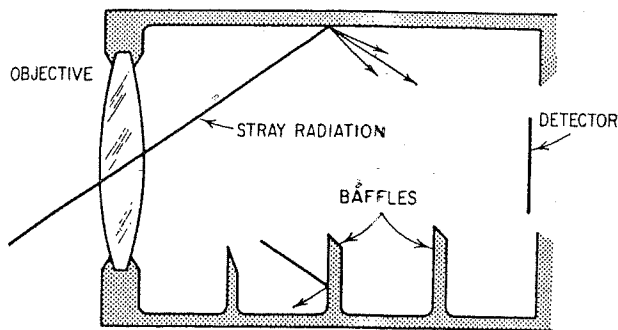


Figure 6.7 Stray (undesired) radiation from outside the useful field of this simple radiometer can be reflected from the inner walls of the housing and degrade the function of the system. Sharp-edged baffles, shown in the lower portion, trap this radiation and prevent the detector from "seeing" a directly illuminated surface.

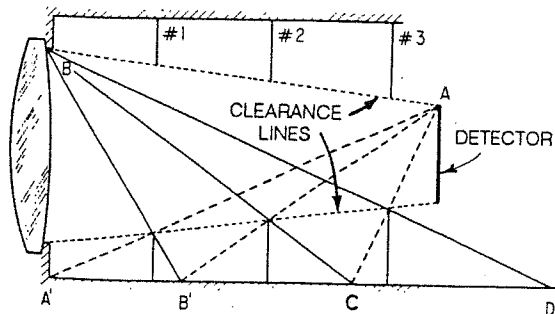


Figure 6.8 Construction for the systematic layout of baffles. Note that baffle #3 shields the wall back to point D; thus, all three baffles could be shifted forward somewhat, so that their coverages overlap.

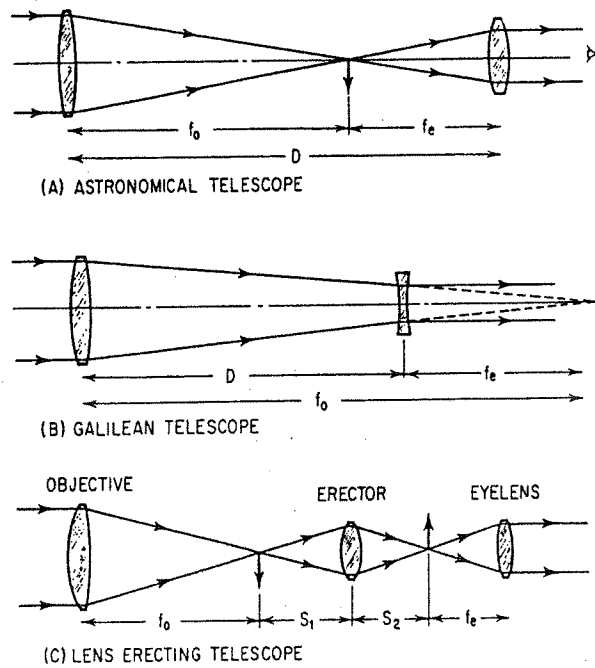


Figure 9.1 The three basic types of telescope.

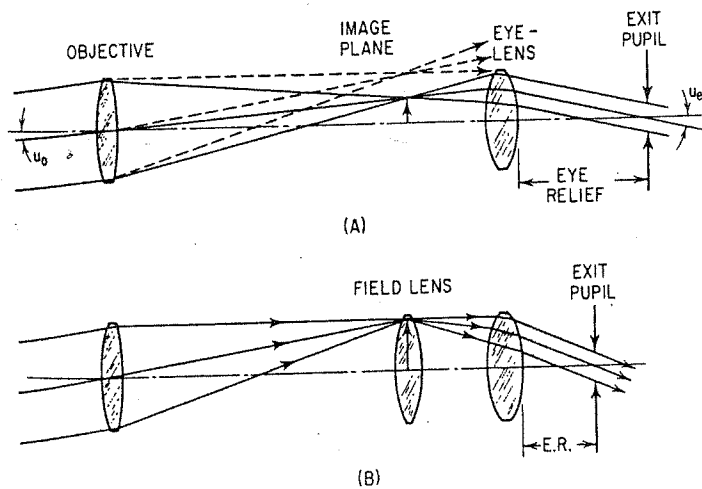


Figure 9.2 The action of the field lens in increasing the field of view.

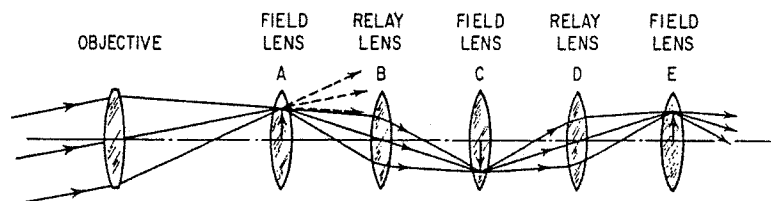


Figure 9.3 A system of relay lenses.

The Eye

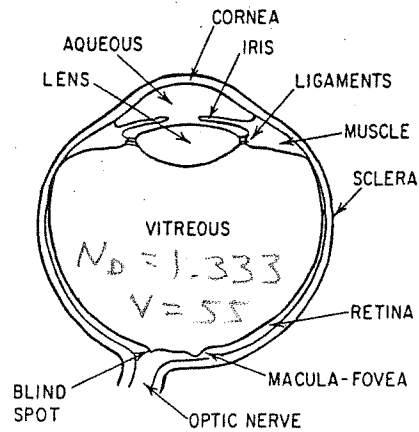


Figure 5.1 Schematic horizontal section of right eyeball (from above).

The following table lists typical values for the radii, thicknesses, and indices of the optical surfaces of the eye. These, of course, vary from individual to individual.

R_1 (air to cornea) + 7.8 mm	t_1 (cornea) 0.6	N_1 1.376
R_2 (cornea to aqueous) + 6.4 mm	t_2 (aqueous) 3.0	N_2 1.336
R_3 (aqueous to lens) + 10.1 mm	t_3 (lens) 4.0	N_3 1.386–1.406
R_4 (lens to vitreous) – 6.1 mm	t_4 (vitreous) 16.9	N_4 1.337

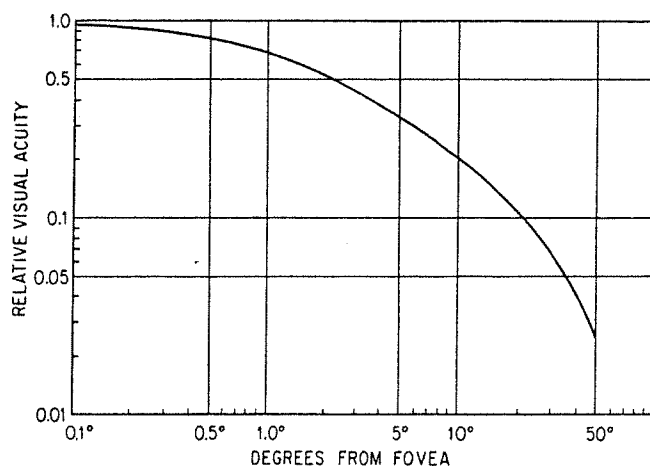


Figure 5.2 The variation of visual acuity (relative to the fovea) with the retinal position of the image. Note that because of the logarithmic scales of the figure, the falloff in visual acuity is far more rapid than the shape of the curve might indicate.

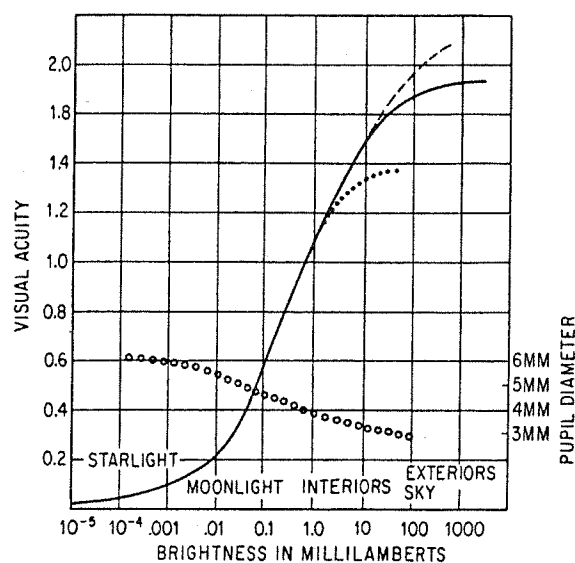


Figure 5.3 Visual acuity as a function of object brightness. Visual acuity in reciprocal minutes. The dashed and dotted lines show the effect of increased and decreased (respectively) surround brightness (1 millilambert is approximately the brightness of a perfect diffuser illuminated by 1 footcandle). The open circle curve indicates the diameter of the pupil; pupil diameters are larger in the young and smaller in the old, especially at lower brightnesses.

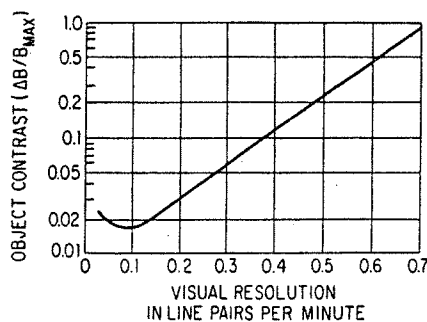


Figure 5.4 The object contrast ($\Delta B/B_{\max}$) necessary for the eye to resolve a pattern of alternating bright and dark bars of equal width. Note that this curve shifts upward in reduced light levels and drops as the light level is increased. For this plot the bright bars had a brightness of $B_{\max} = 23$ foot-lamberts.

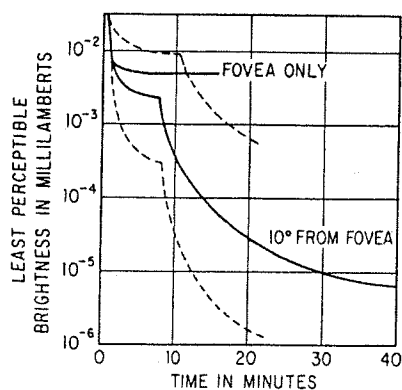


Figure 5.5 The threshold of vision. The minimum brightness perceptible drops sharply with time as the eye adapts itself to darkness. The upper and lower dashed curves show the effect of high and low illumination levels (respectively) before adaptation begins. For areas subtending more than 5° the threshold is almost constant, but rises rapidly as target size is reduced. Curves shown are for a target subtending about 2° .

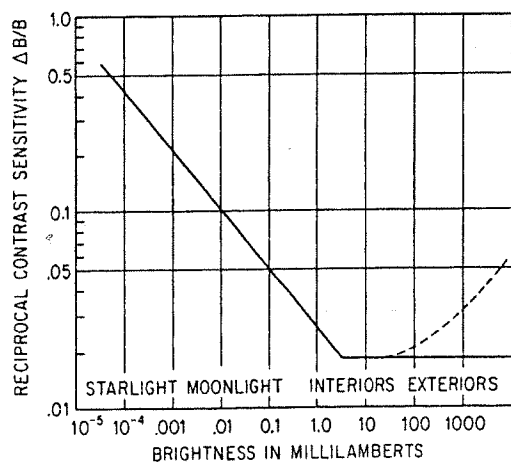


Figure 5.6 The contrast sensitivity of the eye as a function of field brightness. The smallest perceptible difference in brightness between two adjacent fields (ΔB) as a fraction of the field brightness B remains quite constant for brightnesses above 1 millilambert if the field is large. The dashed line indicates the contrast sensitivity for a dark surrounded field. (One millilambert is approximately the brightness of a perfect diffuser illuminated by one footcandle, i.e., one foot-lambert.)

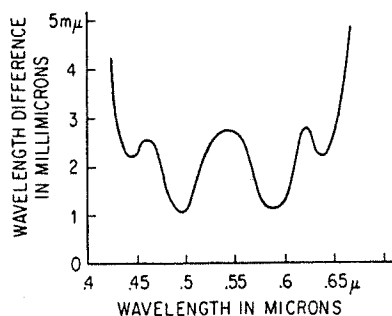


Figure 5.7 Sensitivity of the eye to color differences. The amount by which two colors must differ for the difference to be detectable in a side-by-side comparison is plotted as a function of the wavelength. Some data indicates a more uniform sensitivity of about twice that shown here.

