Definitions

Aberration: An aberration is any departure from what Gaussian optics would predict. The six basic aberrations are chromatic, spherical, coma, astigmatism, field curvature, and distortion.

Accommodation: The act of changing the power of a system to bring objects into focus.

Aerial Image: Light from an object produces a 3D distribution of light in image space. The aerial image is the distribution of light on a mathematical surface, often about best focus, that is the locus of the image points. The aerial image is never the final goal. Ultimately, the light needs to be captured by some detector device.

Afocal: A system is afocal if the transverse and angular magnification is independent of object or image distance. This can be realized by the association of two focal systems for which the image focal point of one is collocated with the object focal point of the other.

Aperture Stop: The physical delimiter of the field that limits the cone of light from coming emitting from each point in the object. The aperture stop does not effect the Gaussian properties of the lens, but does contribute to irradiance, aberrations, and defocusing. A small aperture stop will restrict the cone of light to a smaller angle more closely approximating paraxial optics and improves image quality.

The physical structure in the optical system that most severely restricts on axis light is the aperture stop. In the off-axis case it may not be the aperture stop which limits light the most. Furthermore, the aperture stop is defined for a particular object point so different object points may have different aperture stops.

Aplanetic: No coma aberrations. This is essentially stigmatic imaging in the off-axis case.

Arcminute: One arcminute is 60 arcseconds and 1/60 degrees.

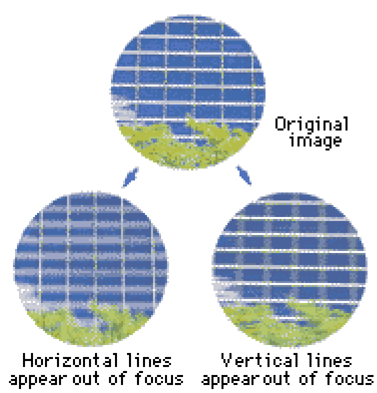
$$\boxed{1\text{ degree} = 60\text{ arcmin}} \qquad \boxed{1\text{ arcmin} = 60\text{ arcsec}}$$

Arcsecond: 60 arcseconds is 1 arcminute.

$$\boxed{1\text{ degree} = 60\text{ arcmin} = 3600\text{ arcsec}}$$

Aperture Stop: A "light blocker" placed on the optical axis to limit the extent of the beam of light in the optical system. If there is more than one place that limits the extent of the beam, the most restrictive is aperture stop.

Astigmatism: This aberration is cylindrical deformation of the wavefront and produces to "line" focal points at different locations. When one focal point is selected, the dimension in line with the focal line is blurred. The optimum focal point is found somewhere between the two line focal points.



Brewster's Angle: The angle of incidence where all light of parallel polarization is transmitted (not reflected). At the Brewster angle, the reflected and refracted ray form a 90 degree angle.

$$\tan\theta_B = \frac{n_2}{n_1}$$

Cardinal Points: A complex optical system can be treated almost as simple as thin lens ray tracing (in the Gaussian Optics sense) by defining the cardinal points. These are the principle points, anti-principle points, focal points, nodal points, and anti-nodal points.

Principle Points, P and P': These are conjugate points where the transverse magnification is defined to be unity, $m_y = 1$. Note: $(m_\alpha)_0$ is the angular magnification at the principle points.

Image Space Principle Point, P': The point where an input ray from the right appears to intersect the output ray.

Object Space Principle Point, P: The point where an input ray from the left appears to intersect the output ray.

Anti-Principle Points, ς and ς': These are conjugate points where the transverse magnification is negative one, $m_y = -1$. This point is always on the optical axis.

Image Space Anti-Principle Point, ς': This point is symmetric about F' with respect to P'.

Object Space Anti-Principle Point, ς: This point is symmetric about F with respect to P.

Focal Point Image, $X^{/}_{F'}$: The image of a point in object space at infinity on axis. This point is located a distance f' to the right of P'.

Focal Point Object, X_F: The image of a point in image space at infinity on axis. This point is located a distance f to the left of P.

Nodal Points, N and N': These are conjugate points where the angular magnification is unity, $m_\alpha = 1$.

Image Space Nodal Point, N': Located to the right of the focal point image by the effective object focal length.