The sensitivity of the eye to light is a function of the wavelength of the light. Under normal conditions of illumination, the eye is most sensitive to yellow-green light at a wavelength of $0.55 \mu\text{m}$, and its sensitivity drops off on either side of this peak. For most purposes the sensitivity of the eye may be considered to extend from $0.4 \mu\text{m}$ to $0.7 \mu\text{m}$. Thus, in designing an optical instrument for visual use, the monochromatic aberrations are corrected for a wavelength of 0.55 or $0.59 \mu\text{m}$ and chromatic aberration is corrected by bringing the red and blue wavelengths to a common focus. The wavelengths usually chosen are either e ($0.5461 \mu\text{m}$) or d ($0.5876 \mu\text{m}$) for the yellow, C ($0.6563 \mu\text{m}$) for the red, and F ($0.4861 \mu\text{m}$) for the blue.

Figure 5.8 shows the sensitivity of the eye as a function of wavelength for normal levels of illumination and also for the dark-adapted eye. Notice that the peak sensitivity for the dark-adapted eye shifts toward the blue end of the spectrum, to a value near $0.51 \mu\text{m}$. This "Purkinje shift" is due to the differing chromatic sensitivities of the rods and cones of the retina, as shown in Fig. 5.8. Figure 5.9 is a tabulation of the values used in plotting Fig. 5.8. Figure 5.10a is a standardized plot of ocular sensitivity which is used in colorimetry determinations. The long-wavelength portion of this curve (Fig. 5.10b) is useful in estimating the visibility of near-infrared searchlights (as used on sniper-scopes, etc.) under conditions where security is desired.

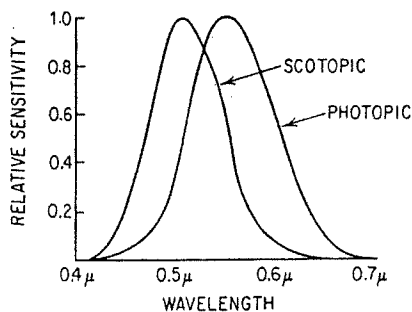


Figure 5.8 The relative sensitivity of the eye to different wavelengths for normal levels of illumination (photopic vision) and under conditions of dark adaptation (scotopic vision).

Wavelength, μm	Photopic	Scotopic	Wavelength, μm	Photopic	Scotopic
0.39	0.0001	0.0022	0.59	0.7570	0.0655
0.40	0.0004	0.0093	0.60	0.6310	0.0332
0.41	0.0012	0.0348	0.61	0.5030	0.0159
0.42	0.0040	0.0966	0.62	0.3810	0.0074
0.43	0.0116	0.1998	0.63	0.2650	0.0033
0.44	0.0230	0.3281	0.64	0.1750	0.0015
0.45	0.0380	0.4550	0.65	0.1070	0.0007
0.46	0.0600	0.5672	0.66	0.0610	0.0003
0.47	0.0910	0.6756	0.67	0.0320	0.0001
0.48	0.1390	0.7930	0.68	0.0170	0.0001
0.49	0.2080	0.9043	0.69	0.0082	0.0000
0.50	0.3230	0.9817	0.70	0.0041	
0.51	0.5030	0.9966	0.71	0.0021	
0.52	0.7100	0.9352	0.72	0.0010	
0.53	0.8620	0.8110	0.73	0.0005	
0.54	0.9540	0.6497	0.74	0.0003	
0.55	0.9950	0.4808	0.75	0.0001	
0.56	0.9950	0.3288	0.76	0.0001	
0.57	0.9520	0.2076	0.77	0.0000	
0.58	0.8700	0.1212			

Figure 5.9 The standard relative luminosity factors (relative sensitivity or response) for photopic and scotopic conditions.

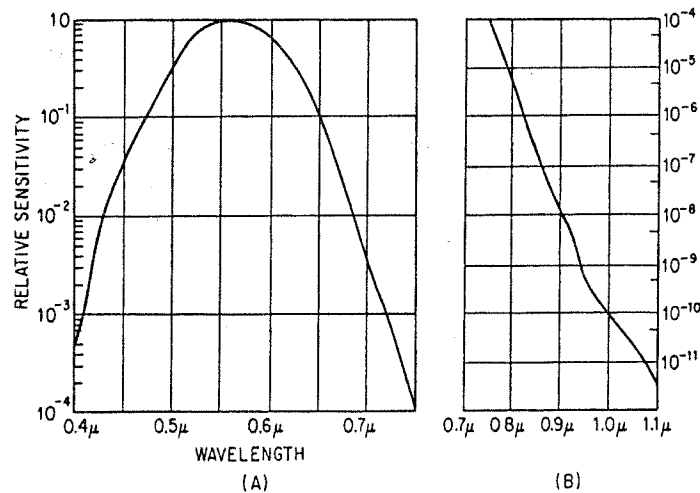


Figure 5.10 (a) Relative sensitivity of a standardized normal eye to light of varying wavelengths. (b) Sensitivity in the near-infrared.

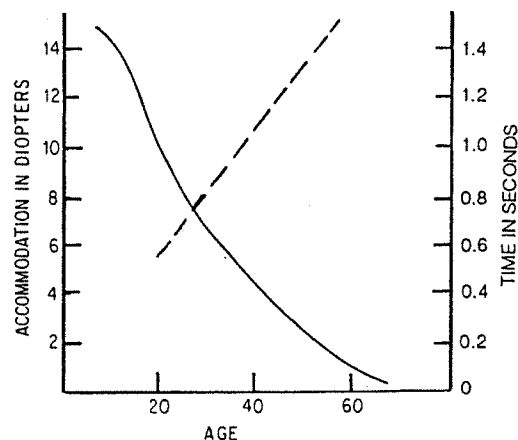


Figure 5.11 The variation of accommodation power with age (solid line). The dashed line indicates the time in seconds to accommodate to 1.3 diopters.

Cauchy
$$N = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} + \dots \quad (7.8)$$

Hartmann
$$N = a + \frac{b}{(c - \lambda)} + \frac{d}{(e - \lambda)} \quad (7.9)$$

Conrady
$$N = a + \frac{b}{\lambda} + \frac{c}{\lambda^{3.5}} \quad (7.10)$$

Kettler-Drude
$$N^2 = a + \frac{b}{c - \lambda^2} + \frac{d}{e - \lambda^2} + \dots \quad (7.11)$$

Sellmeier
$$N^2 = a + \frac{b\lambda^2}{c - \lambda^2} + \frac{d\lambda^2}{e - \lambda^2} + \dots \quad (7.12)$$

Herzberger
$$N = a + b\lambda^2 + \frac{e}{(\lambda^2 - 0.035)} + \frac{d}{(\lambda^2 - 0.035)^2} \quad (7.13)$$

$$N^2 = a + b\lambda^2 + \frac{c}{\lambda^2} + \frac{d}{\lambda^4} + \frac{e}{\lambda^6} + \frac{f}{\lambda^8} \quad (7.14)$$

The dispersion of a material is the rate of change of index with respect to wavelength, that is, $dN/d\lambda$. From Fig. 7.1 and 7.2, it can be seen that the dispersion is large at short wavelengths and becomes less at longer wavelengths. At still longer wavelengths, the dispersion increases again as the long-wavelength absorption band is approached.

For materials which are used in the visible spectrum, the refractive characteristics are conventionally specified by giving two numbers, the index of refraction for the helium d line (0.5876 μm) and the Abbe V -number, or reciprocal relative dispersion. The V -number, or V -value, is defined as

$$V = \frac{N_d - 1}{N_F - N_C} \quad (7.15)$$

where N_d , N_F , and N_C are the indices of refraction for the helium d line, the hydrogen F line (0.4861 μm) and the hydrogen C line (0.6563

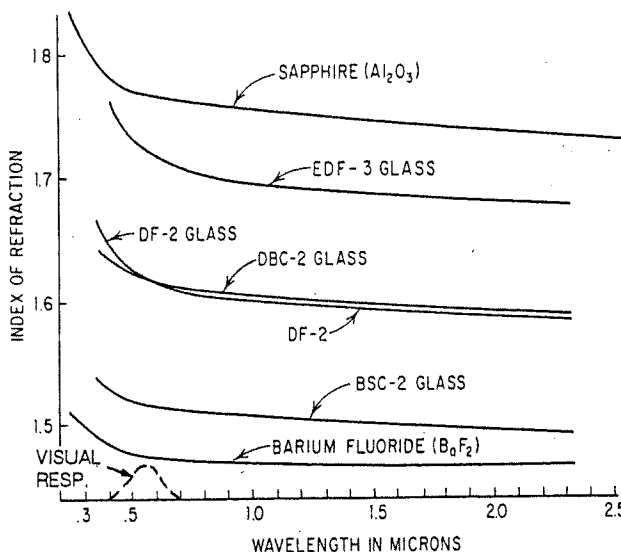


Figure 7.2 The dispersion curves for several optical materials.

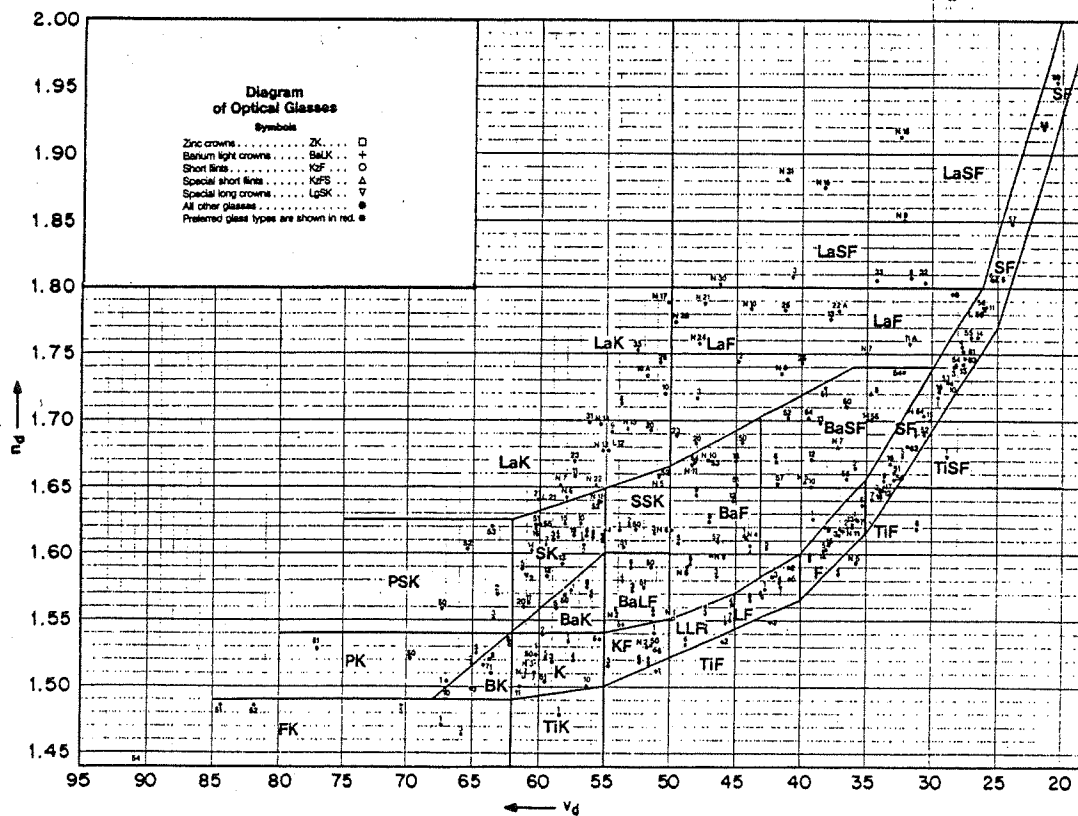


Figure 7.3 The "glass veil." Index (n_d) plotted against the reciprocal relative dispersion (Abbe V-value). The glass types are indicated by the letters in each area. The "glass line" is made up of the glasses of types K, KF, LLF, F, and SF which are strung along the bottom of the veil. (Note that K stands for *kron*, German for "crown," S stands for *schwer*, or "heavy or dense.") (Courtesy of Schott Glass Technologies, Inc., Duryea, Pa.)