Object Space Nodal Point, N: Located to the left of the focal point object by the effective image focal length.

Anti-Nodal Points, ν and ν': These are conjugate points where the angular magnification is unity, $m_\alpha = 1$.

Image Space Anti-Nodal Point, ν': This is symmetric about the focal point image with respect to N'.

Object Space Anti-Nodal Point, ν: This is symmetric about the focal point image with respect to N.

Chief Rays: Originates at the edge of an object field and passes through the approximate center of the limiting aperture (through center of entrance and exit pupils) and intersects the conjugate edge of the image field. The chief rays are closely associated with the field of view (FOV).

Chromatic Aberrations: Due to the fact that the index of refraction varies with wavelength (dispersion), chromatic aberrations cause the power of a lens to be wavelength dependent. This has the effect of focusing light of different color at different points, blurring the image.

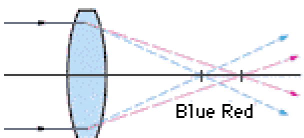


Fig.1
Axial chromatic aderration

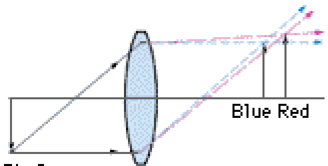


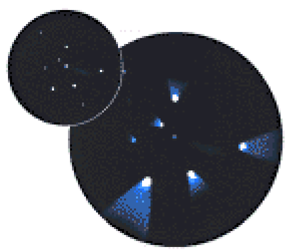
Fig.2
Magnification chromatic aderration


The image is blurred and appears colored at the fringe.

Collineation: An alternate term for the *Matrix method*.

Color: Color is best associated with the frequency of light.

Coma: This aberration causes image points to have a comet like appearance. It is caused by rays being refracted differently about the chief ray. The optimum focal point remains at the paraxial focal point. A tilted reference wavefront can improve this aberration.


Point present a comet-shaped appearance.

Conjugate: Points or planes that are conjugates are images of each other.

Convergence: The tendency of a beam to converge to a single point. A convex lens can converge light. A convergent beam may form of image point.

Critical Angle: At the critical angle, an incident ray is totally reflected (Total Internal Reflection, TIR).

$$\sin\theta_C = \frac{n_2}{n_1}$$

Depth of Field: For a fixed image distance, the depth of field is the range over which the object can be moved and still obtain a sharp image. The depth of field is conjugate with depth of focus.

Depth of Focus: For a fixed object distance, the depth of focus is the range over which a detector at the image focal point can be moved and still obtain a sharp image. The depth of focus is conjugate with depth of field.

Descartes Law (Snell's Law): The incident, reflected, and refracted rays are all coplanar.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Descartes' Formula (Imaging Equation): This equation relates the object and image distances with focal length and index of refraction.

$$\frac{n'}{x'} = \frac{n}{x} + \frac{n'}{f'}$$

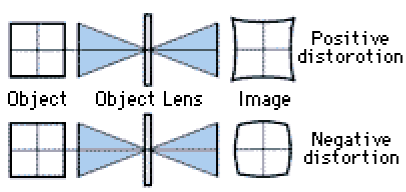
Dielectric Mirror: Specially alternating layers of high and low refractive index materials. These are typically reflection enhancement coatings. There are also anti-reflection coatings using the same principle.

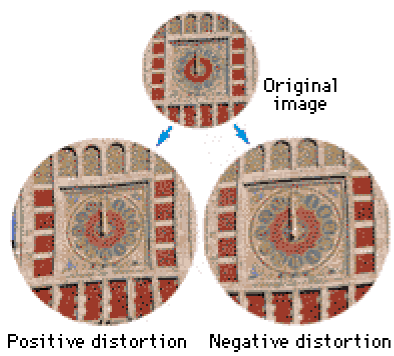
Diffraction: This behavior is the deviation of light not predicted by the ray model.

Dipvergence: Forcing the eyes to move at different elevations.

Dispersion: The index of refraction depends on frequency.

Distortion: Distortion represents an apparent change in magnification along the image plane. The image is still stigmatic (sharp/focused), but is distorted. Two distortions are distinguished: barrel (negative) and pincushion (positive). When the pupil is located at the lens, no distortion is produced. When the pupil is located between the lens and image, positive distortion is observed. When the pupil is located between the object and the lens, negative distortion is observed.