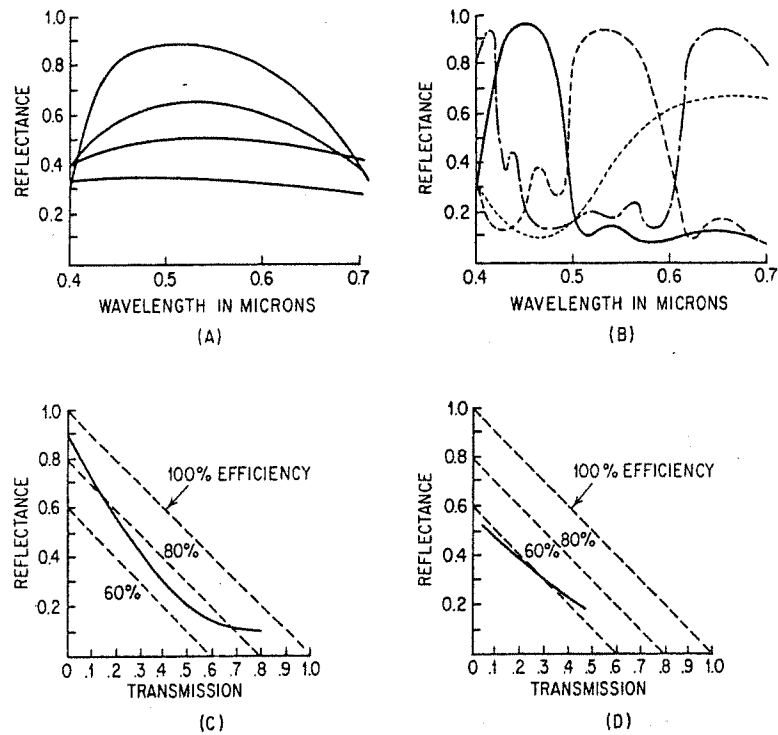


Figure 7.21 Characteristics of partial reflectors. (a) Multilayer "neutral" semi-reflectors (efficiency better than 99 percent). (b) Dichroic multilayer reflectors—blue, green, red, and yellow reflection. (c) Visual efficiency of aluminum semireflectors. (d) Visual efficiency of chrome semireflectors.

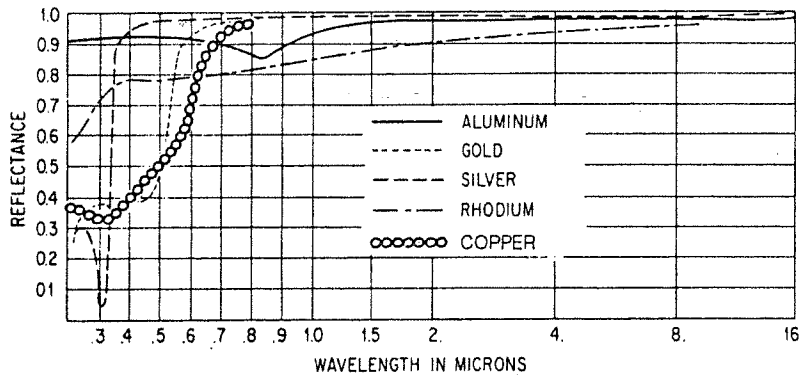


Figure 7.19 Spectral reflectance for evaporated metal films on glass. Data represents new coatings, under ideal conditions.

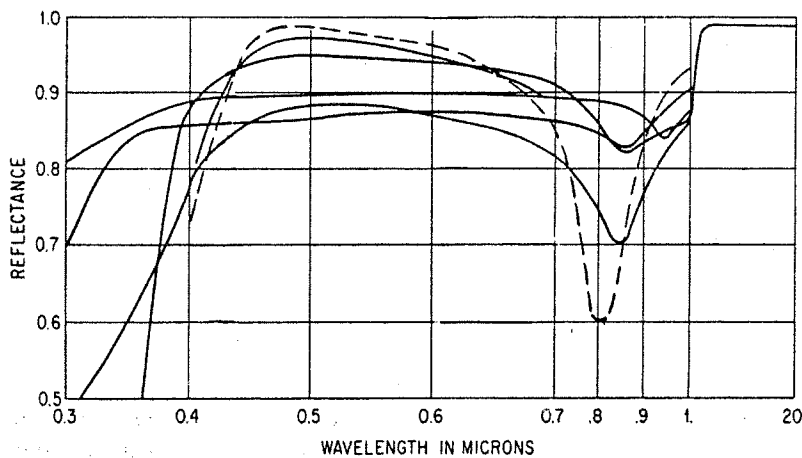


Figure 7.20 Spectral reflectance of aluminum mirrors. The solid curves are for aluminum films with various types of thin film overcoatings—either for protection or for increased reflectivity. The dashed line is an extra-high-reflectance multilayer coating. All coatings shown are commercially available.

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3.2 The Aberration Polynomial and The Seidel Aberrations

With reference to Fig. 3.1, we assume an optical system with symmetry about the optical axis. Because of this symmetry we can, without any loss of generality, define the object point as lying on the y axis; its distance from the optical axis is $y = h$. We define a ray starting from the object point and passing through the system aperture at a point described by its polar coordinates (s, θ) . The ray intersects the image plane at the point y', z' .

We wish to know the form of the equation which will describe the image plane intersection coordinates y' and z' as a function of h, s , and θ ; the equation will be a power series expansion. While it is impractical to derive an exact expression for other than very simple systems or for more than a few terms of the power series, it is possible to determine the general form of the equation. This is simply because we have assumed an axially symmetrical system. For example, a ray which intersects the axis in object space must also intersect it in image space. Every ray passing through the same axial point in object space and also passing through the same annular zone in the aperture (i.e., with the same value of s) must pass through the same axial point in image space. A ray in front of the meridional (x, y) plane has a mirror-image ray behind the meridional plane which is identical except for the (reversed) signs of z' and θ . Similarly, rays originating from $\pm h$ in the object and passing through corresponding upper and lower aperture points must have identical z' intersections and oppositely signed y' values. With this sort of logic one can derive equations such as the following:

$$\begin{aligned} y' = & A_1 s \cos \theta + A_2 h \\ & + B_1 s^3 \cos \theta + B_2 s^2 h (2 + \cos 2\theta) + (3B_3 + B_4) s h^2 \cos \theta + B_5 h^3 \\ & + C_1 s^5 \cos \theta + (C_2 + C_3 \cos 2\theta) s^4 h + (C_4 + C_6 \cos^2 \theta) s^3 h^2 \cos \theta \\ & + (C_7 + C_8 \cos 2\theta) s^2 h^3 + C_{10} s h^4 \cos \theta + C_{12} h^5 + D_1 s^7 \cos \theta + \dots \end{aligned} \quad (3.1)$$

$$\begin{aligned} z' = & A_1 s \sin \theta \\ & + B_1 s^3 \sin \theta + B_2 s^2 h \sin 2\theta + (B_3 + B_4) s h^2 \sin \theta \\ & + C_1 s^5 \sin \theta + C_3 s^4 h \sin 2\theta + (C_5 + C_6 \cos^2 \theta) s^3 h^2 \sin \theta \\ & + C_9 s^2 h^3 \sin 2\theta + C_{11} s h^4 \sin \theta + D_1 s^7 \sin \theta + \dots \end{aligned} \quad (3.2)$$

where A_n , B_n , etc., are constants, and h , s , and θ have been defined above and in Fig. 3.1.

Notice that in the A terms the exponents of s and h are unity. In the B terms the exponents total 3, as in s^3 , s^2h , sh^2 , and h^3 . In the C terms the exponents total 5, and in the D terms, 7. These are referred to as the first-order, third-order, and fifth-order terms, etc. There are 2 first-order terms, 5 third-order, 9 fifth-order, and $[(n+3)(n+5)/8-1]$ n th-order terms. In an axially symmetrical system there are no even-order terms; only odd-order terms may exist (unless we depart from symmetry as, for example, by tilting a surface or introducing a toroidal or other nonsymmetrical surface).

It is apparent that the A terms relate to the paraxial (or first-order) imagery discussed in Chapter 2. A_2 is simply the magnification (h'/h), and A_1 is a measure of the distance from the paraxial focus to our "image plane." All the other terms in Eqs. 3.1 and 3.2 are called transverse aberrations. They represent the distance by which the ray misses the ideal image point as described by the paraxial imaging equations of Chapter 2.

The B terms are called the third-order, or Seidel, or primary aberrations. B_1 is spherical aberration, B_2 is coma, B_3 is astigmatism, B_4 is

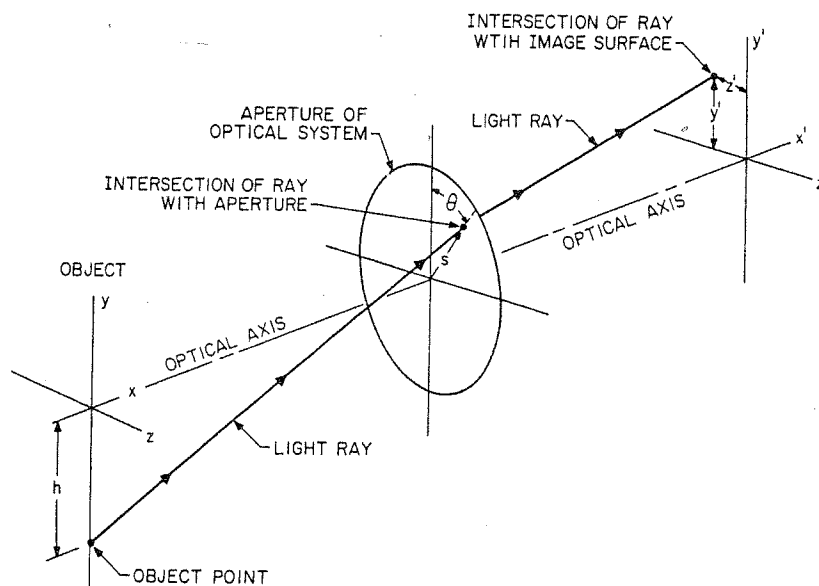


Figure 3.1 A ray from the point $y = h$, ($z = 0$) in the object passes through the optical system aperture at a point defined by its polar coordinates, (s, θ) , and intersects the image surface at y' , z' .

Petzval, and B_5 is distortion. Similarly, the C terms are called the fifth-order or secondary aberrations. C_1 is fifth-order spherical aberration; C_2 and C_3 are linear coma; C_4 , C_5 , and C_6 are oblique spherical aberration; C_7 , C_8 , and C_9 are elliptical coma; C_{10} and C_{11} are Petzval and astigmatism; and C_{12} is distortion.

The 14 terms in D are the seventh-order or tertiary aberrations; D_1 is the seventh-order spherical aberration. A similar expression for OPD, the wave front deformation, is given in Chapter 11, p. 334.

As noted above, the Seidel aberrations of a system in monochromatic light are called spherical aberration, coma, astigmatism, Petzval curvature, and distortion. In this section we will define each aberration and discuss its characteristics, its representation, and its effect on the appearance of the image. Each aberration will be discussed as if it alone were present; obviously in practice one is far more likely to encounter aberrations in combination than singly.

3.2.1 Spherical aberration

Spherical aberration can be defined as the variation of focus with aperture. Figure 3.2 is a somewhat exaggerated sketch of a simple lens forming an "image" of an axial object point a great distance away. Notice that the rays close to the optical axis come to a focus (intersect the axis) very near the paraxial focus position. As the ray height at the lens increases, the position of the ray intersection with the optical axis moves farther and farther from the paraxial focus. The distance from the paraxial focus to the axial intersection of the ray is called longitudinal spherical aberration. Transverse, or lateral, spherical aberration is the name given to the aberration when it is measured in the "vertical" direction. Thus, in Fig. 3.2 AB is the longitudinal, and AC the transverse spherical aberration of ray R .

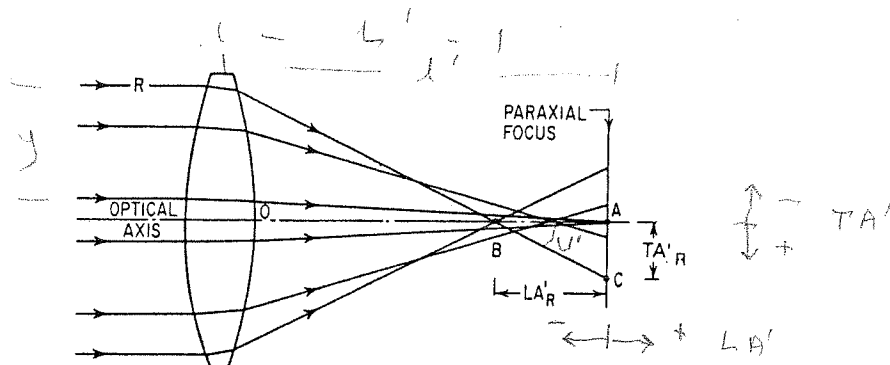


Figure 3.2 A simple converging lens with undercorrected spherical aberration. The rays farther from the axis are brought to a focus nearer the lens.

Since the magnitude of the aberration obviously depends on the height of the ray, it is convenient to specify the particular ray with which a certain amount of aberration is associated. For example, marginal spherical aberration refers to the aberration of the ray through the edge or margin of the lens aperture.

Spherical aberration is determined by tracing a paraxial ray and a trigonometric ray from the same axial object point and determining their final intercept distances l' and L' . In Fig. 3.2, l' is distance OA and L' (for ray R) is distance OB . The longitudinal spherical aberration of the image point is abbreviated LA' and

$$LA' = L' - l' \quad \checkmark \quad LA' = \text{Long Sp} \quad (3.3) \quad \text{H6}$$

Transverse spherical aberration is related to LA' by the expression

$$TA'_R = -LA' \tan U'_R = -(L' - l') \tan U'_R \quad (3.4)$$

where U'_R is the angle the ray R makes with the axis. Using this sign convention, spherical aberration with a negative sign is called undercorrected spherical, since it is usually associated with simple uncorrected positive elements. Similarly, positive spherical is called overcorrected, and is generally associated with diverging elements.

The spherical aberration of a system is usually represented graphically. Longitudinal spherical is plotted against the ray height at the lens, as shown in Fig. 3.3a, and transverse spherical is plotted against the final slope of the ray, as shown in Fig. 3.3b. Figure 3.3b is called a ray intercept curve. It is conventional to plot the ray through the top of the lens on the right in a ray intercept plot.

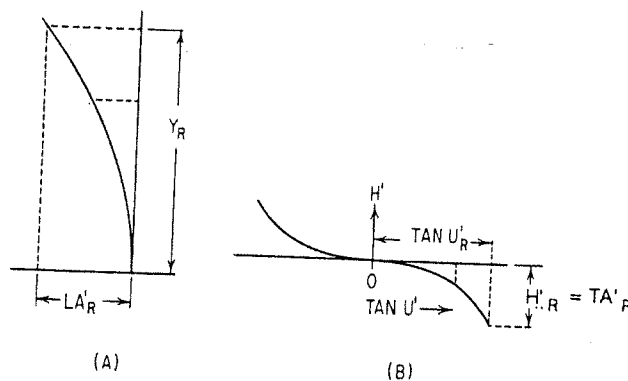


Figure 3.3 Graphical representation of spherical aberration. (a) As a longitudinal aberration, in which the longitudinal spherical aberration (LA') is plotted against ray height (Y). (b) As a transverse aberration, in which the ray intercept height (H') at the paraxial reference plane is plotted against the final ray slope ($\tan U'$).

For a given aperture and focal length, the amount of spherical aberration in a simple lens is a function of object position and the shape, or bending, of the lens. For example, a thin glass lens with its object at infinity has a minimum amount of spherical at a nearly plano-convex shape, with the convex surface toward the object. A meniscus shape, either convex-concave or concave-convex has much more spherical aberration. If the object and image are of equal size (each being two focal lengths from the lens), then the shape which gives the minimum spherical is equiconvex.

The image of a point formed by a lens with spherical aberration is usually a bright dot surrounded by a halo of light; the effect of spherical on an extended image is to soften the contrast of the image and to blur its details.

In general, a positive, converging lens will introduce undercorrected spherical aberration to a system, and a negative lens, the reverse, although there are certain exceptions to this.

Figure 3.3 illustrated two ways to present spherical aberration, as either a longitudinal or a transverse aberration. Equation 3.4 showed the relation between the two. The same relationship is also appropriate for astigmatism and field curvature (Section 3.2.3) and axial chromatic (Section 3.3). Note that coma, distortion, and lateral chromatic do not have a longitudinal measure. All of the aberrations can also be expressed as angular aberrations. The angular aberration is simply the angle subtended from the second nodal (or in air, principal) point by the transverse aberration. Thus

$$AA = \frac{TA}{s'} \quad (3.5)$$

Yet a fourth way to measure an aberration is by the departure of the actual wave front from a perfect reference sphere centered on the ideal image point, as discussed in Section 3.6 and Chapter 11.

The transverse measure of an aberration is directly related to the size of the image blur. Graphing it as a ray intercept plot (e.g., Fig. 3.3b and Fig. 3.24) allows the viewer to identify the various types of aberration afflicting the optical system. This is of great value to the lens designer, and the ray intercept plot of the transverse aberrations is an almost universally used presentation of the aberrations. As discussed later (in Chapter 11), the OPD, or wave-front deformation, is the most useful measure of image quality for well-corrected systems, and a statement of the amount of the OPD is usually accepted as definitive in this regard. The longitudinal presentation of the aberrations is most useful in understanding field curvature and axial chromatic, especially secondary spectrum.

3.2.2 Coma

Coma can be defined as the variation of magnification with aperture. Thus, when a bundle of oblique rays is incident on a lens with coma, the rays passing through the edge portions of the lens are imaged at a different height than those passing through the center portion. In Fig. 3.4, the upper and lower rim rays A and B , respectively, intersect the image plane above the ray P which passes through the center of the lens. The distance from P to the intersection of A and B is called the tangential coma of the lens, and is given by

$$\text{Coma}_T = H'_{AB} - H'_P \quad (3.6)$$

where H'_{AB} is the height from the optical axis to the intersection of the upper and lower rim rays and H'_P is the height from the axis to the intersection of the ray P with the plane perpendicular to the axis and passing through the intersection of A and B . The appearance of a point image formed by a comatic lens is indicated in Fig. 3.5. Obviously the aberration is named after the comet shape of the figure.

Figure 3.6 indicates the relationship between the position at which the ray passes through the lens aperture and the location which it occupies in the coma patch. Figure 3.6a represents a head-on view of the lens aperture, with ray positions indicated by the letters A through H and A' through H' , with the primed rays in the inner circle. The resultant coma patch is shown in Fig. 3.6b with the ray locations marked with corresponding letters. Notice that the rays which formed a circle on the aperture also form a circle in the coma patch, but as the rays go around the aperture circle once, they go around the image circle twice. The primed rays of the smaller circle in the aperture also form a correspondingly smaller circle in the image, and the central ray P is at the point of the figure. Thus the comatic image can be viewed as being made up of a series of different-sized circles arranged

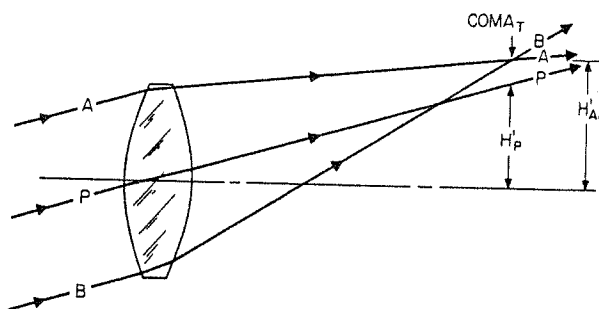


Figure 3.4 In the presence of coma, the rays through the outer portions of the lens focus at a different height than the rays through the center of the lens.

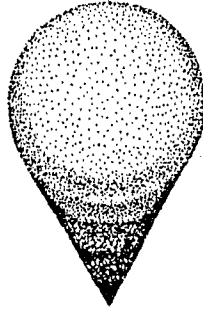


Figure 3.5 The coma patch. The image of a point source is spread out into a comet-shaped flare.

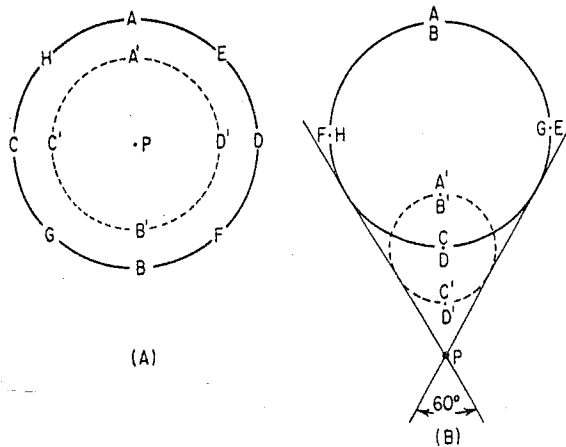


Figure 3.6 The relationship between the position of a ray in the lens aperture and its position in the coma patch. (a) View of the lens aperture with rays indicated by letters. (b) The letters indicate the positions of the corresponding rays in the image figure. Note that the diameters of the circles in the image are proportional to the square of the diameters in the aperture.

tangent to a 60° angle. The size of the image circle is proportional to the square of the diameter of the aperture circle.

In Fig. 3.6b the distance from P to AB is the tangential coma of Eq. 3.6. The distance from P to CD is called the sagittal coma and is one-third as large as the tangential coma. About 55 percent of all the energy in the coma patch is concentrated in the small triangular area between P and CD ; thus the sagittal coma is a somewhat better measure of the effective size of the image than is the tangential coma.

Coma is a particularly disturbing aberration since its flare is nonsymmetrical. Its presence is very detrimental to accurate determination of the image position since it is much more difficult to locate

the "center of gravity" of a coma patch than for a circular blur such as that produced by spherical aberration.

Coma varies with the shape of the lens element and also with the position of any apertures or diaphragms which limit the bundle of rays forming the image. In an axially symmetrical system there is no coma on the optical axis. The size of the coma patch varies directly with its distance from the axis.

3.2.3 Astigmatism and field curvature

In the preceding section on coma, we introduced the terms tangential and sagittal; a fuller discussion of these terms is appropriate at this point. If a lens system is represented by a drawing of its axial section, rays which lie in the plane of the drawing are called meridional or tangential rays. Thus rays A , P , and B of Fig. 3.6 are tangential rays. Similarly, the plane through the axis is referred to as the meridional, or tangential, plane, as may *any* plane through the axis.

Rays which do not lie in a meridional plane are called skew rays. The oblique meridional ray through the center of the aperture of a lens system is called the principal, or chief, ray. If we imagine a plane passing through the chief ray and perpendicular to the meridional plane, then all the (skew) rays from the object which lie in this plane are sagittal rays. Thus in Fig. 3.6 all the rays except A , A' , P , B' and B are skew rays and the sagittal rays are C , C' , D' and D .

Now the image of a point source formed by a fan of rays in the tangential plane will be a line image; this line, called the tangential image, is perpendicular to the tangential plane, that is, it lies in the sagittal plane. Conversely, the image formed by the rays of the sagittal fan is a line which lies in the tangential plane.

Astigmatism occurs when the tangential and sagittal (sometimes called radial) images do not coincide. In the presence of astigmatism, the image of a point source is not a point, but takes the form of two separate lines as shown in Fig. 3.7. Between the astigmatic foci the image is an elliptical or circular blur. (Note that if diffraction effects are significant, this blur may take on a square or rectangular character.)

Unless a lens is poorly made, there is no astigmatism when an *axial* point is imaged. As the imaged point moves further from the axis, the amount of astigmatism gradually increases. Off-axis images seldom lie exactly in a true plane; when there is primary astigmatism in a lens system, the images lie on curved surfaces which are paraboloid in shape. The shape of these image surfaces is indicated for a simple lens in Fig. 3.8.

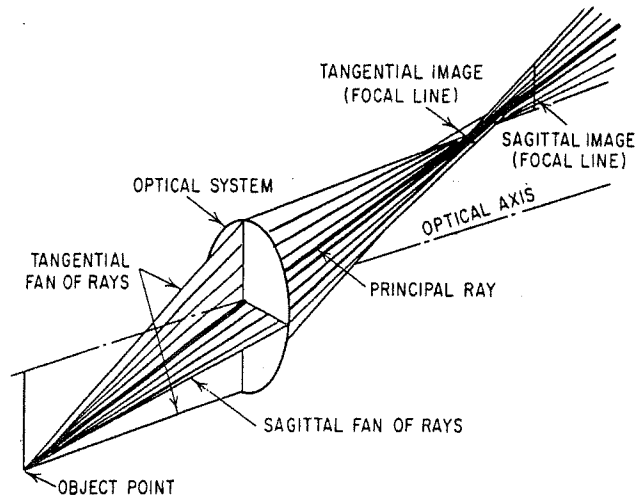


Figure 3.7 Astigmatism.