Divergence: The tendency of a beam to spread, widen, or propagate outward from a point. A divergent beam cannot form a well focused image unless a convex lens (or positive optical system) is used to counteract the divergence.

Emmetropic: An eye is emmetropic when the light focuses on the retina. This is the ideal case.

Entrance Pupil: Image of the aperture stop as seen from the object space. The entrance and exit pupils are conjugates.

Exit Pupil: Image of the aperture stop as seen from the image space. The entrance and exit pupils are conjugates.

Extremal: A path from point A to B is an extremal if the first derivative of the function defining the path is zero. That is, this path is very stable.

Fermat's Principle: In an isotropic media, the optical path between two points A and B through which the ray passes is an extremal of the optical path computed between A and B.

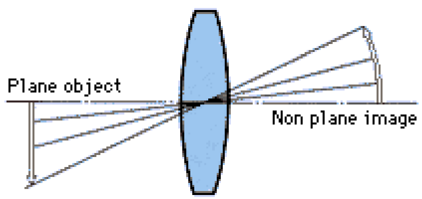
Fermat's Principle: Originally, Fermat stated his principle that light travels the path that minimizes the transit time. While still called Fermat's principle, today it has been extended to state that the path between two points is such that the optical path is equal, in the first order approximation, to other paths in close proximity. Another modern state of Fermat's principle is that the path between two points is such that the transit time is stationary. Fermat's principle can be written quantitatively as

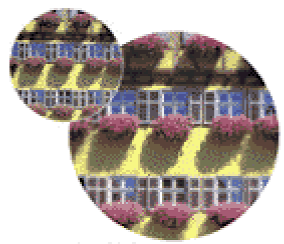
$$\frac{\partial P}{\partial \overline{V}} = 0$$

where P represents all the variables that define the optical path (distance, index, etc…).

Another definition: In an isotropic media, the optical path between two points A and B through which the ray passes is an extremal of the optical path computed between A and B.

Field Curvature: This aberration describes the case where the focused image lies on a curved surface and cannot be focused onto a plane.





The periphery of the field appears out of focus.

Field of View: The region of light from object space from which light is captured, or the region of image space that is used. This can be described in many ways (i.e. angle, linear, area, etc…).

Field Stop: A physical delimiter of the field. This can be an aperture or detector itself and can reside in object or image space. If the chief ray has too large of an angle at the aperture stop, it may be blocked by another aperture. The aperture blocking the chief ray is the field stop.

F-Number: The F-number is defined as the focal length divided by the size of the entrance pupil. For a lens, this is the diameter of the lens. The F-number is written as FN, F/no., or F/#. This is defined for an object at infinity and should not be confused with the *working F-number*.

$$\text{FN} = \text{F/no.} = \text{F/\#} = \frac{\text{Focal Length}}{\text{Pupil Diameter}} = \frac{|f'|}{D} = \frac{1}{2\tan\theta'_{\text{max}}}$$

Working F-Number: Defined like F-number but takes into account how lens is being used (i.e. position of object/image).

$$\text{FN}_{\text{Image}} = \frac{|x'|}{D} = \frac{1}{2\tan\theta'_{\text{max}}}$$

$$\text{FN}_{\text{Image}} = \frac{|x|}{D} = \frac{1}{2\tan\theta_{\text{max}}}$$

Focal Point: A point where plane wave incident light is forced by an optical system to converge, or appear to converge.

Focal Plane: A plane symmetric about the optical axis located at the focal point.