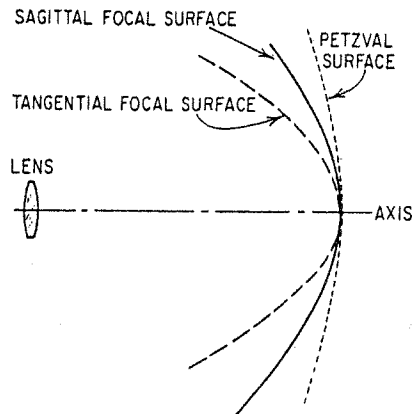


Figure 3.8 The primary astigmatism of a simple lens. The tangential image is three times as far from the Petzval surface as the sagittal image.

The amount of astigmatism in a lens is a function of the shape of the lens and its distance from the aperture or diaphragm which limits the size of the bundle of rays passing through the lens. In the case of a simple lens or mirror whose own diameter limits the size of the ray bundle, the astigmatism is equal to the square of the distance from the axis to the image (i.e., the image height) divided by the focal length of the element.

Every optical system has associated with it a sort of basic field curvature, called the Petzval curvature, which is a function of the index of refraction of the lens elements and their surface curvatures. When

there is no astigmatism, the sagittal and tangential image surfaces coincide with each other and lie on the Petzval surface. When there is primary astigmatism present, the tangential image surface lies three times as far from the Petzval surface as the sagittal image; note that both image surfaces are on the same side of the Petzval surface, as indicated in Fig. 3.8.

When the tangential image is to the left of the sagittal image (and both are to the left of the Petzval surface) the astigmatism is called negative, undercorrected, or inward-(toward the lens) curving. When the order is reversed, the astigmatism is overcorrected, or backward-curving. In Fig. 3.8, the astigmatism is undercorrected and all three surfaces are inward-curving.

Positive lenses introduce inward curvature of the Petzval surface to a system, and negative lenses introduce backward curvature. The Petzval curvature (i.e., the *longitudinal* departure of the Petzval surface from the ideal flat image surface) of a thin simple element is equal to one-half the square of the image height divided by the focal length and index of the element. Note that "field curvature" means the longitudinal departure of the focal surfaces from the ideal image surface (which is usually flat.)

3.2.4 Distortion

When the image of an off-axis point is formed farther from the axis or closer to the axis than the image height given by the paraxial expressions of Chapter 2, the image of an extended object is said to be distorted. The amount of distortion is the displacement of the image from the paraxial position, and can be expressed either directly or as a percentage of the paraxial image height.

The amount of distortion ordinarily increases as the image size increases; the distortion itself usually increases as the cube of the image height (percentage distortion increases as the square). Thus, if a centered rectilinear object is imaged by a system afflicted with distortion, it can be seen that the images of the corners will be displaced more (in proportion) than the images of the points making up the sides. Figure 3.9 shows the appearance of a square figure imaged by a lens system with distortion. In Fig. 3.9a the distortion is such that the images are displaced outward from the correct position, resulting in a flaring or pointing of the corners. This is overcorrected, or pincushion, distortion. In Fig. 3.9b the distortion is of the opposite type and the corners of the square are pulled inward more than the sides; this is negative, or barrel, distortion.

A little study of the matter will show that a system which produces

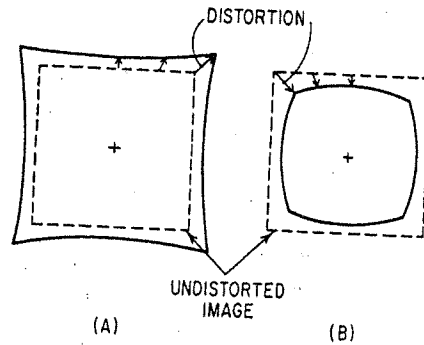


Figure 3.9 Distortion. (a) Positive, or pincushion, distortion. (b) Negative, or barrel, distortion. The sides of the image are curved because the amount of distortion varies as the cube of the distance from the axis. Thus, in the case of a square, the corners are distorted $2\sqrt{2}$ as much as the center of the sides.

distortion of one sign will produce distortion of the opposite sign when object and image are interchanged. Thus a camera lens with barrel distortion will have pincushion distortion if used as a projection lens (i.e., when the film is replaced by a slide). Obviously if the same lens is used both to photograph and to project the slide, the projected image will be rectilinear (free of distortion) since the distortion in the slide will be exactly canceled out upon projection.

3.3 Chromatic Aberrations

Because of the fact that the index of refraction varies as a function of the wavelength of light, the properties of optical elements also vary with wavelength. Axial chromatic aberration is the longitudinal variation of focus (or image position) with wavelength. In general, the index of refraction of optical materials is higher for short wavelengths than for long wavelengths; this causes the short wavelengths to be more strongly refracted at each surface of a lens so that in a simple positive lens, for example, the blue light rays are brought to a focus closer to the lens than the red rays. The distance along the axis between the two focus points is the longitudinal axial chromatic aberration. Figure 3.10 shows the chromatic aberration of a simple positive element. When the short-wavelength rays are brought to a focus to the left of the long-wavelength rays, the chromatic is termed undercorrected, or negative.

The image of an axial point in the presence of chromatic aberration is a central bright dot surrounded by a halo. The rays of light which are in focus, and those which are nearly in focus, form the bright dot. The out-of-focus rays form the halo. Thus, in an undercorrected visual instrument, the image would have a yellowish dot (formed by the orange, yellow, and green rays) and a purplish halo (due to the red and blue rays). If the screen on which the image is formed is moved toward

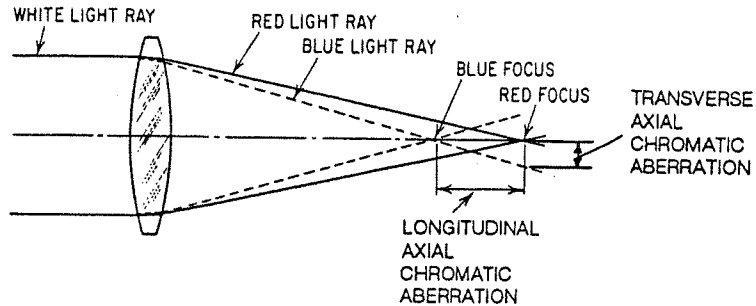


Figure 3.10 The undercorrected longitudinal chromatic aberration of a simple lens is due to the blue rays undergoing a greater refraction than the red rays.

the lens, the central dot will become blue; if it is moved away, the central dot will become red.

When a lens system forms images of different sizes for different wavelengths, or spreads the image of an off-axis point into a rainbow, the difference between the image heights for different colors is called *lateral color*, or *chromatic difference of magnification*. In Fig. 3.11 a simple lens with a displaced diaphragm is shown forming an image of an off-axis point. Since the diaphragm limits the rays which reach the lens, the ray bundle from the off-axis point strikes the lens above the axis and is bent downward as well as being brought to a focus. The blue rays are bent more than the red and thus form their image nearer the axis.

The chromatic variation of index also produces a variation of the monochromatic aberrations discussed in Section 3.2. Since each aberration results from the manner in which the rays are bent at the surfaces of the optical system, it is to be expected that, since rays of different color are bent differently, the aberrations will be somewhat

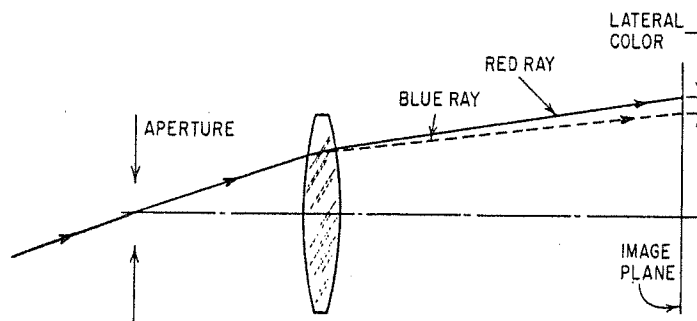


Figure 3.11 Lateral color, or chromatic difference of magnification, results in different-sized images for different wavelengths.

different for each color. In general this proves to be the case, and the effects are of practical importance when the basic aberrations are well corrected.

3.4 The Effect of Lens Shape and Stop Position on the Aberrations

A consideration of either the thick-lens focal length equation

$$\frac{1}{f} = (N - 1) \left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(N - 1)}{N} \frac{t}{R_1 R_2} \right]$$

or the thin-lens focal length equation

$$\frac{1}{f} = (N - 1) \left[\frac{1}{R_1} - \frac{1}{R_2} \right] = (N - 1)(C_1 - C_2)$$

reveals that for a given index and thickness, there is an infinite number of combinations of R_1 and R_2 which will produce a given focal length. Thus a lens of some desired power may take on any number of different shapes or "bendings." The aberrations of the lens are changed markedly as the shape is changed; this effect is the basic tool of optical design.

As an illustrative example, we will consider the aberrations of a thin positive lens made of borosilicate crown glass with a focal length of 100 mm and a clear aperture of 10 mm (a speed of $f/10$) which is to image an infinitely distant object over a field of view of $\pm 17^\circ$. A typical borosilicate crown is 517:642, which has an index of 1.517 for the helium d line ($\lambda = 5876 \text{ \AA}$), an index of 1.51432 for C light ($\lambda = 6563 \text{ \AA}$), and an index of 1.52238 for F light ($\lambda = 4861 \text{ \AA}$).

(The aberration data presented in the following paragraphs were calculated by means of the thin-lens third-order aberration equations of Chapter 10.)

If we first assume that the stop or limiting aperture is in coincidence with the lens, we find that several aberrations do *not* vary as the lens shape is varied. Axial chromatic aberration is constant at a value of -1.55 mm (undercorrected); thus the blue focus (F light) is 1.55 mm nearer the lens than the red focus (C light). The astigmatism and field curvature are also constant. At the edge of the field (30 mm from the axis) the sagittal focus is 7.5 mm closer to the lens than the paraxial focus, and the tangential focus is 16.5 mm inside the paraxial focus. Two aberrations, distortion and lateral color, are zero when the stop is at the lens.

Spherical aberration and coma, however, vary greatly as the lens shape is changed. Figure 3.12 shows the amount of these two aberrations.

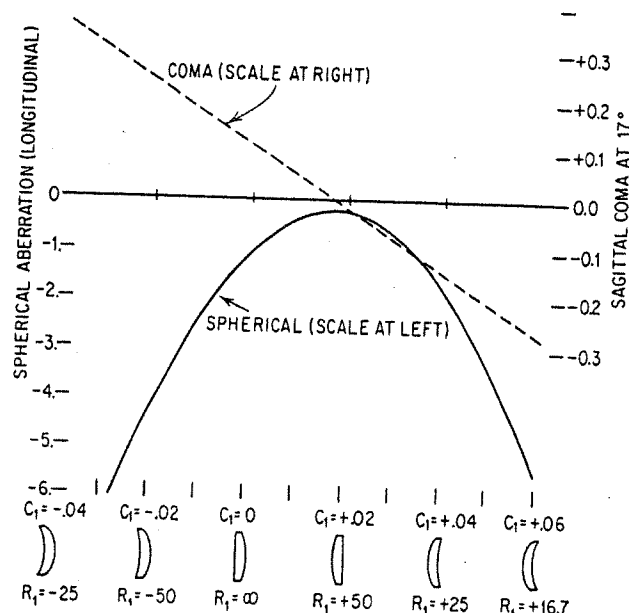


Figure 3.12 Spherical aberration and coma as a function of lens shape. Data plotted are for a 100-mm focal length lens (with the stop at the lens) at $f/10$ covering $\pm 17^\circ$ field.

tions plotted against the curvature of the first surface of the lens. Notice that coma varies linearly with lens shape, taking a large positive value when the lens is a meniscus with both surfaces concave toward the object. As the lens is bent through plano-convex, convex-plano, and convex meniscus shapes, the amount of coma becomes more negative, assuming a zero value near the convex-plano form.

The spherical aberration of this lens is always undercorrected; its plot has the shape of a parabola with a vertical axis. Notice that the spherical aberration reaches a minimum (or more accurately, a maximum) value at approximately the same shape for which the coma is zero. This, then, is the shape that one would select if the lens were to be used as a telescope objective to cover a rather small field of view.