Fresnel Reflection (Normal Incidence): The Fresnel coefficient of reflection, r, for normal incidence is

$$r = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \qquad t = 1 - r = \frac{4 n_1 n_2}{\left(n_1 + n_2 \right)^2}$$

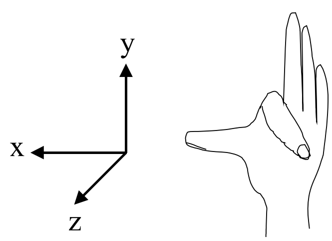
Geometric Path Length: This is the physical distance along a path. This ignores index of refraction and transit time.

$$L = \int_a^b ds \qquad ds = \sqrt{(dx)^2 + (dy)^2 + (dz)^2}$$

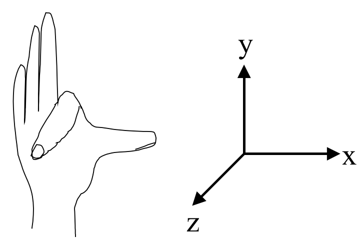
Geometrical Wavefront: Given rays emanating from a single point, the geometrical wavefront is a surface that is the locus of constant optical path length for the source (equiphase surfaces).

Grazing Incidence: All incident energy is reflected.

Handedness: A description of the orientation of an image. In a right handed system, the thumb points along the positive x-axis, the index finger points along the positive z-axis, and the rest point along the positive y-axis. Likewise with the left hand in a left handed system. Every reflection in an optical systems produces a change in handedness.



Left Handed System



Right Handed System

Hughens Principle: The wavefront at some arbitrary point as a function of a previous wavefront can be determined from the envelope of secondary wavelets emitted at each point along the previous wavefront. This is a key theorem in diffraction theory.

Image: The optical counterpart of an object produced by a lens, mirror, or other optical systems.

Image Inversion: An image is inverted when it is rotated by 180 degrees. Any number of inversions does not change handedness.

Image Irradiance: The brightness of the image. This can be approximated from geometrical optics, but more detailed models are based on wave optics.

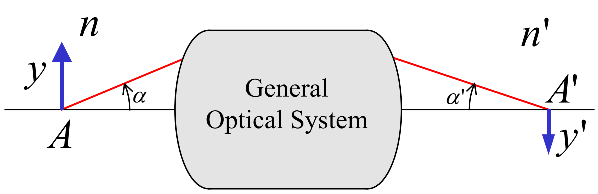
Image Reversal: An image reversal happens when one coordinate is flipped. An odd number of reversals produces a change in handedness. An even number does not.

Imaging Equation (Descartes' Formula): This equation relates the object and image distances with focal length and index of refraction.

$$\frac{n'}{x'} = \frac{n}{x} + \frac{n'}{f'}$$

Index of Refraction: The refractive index characterizes the fact that the speed of light depends on the medium of propagation.

Lagrange-Helmholtz Equation: Otherwise known as optical invariance, the product is invariant upon imaging through a general system.



$$n y \alpha = n' y' \alpha'$$

Lens Maker's Formula: While not being very useful for making lenses, this formula relates the radius of curvature for each surface of a thin lens with the lens power.

$$C = -\frac{1}{f} = \frac{1}{f'} = (N-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

where N is the refractive index of the lens. This can be extended to account for a different refractive index on each side of the lens.

$$C = -\frac{n}{f} = \frac{n'}{f'} = \frac{N-n}{R_1} - \frac{N-n'}{R_2}$$

A further generalization can be made for a thick lens, where the surfaces are separated by a distance d.

$$C = -\frac{n}{f} = \frac{n'}{f'} = \frac{N-n}{R_1} - \frac{N-n'}{R_2} + \frac{d(N-n)(N-n')}{R_1 R_2 N}$$

Magnification: There are three varieties of magnification.

(1) **Transverse (or Linear) Magnification**: The height of the image is changed.

$$m_y = \frac{y'}{y}$$

(2) **Angular Magnification**: Light entering an optical system at some angle will exit with a magnified angle.

$$m_\alpha = \frac{\alpha'}{\alpha}$$

(3) **Axial Magnification**: Axial shifts of the object result in magnified axial shifts of image.

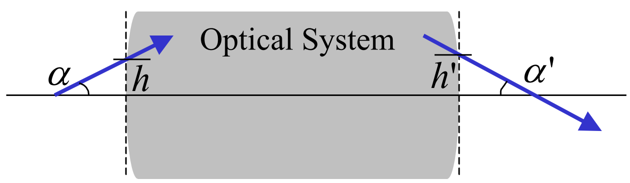
$$m_x = \frac{dx'}{dx}$$

Malus and Dupin Theorem: If a smooth surface, not necessarily flat, can be made such that a group of rays are all incident at right angles, the group of rays are called normally congruent. *A group of rays will preserve its normal congruence after any number of reflections and refractions according to the Malus and Dupin Theorem.*

An interpretation of this theorem is that this surface represents the wavefront. Rays are always perpendicular to the wavefront.