Let us now select a particular shape for the lens, say, $C_1 = -0.0193$, and investigate the effect of placing the stop away from the lens, as shown in Fig. 3.13. The spherical and axial chromatic aberrations are completely unchanged by shifting the stop, since the axial rays strike the lens in exactly the same manner regardless of where the stop is located. The lateral color and distortion, however, take on positive values when the stop is behind the lens and negative when it is before the lens. Figure 3.14 shows a plot of lateral color, distortion, coma, and tangential field curvature as a function of the stop position. The most pronounced effects of moving the stop are found in the variations of

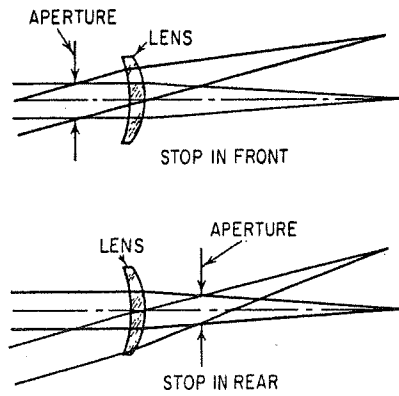


Figure 3.13 The aperture stop away from the lens. Notice that the oblique ray bundle passes through an entirely different part of the lens when the stop is in front of the lens than when it is behind the lens.

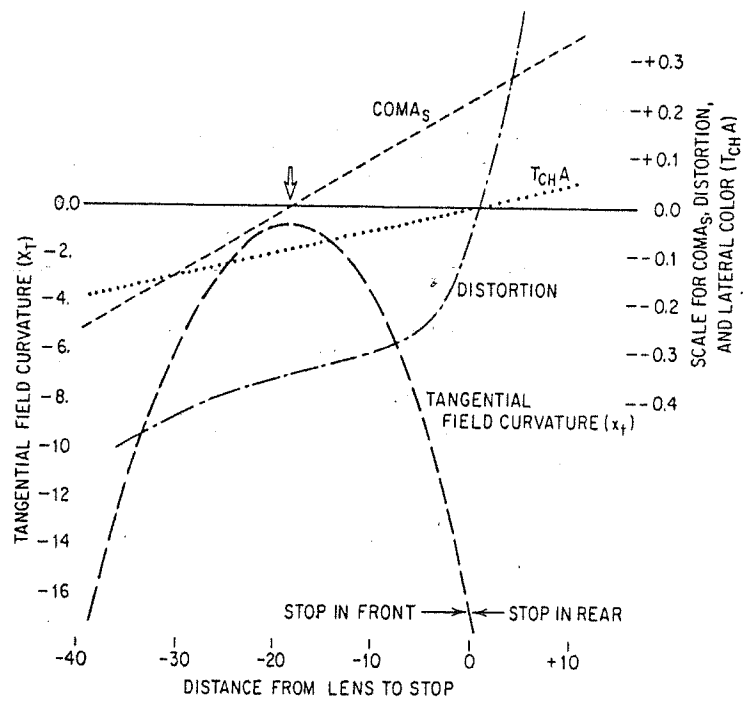


Figure 3.14 Effect of shifting the stop position on the aberrations of a simple lens. The arrow indicates the "natural" stop position where coma is zero. ($e f l = 100$, $C_1 = -0.0193$, speed = $f/10$, field = $\pm 17^\circ$.)

coma and astigmatism. As the stop is moved toward the object, the coma decreases linearly with stop position, and has a zero value when the stop is about 18.5 mm in front of the lens. The astigmatism becomes less negative so that the position of the tangential image approaches the paraxial focal plane. Since astigmatism is a quadratic function of stop position, the tangential field curvature (x_t) plots as a parabola. Notice that the parabola has a maximum at the same stop position for which the coma is zero. This is called the *natural* position of the stop, and for all lenses with undercorrected primary spherical aberration, the natural, or coma-free, stop position produces a more backward curving (or less inward curving) field than any other stop position.

Figure 3.12 showed the effect of lens shape with the stop fixed in contact with the lens, and Fig. 3.14 showed the effect of stop position with the lens shape held constant. There is a "natural" stop position for each shape of the simple lens we are considering. In Fig. 3.15, the aberrations of the lens have again been plotted against the lens shape; however, in this figure, the aberration values are those which occur

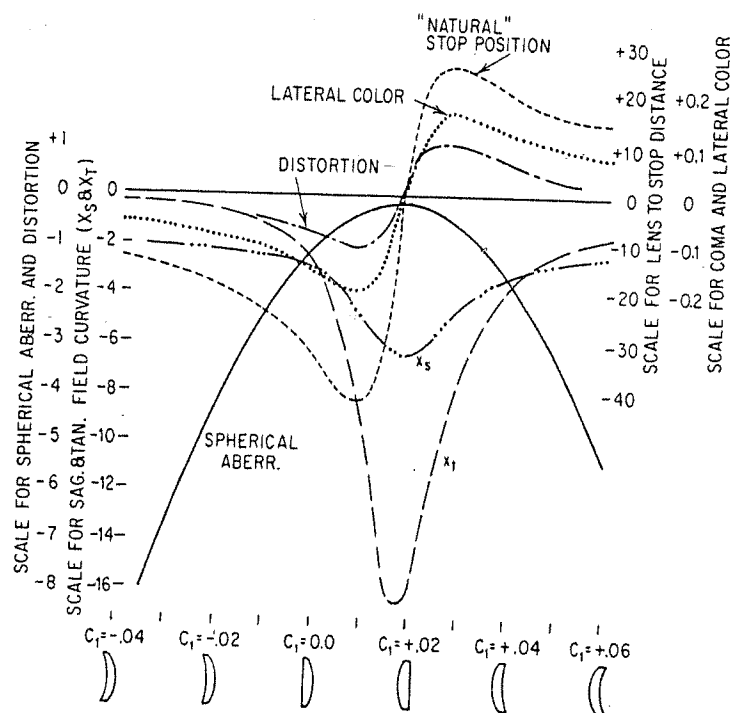


Figure 3.15 The variation of the aberrations with lens shape when the stop is located in the "natural" (coma free) position for each shape. Data is for 100-mm $f/10$ lens covering $\pm 17^\circ$ field, made from BSC-2 glass (517:645).

when the stop is in the natural position. Thus, for each bending the coma has been removed by choosing this stop position, and the field is as far backward curving as possible.

Notice that the shape which produces minimum spherical aberration also produces the maximum field curvature, so that this shape, which gives the best image near the axis, is not suitable for wide field coverage. The meniscus shapes at either side of the figure represent a much better choice for a wide field, for although the spherical aberration is much larger at these bendings, the field is much more nearly flat. This is the type of lens used in inexpensive box cameras at speeds of $f/11$ or $f/16$.

3.5 Aberration Variation with Aperture and Field

In the preceding section, we considered the effect of lens shape and aperture position on the aberrations of a simple lens, and in that discussion we assumed that the lens operated at a fixed aperture of $f/10$ (stop diameter of 10 mm) and covered a fixed field of $\pm 17^\circ$ (field diameter of 60 mm). It is often useful to know how the aberrations of such a lens vary when the size of the aperture or field is changed.

Figure 3.16 lists the relationships between the primary aberrations and the semi-aperture y (in column one) and the image height h (in column two). To illustrate the use of this table, let us assume that we have a lens whose aberrations are known; we wish to determine the size of the aberrations if the aperture diameter is increased by 50 percent and the field coverage reduced by 50 percent. The new y will be 1.5 times the original, and the new h will be 0.5 times the original.

Aberration	vs. Aperture	vs. Field Size or Angle
Spherical (longitudinal)	y^2	—
Spherical (transverse)	y^3	—
Coma	y^2	h
Petzval curvature (longitudinal)	—	h^2
Petzval curvature (transverse)	y	h^2
Astigmatism and field curvature (longitudinal)	—	h^2
Astigmatism and field curvature (transverse)	y	h^2
Distortion (linear)	—	h^3
Distortion (in percent)	—	h^2
Axial chromatic (longitudinal)	—	—
Axial chromatic (transverse)	y	—
Lateral chromatic	—	h
Lateral chromatic (CDM)	—	—

Figure 3.16 The variation of the primary aberrations with aperture and field.

Aberrations

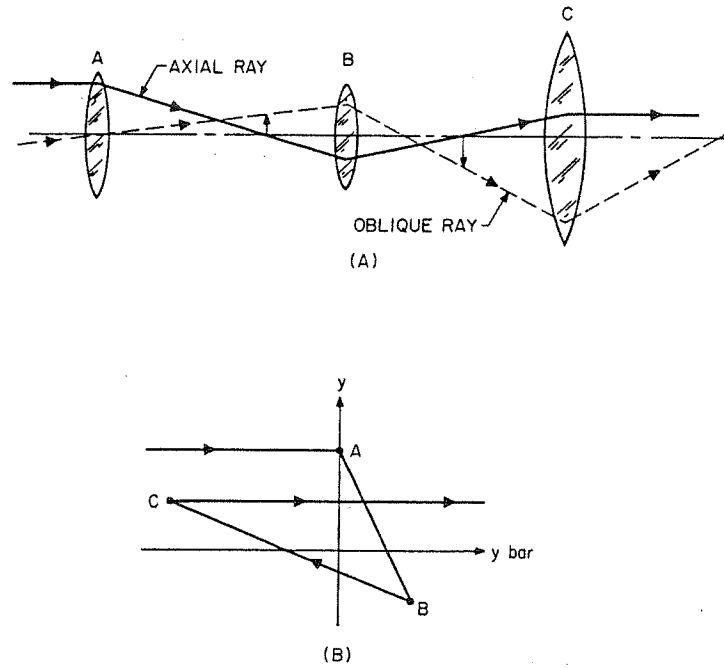


Figure 2.20 (a) Schematic of an optical system and (b) the corresponding y-ybar diagram.

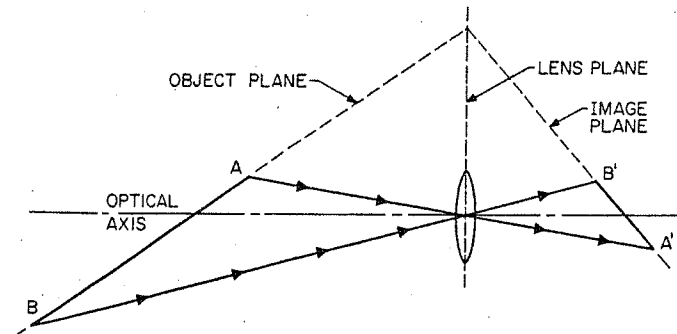


Figure 2.21 The Scheimpflug condition. The object plane and the image plane intersect at the plane of the lens.

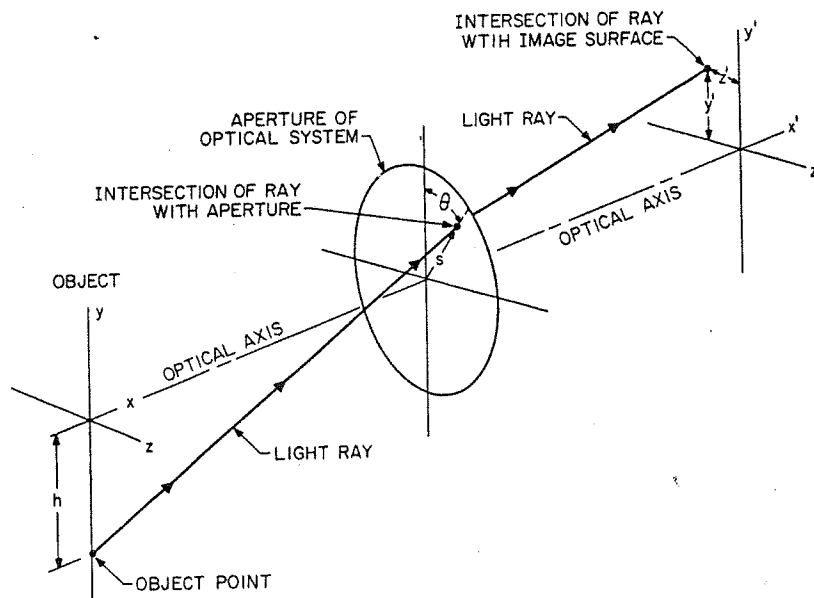


Figure 3.1 A ray from the point $y = h$, ($z = 0$) in the object passes through the optical system aperture at a point defined by its polar coordinates, (s, θ) , and intersects the image surface at y', z' .

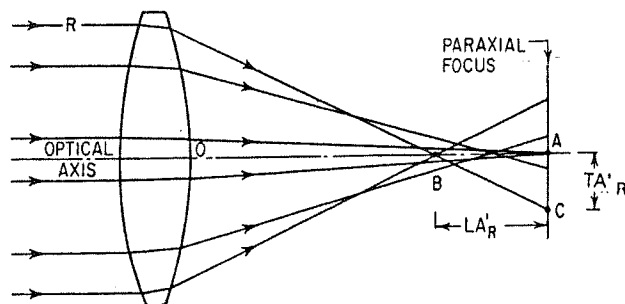


Figure 3.2 A simple converging lens with undercorrected spherical aberration. The rays farther from the axis are brought to a focus nearer the lens.