Marginal Rays: Originates at the axial object point and passes through the very edge of the limiting aperture and passes through the conjugate image point. This ray defines the outer most ray accepted by system and is closely associated with the amount of light passing through the system.

Matrix Method: The matrix method relates the angle and height of a ray cross through conjugate planes. This is also called collineation.



$$\begin{pmatrix} h' \\ \alpha' \end{pmatrix} = \begin{pmatrix} m_y & 0 \\ -\frac{1}{f} & m_\alpha \end{pmatrix} \begin{pmatrix} h \\ \alpha \end{pmatrix}$$

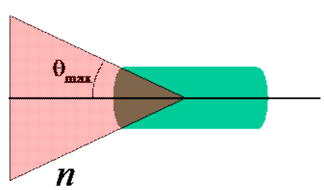
Myopia (Far Sighted): When light is focuses in front of the retina and not on it.

Negative System: A negative system will increase the divergence of an optical beam. Parallel beams will appear as if to be diverging from the focal point.

Newton's Formula: This equation relates transverse magnification with object and image distances and focal length.

$$m_y = -\frac{f}{\overline{FA}} = -\frac{\overline{F'A'}}{f'}$$

Numerical Aperture: A measure of the angular extent of a pupil.



$$NA = n \sin\theta_{max}$$

Optical Path Length: The optical path length is different than the geometrical path length in that it accounts for index of refraction. Given the index of refraction as a function of position in the optical system, n(x,y,z), the optical path length is defined as

$$L = \int_a^b n(x,y,z)\,ds \qquad ds = \sqrt{(dx)^2 + (dy)^2 + (dz)^2}$$

Optical Power: The ability of an optical system to bend or refract light.

Optical System (Imaging Systems): An ensemble of surfaces separating various media of different refractive index. Usually the media is homogeneous and isotropic. The surfaces may be refractive or reflective. An optical system acts as a ray deviator to serve a usual optical transformation of some kind.

Dioptric Systems: All surfaces are refractive.
Catadoptric Systems: All reflective or a combination of reflective and refractive surfaces.

Optics: The study of the behavior of light that may cover any part of the spectrum from ultraviolet (λ=0.2nm) to the far infrared (λ=10um).

Polarization: The alignment of the vibrating electric field. Linear polarization requires that the electric field oscillates along a straight line. Circular polarization requires that the electric field trace a 360 degree path as it propagates.

Positive System: A positive system will increase the convergence of an optical beam. Parallel rays will converge to the focal point.

Primary Aberrations: Also called Seidel, or third order aberrations, they include spherical, coma, astigmatism, field curvature, and distortion. Interestingly, while they represent departure from paraxial optics, they can be quantified by paraxial quantities.

Prism: A solid piece of refractive material for manipulating optical beams passing through it. These devices require no alignment, are more robust than mirrors, last longer than mirrors, but are heavier and more expensive.

Dispersive/Non-Dispersive: If light enters and exits the prism with normal incidence, the prism is non dispersive. Otherwise, the prism is dispersive and will refract each color of light differently.

Roof/Non-Roof: A roof does not change handedness, but flips the axis that is perpendicular to the plane of incidence on the roof.

Pupil: Pupils are the limiting aperture as seen from a particular point.

Entrance Pupil: Limiting aperture seen from object space. If the aperture is in object space, then the aperture is the entrance pupil. If the aperture is in image space, then the entrance pupil is the image formed from the aperture as seen from object space.

Exit Pupil: Limiting aperture seen from image space. If the aperture is in image space, then the aperture is the exit pupil. If the aperture is in object space, then the exit pupil is the image formed from the aperture as seen from image space.

Real Image: A real image of formed when an optical system forces light from an object to converge to a single point. A screen placed at this location will show the image.