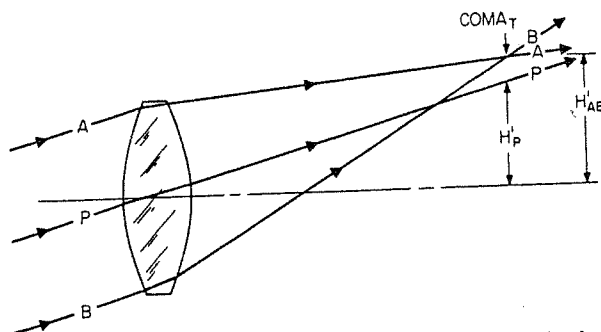


Figure 3.4 In the presence of coma, the rays through the outer portions of the lens focus at a different height than the rays through the center of the lens.

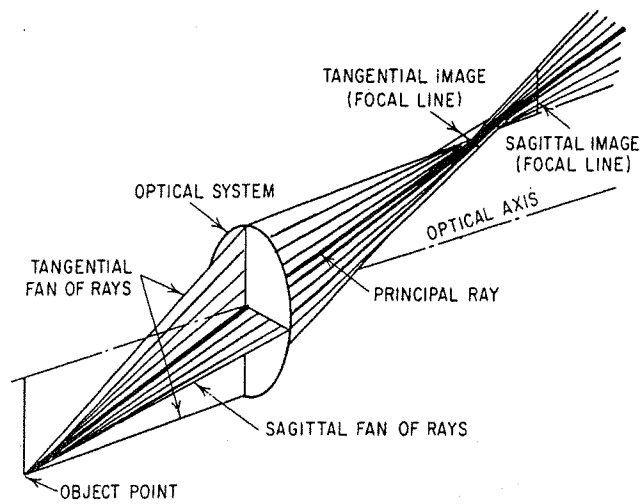


Figure 3.7 Astigmatism.

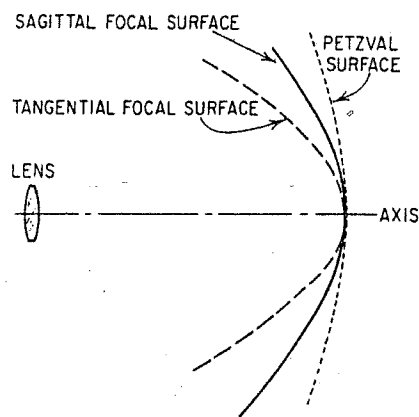


Figure 3.8 The primary astigmatism of a simple lens. The tangential image is three times as far from the Petzval surface as the sagittal image.

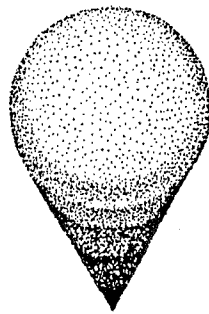


Figure 3.5 The coma patch. The image of a point source is spread out into a comet-shaped flare.

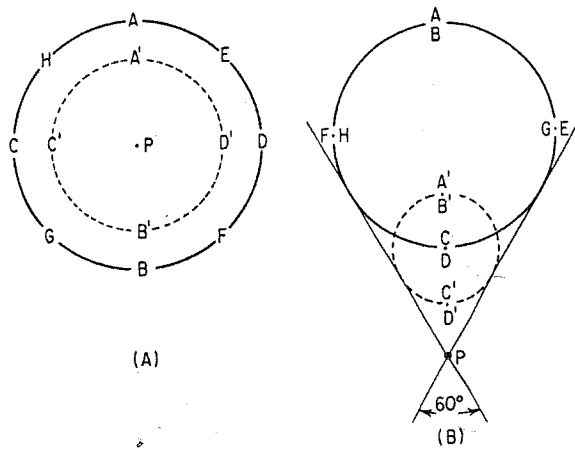


Figure 3.6 The relationship between the position of a ray in the lens aperture and its position in the coma patch. (a) View of the lens aperture with rays indicated by letters. (b) The letters indicate the positions of the corresponding rays in the image figure. Note that the diameters of the circles in the image are proportional to the square of the diameters in the aperture.

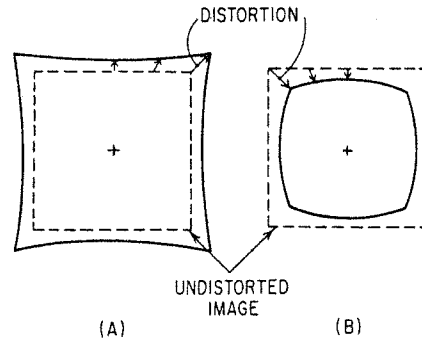


Figure 3.9 Distortion. (a) Positive, or pincushion, distortion. (b) Negative, or barrel, distortion. The sides of the image are curved because the amount of distortion varies as the cube of the distance from the axis. Thus, in the case of a square, the corners are distorted $2\sqrt{2}$ as much as the center of the sides.

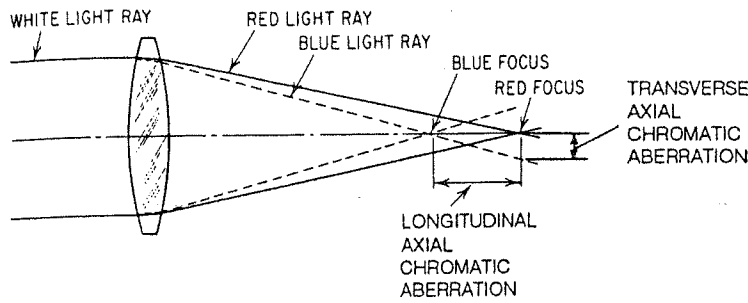


Figure 3.10 The undercorrected longitudinal chromatic aberration of a simple lens is due to the blue rays undergoing a greater refraction than the red rays.

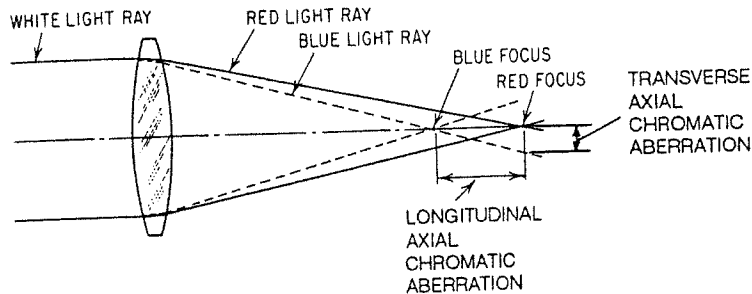


Figure 3.10 The undercorrected longitudinal chromatic aberration of a simple lens is due to the blue rays undergoing a greater refraction than the red rays.

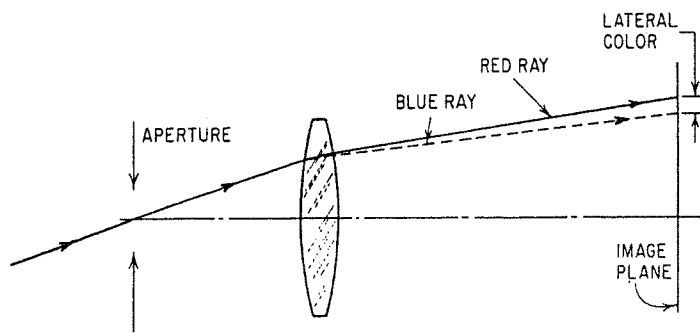


Figure 3.11 Lateral color, or chromatic difference of magnification, results in different-sized images for different wavelengths.

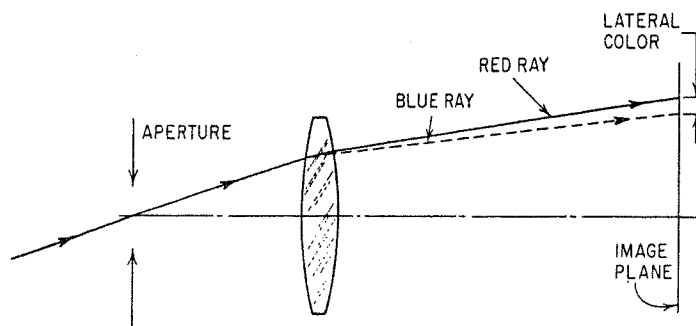


Figure 3.11 Lateral color, or chromatic difference of magnification, results in different-sized images for different wavelengths.

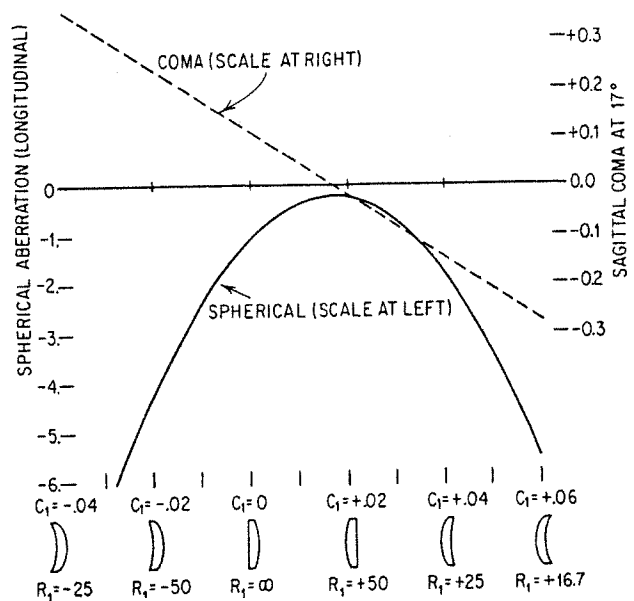


Figure 3.12 Spherical aberration and coma as a function of lens shape. Data plotted are for a 100-mm focal length lens (with the stop at the lens) at $f/10$ covering $\pm 17^\circ$ field.

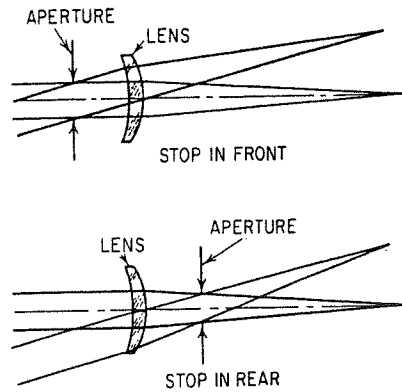


Figure 3.13 The aperture stop away from the lens. Notice that the oblique ray bundle passes through an entirely different part of the lens when the stop is in front of the lens than when it is behind the lens.

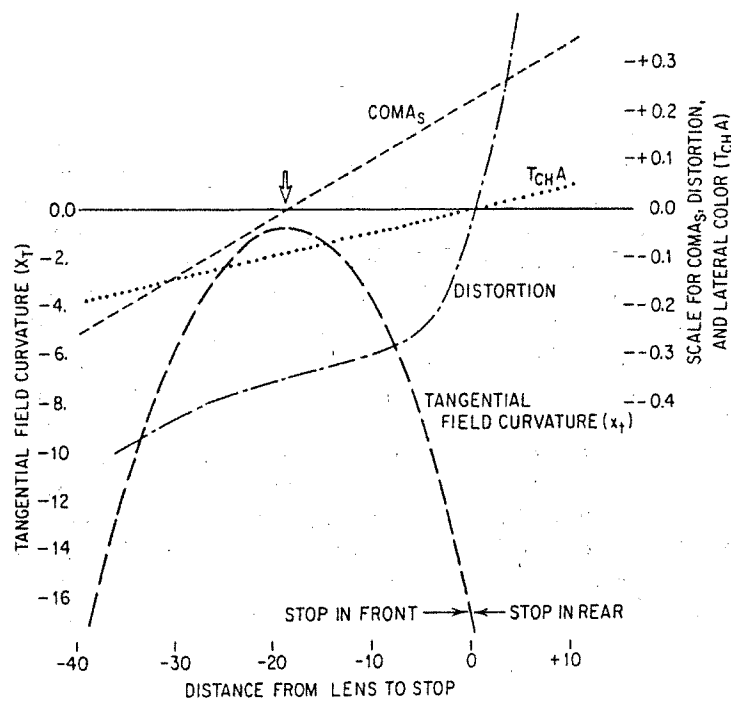


Figure 3.14 Effect of shifting the stop position on the aberrations of a simple lens. The arrow indicates the "natural" stop position where coma is zero. ($e f l = 100$, $C_1 = -0.0193$, speed = $f/10$, field = $\pm 17^\circ$.)

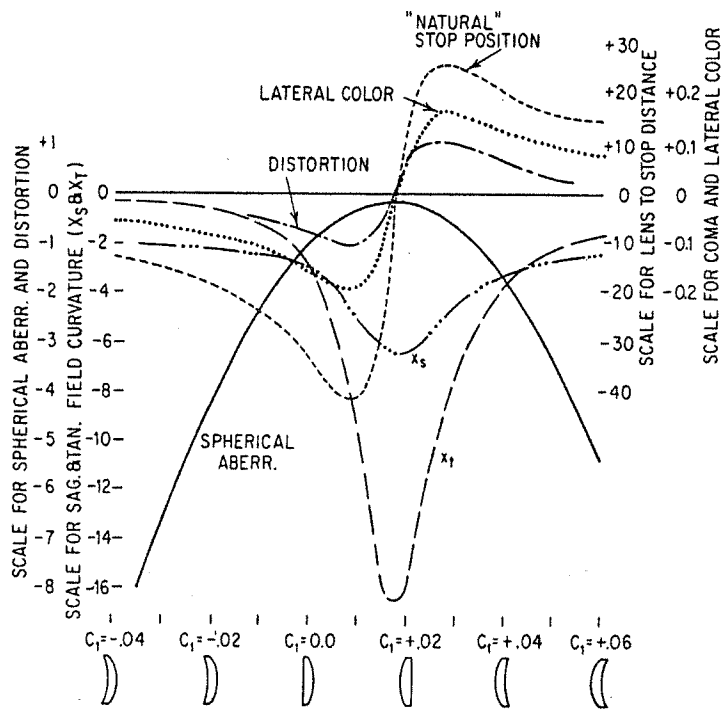


Figure 3.15 The variation of the aberrations with lens shape when the stop is located in the "natural" (coma free) position for each shape. Data is for 100-mm $f/10$ lens covering $\pm 17^\circ$ field, made from BSC-2 glass (517:645).

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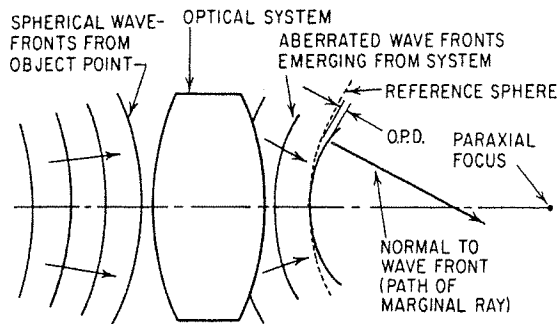


Figure 3.17 The optical path difference (OPD) is the distance between the emerging wave front and a reference sphere (centered in the image plane) which coincides with the wave front at the axis. The OPD is thus the difference between the marginal and axial paths through the system for an axial point.

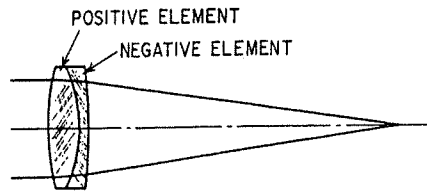


Figure 3.18 Achromatic doublet telescope objective. The powers and shapes of the two elements are so arranged that each cancels the aberrations of the other.

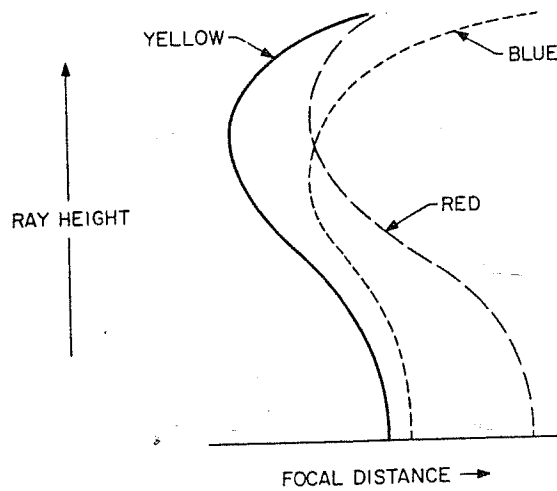


Figure 3.21 Spherochromatism. The longitudinal aberration of a "corrected" lens is shown for three wavelengths. The marginal spherical for yellow light is corrected, but is overcorrected for blue light and undercorrected for red. The chromatic aberration is corrected at the zone, but is overcorrected above it and undercorrected below. A transverse plot of these aberrations is shown in Fig. 3.24k.

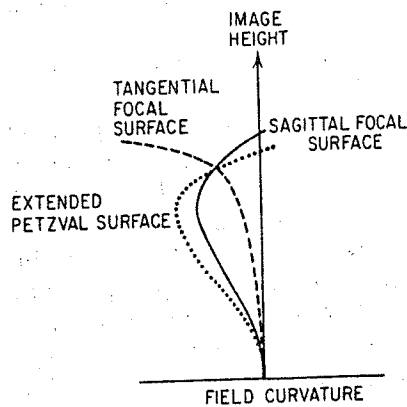


Figure 3.22 Field curvature of a photographic anastigmat. The astigmatism has been corrected for one zone of the field, but is overcorrected inside this zone and undercorrected beyond it.

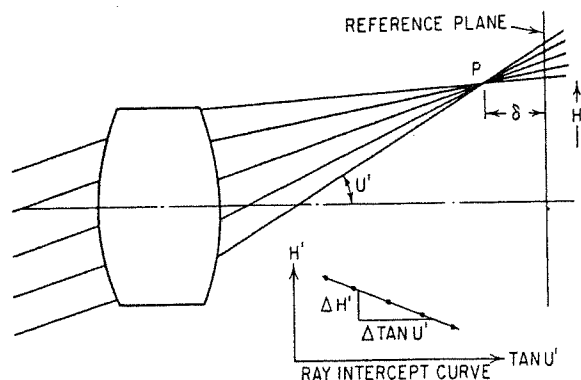


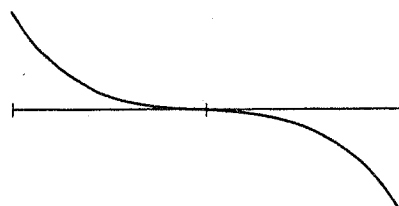
Figure 3.23 The ray intercept curve (H' vs. $\tan U'$) of a point which does not lie in the reference plane is a tilted straight line. The slope of the line ($\Delta H'/\Delta \tan U'$) is mathematically identical to δ , the distance from the reference plane to the point of focus P . Note that δ is equal to X_T , the tangential field curvature, when the paraxial focal plane is chosen as the reference plane.

It is apparent that the ray intercept curves which are "odd" functions, that is, the curves which have a rotational or point symmetry about the origin, can be represented mathematically by an equation of the form

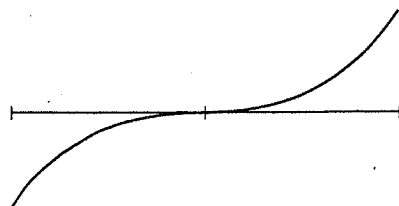
$$y = a + bx + cx^3 + dx^5 + \dots$$

or

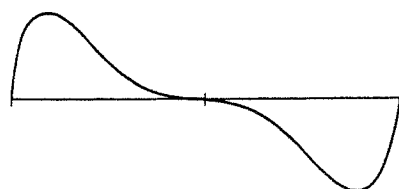
$$H' = a + b \tan U' + c \tan^3 U' + d \tan^5 U' + \dots \quad (3.7)$$



(A) UNDERCORRECTED SPHERICAL ABERRATION

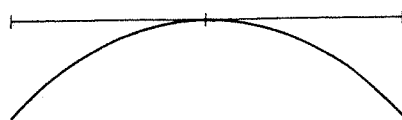


(B) OVERCORRECTED SPHERICAL ABERRATION

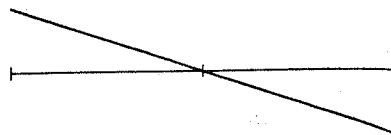


(C) UNDERCORRECTED ZONAL SPHERICAL ABERRATION

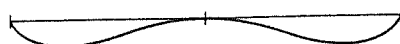
Figure 3.24 The ray intercept plots for various aberrations. The ordinate for each curve is H , the height at which the ray intersects the (paraxial) image plane. The abscissa is $\tan U$, the final slope of the ray with respect to the optical axis. Note that it is conventional to plot the ray through the top of the lens at the right of the figure, and that curves for image points above the axis are customarily shown. (Figure continues with parts (d) to (i) on page 82.)



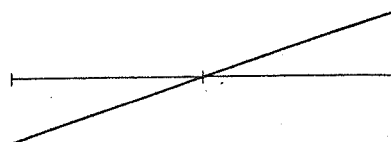
(D) UNDERCORRECTED COMA



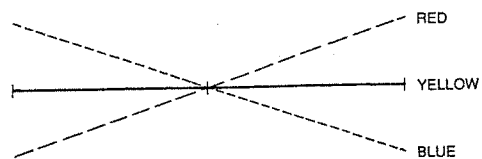
(G) INWARD CURVING TANGENTIAL FIELD



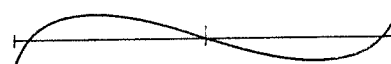
(E) COMA -- THIRD AND FIFTH ORDER



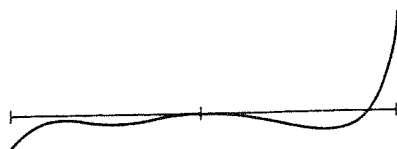
(H) BACKWARD CURVING TANGENTIAL FIELD



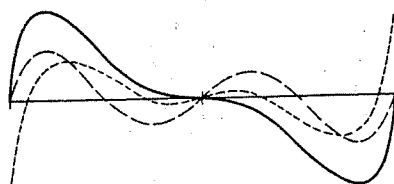
(F) UNDERCORRECTED AXIAL CHROMATIC ABERRATION



(I) OVERCORRECTED SPHERICAL
REFOCUSSED FOR MINIMUM BLUR



(J) A "TYPICAL" OFF-AXIS CURVE



(K) ON-AXIS PLOT FOR AN ACHROMATIC DOUBLET,
SHOWING ZONAL SPHERICAL, SECONDARY
SPECTRUM, AND SPHERO-CHROMATISM

Figure 3.24 (Continued)

Blackbody

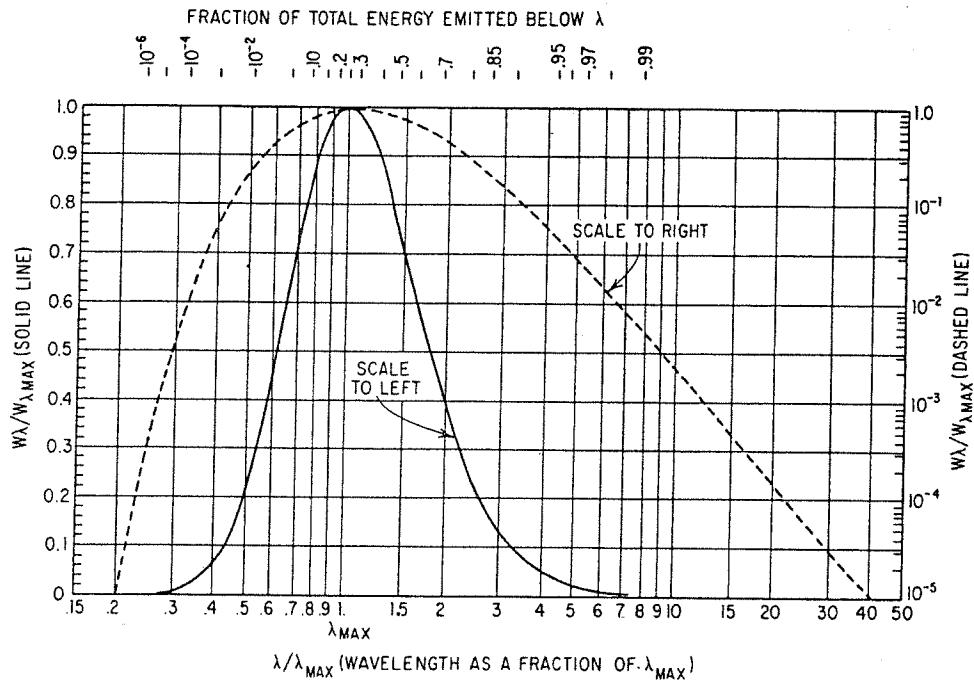


Figure 8.7 Spectral distribution of blackbody radiation.