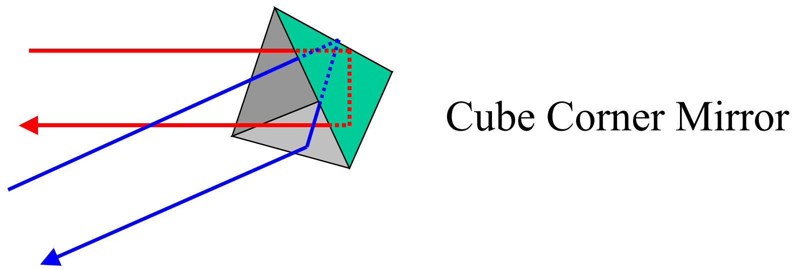
Recorded Image: The recorded image varies with the position of the receiving surface due to possible defocus. The receiving surface is most often positioned to coincide with the best focus aerial image.

Reflectance: Describes the fraction of the incident light that is reflected.

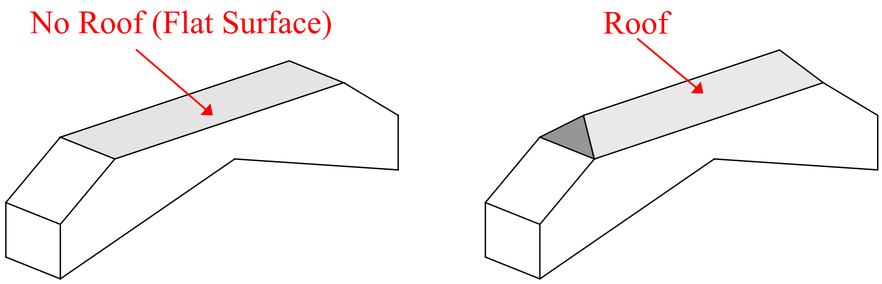
$$\boxed{R = r^2}$$

Reflectivity, r: Describes the fraction of the incident field that is reflected.

Retro-Reflective Mirror: This is a device that always reflects light in the same direction it came.

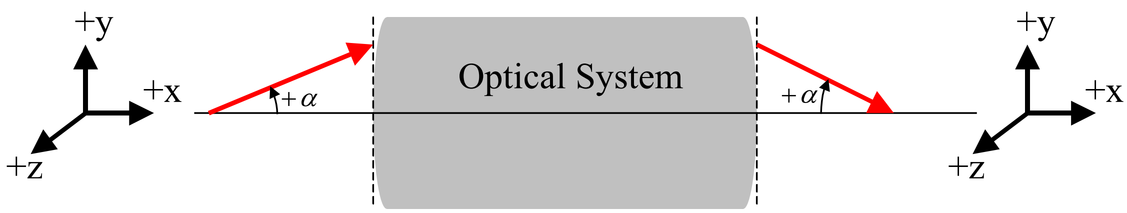


Roof: A reflective surface on a prism that is comprised of two perpendicular surfaces. The purpose of a roof is to invert the axis perpendicular to the plane of incidence on the roof.



Seidel Aberrations: Also called primary, or third order aberrations, they include spherical, coma, astigmatism, field curvature, and distortion. Interestingly, while they represent departure from paraxial optics, they can be quantified by paraxial quantities.

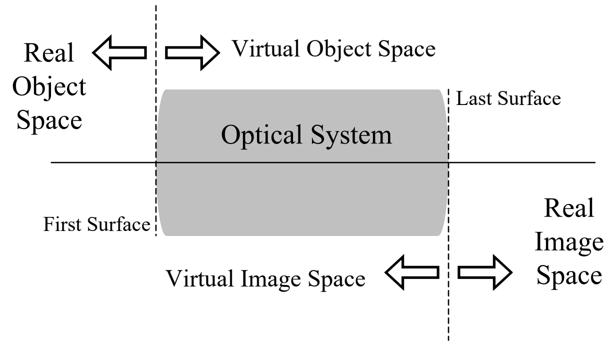
Sign Convention (Imaging): Propagation is from left to right unless specified otherwise.



Snell's Law (Descartes Law): The incident, reflected, and refracted rays are all coplanar.

$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

Space: There are four general spaces defined for an optical system.



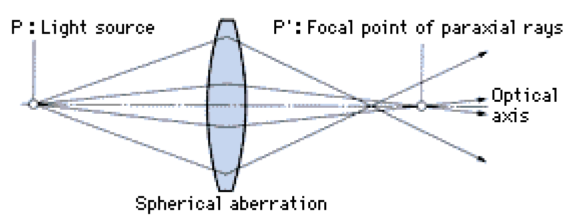
Real Object Space: This is the region to the left of the first surface of an optical system.
Virtual Object Space: This is the region to the right of the first surface of an optical system.
Real Image Space: This is the space to the right of the last surface of an optical system.
Virtual Image Space: This is the space to the left of the last surface of an optical system.

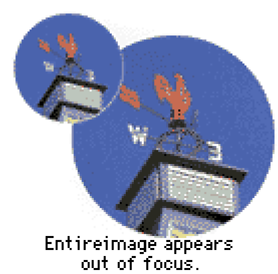
Speed: The speed of a lens relates to the f# necessary to provide enough light for a certain 'speed' shutter. Quick shutter speeds require more light on the detector which is provided by low F# systems. Thus, a fast lens refers to low F#. A slow lens refers to a high F#. This can also be thought of as focusing the light "quicker" (i.e. at a shorter distance).

Specular Reflection: Light reflected from a surface stays in the plane formed by the incident ray and the surface normal. Therefore, the incident and reflected rays are coplanar. The angle of incidence equals the angle of reflection in magnitude. This is true regardless of the shape of the surface.

$$\boxed{|\theta_{\text{inc}}| = |\theta_{\text{refl}}|}$$

Spherical Aberrations: This is the only on axis aberration and is rotationally symmetric about the optical axis. The optimum focal point does not coincide with the paraxial focal point. The severity of the spherical aberration varies to the fourth power of distance away from the optical axis (r^4).





Stereopsis: A detailed comparison of the two retinal images on the basis of paraxial geometry. It yields a vivid and highly accurate perception of 3D space.

Stigmatic Imaging: A point-to-point imaging condition. No aberrations. In a stigmatic system, all possible optical paths have the same time of travel, or same optical path length. The optical path length of all rays between two points in a stigmatic system are identical. An optical system that is stigmatic produces only spherical and plane wavefronts from spherical or plane wavefronts. A stigmatic system only suffers from amplitude distortions.

Geometrical Path Length (A to B): $\overline{AB}$

Optical Path Length (A to B): $[AB]$

In stigmatic systems,

$$\frac{\partial[AB]}{\partial\text{path}} = 0$$

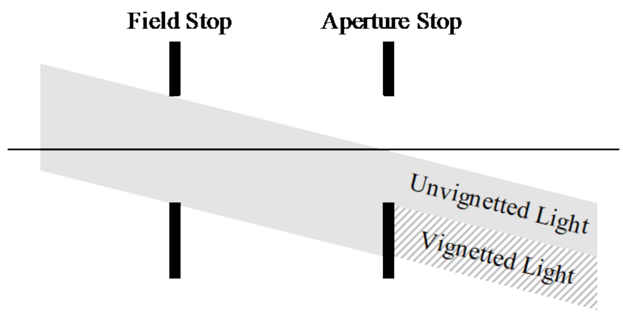
Stigmatism: A general descriptive term for an optical system which relates to the quality of the image with respect to the shape of the wavefront.

Stereoscopic Space: The unique capability of the binocular visual systems to evaluate depth relations among objects and surfaces.

Total Internal Reflection (TIR): This is the phenomena when light is incident greater than the critical angle and all light is reflected.

Tunnel Diagram: A tunnel diagram of an optical system unfolds the actual optical axis so that it is modeled as if propagation in a straight line from left to right. It is formed by folding the prism around the reflecting surfaces sequentially.

Vignetting: Vignetting occurs when an image forming bundle of rays is truncated and effects the image irradiance towards the edges of the image. Sometimes vignetting is used to improve image quality by eliminating light that would blur the image.



Virtual Image: When an optical system makes it appear as if light is diverging from a point, when in fact it is not. A virtual image will never appear on a screen.

Wavefronts: When rays form a point source have passed through a lens system, there always exist surfaces that are perpendicular to all the emerging rays: These surfaces are the wavefronts. This applies to isotropic media.