Geometrical Optics Review

A. Refraction at Single Spherical or Plane Surfaces

Curvature & Sagitta

Plane Surface: a surface where all rays normal to surface are parallel.
Spherical Surface: a surface where all normal rays pass through a single point.
Curvature: the angle through which the surface turns in a unit length of arc.

Curvature: $(R) = 1/r$

Where r = radius of curvature
Curvature can be measured with a **spherometer**.

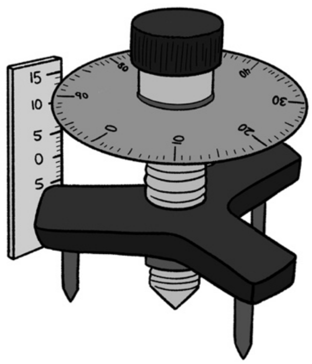
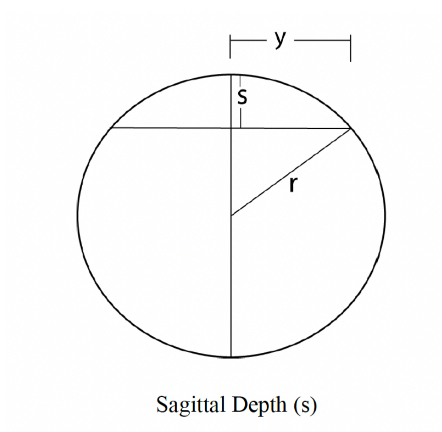


Figure 1 Spherometer

The spherometer rests on the lens surface and the center pin is adjusted to make contact with the lens. The spherometer provides a measurement of the sagittal depth of the surface. The sagittal depth can be used to calculate the radius of curvature.
Sagitta: the distance between a point on the circle and the midpoint of a chord of a circle.



$$r = \frac{y^2}{2s}$$

Figure 2 Sagittal Depth & Derivation of Approximate Formmula

Measuring the Sagittal Depth of a Lens with a Lens Clock

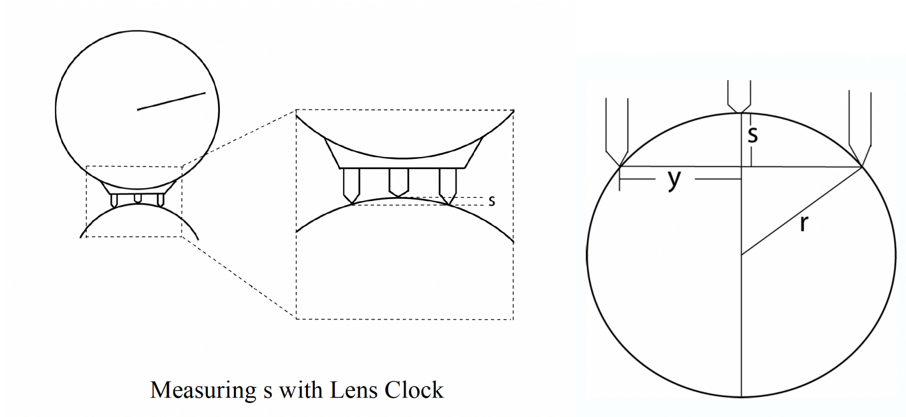


Figure 3 Lens Clock Operation

Sagittal depth (s) can be measured directly with a Lens Clock. The center movement is s. Y is the distance from the center pin to an outer pin. N is assumed to be 1.53 for moat lens clocks.

Refractive Index

The index of refraction for a substance is the ratio of the speed of light in air to the spend of light in the substance. The higher the index, the slower the velocity of light in the substance.
The index of refraction varies slightly with the wavelength of light.

$$n = \frac{velocity\ of\ light\ in\ air}{velocity\ of\ light\ in\ substance}$$

Index of refraction of ophthalmic lens materials

Crown Glass	1.523
CR 39	1.499
Polycarbonate	1.586
Trivex	1.53

Rectilinear Propagation

The concept of **Rectilinear Propagation** means that light travels in straight line.

Optical Medium: the space through which light travels.
Isotropic: medium has the same properties in all directions.
Homogenous: medium that has the same properties throughout its mass.

Vergence & Dioptric Power

Vergence: (measured in diopters) the amount of convergence or divergence of light rays.
The reciprocal of the distance (in meters) from a point to a source or a point focus.
Incident Vergence: vergence measured to the source
Emergent Vergence: vergence measured to the focus

Diopter

The diopter is the unit of power for vergence

$$L(diopters) = \frac{1}{l\ (meters)}$$

Object – Image Relationships

Location of Focal Points

Example: +5.00D thin lens with index of 1.52

$F = \frac{n}{f}$ +5.00D = $\frac{-1.00}{f}$ f = -20.00cm

$F' = \frac{n'}{f'}$ +5.00D = $\frac{1.52}{f'}$ f' = +30.40cm

Real Images

Real Images are formed by converging light rays.
Real Images can be focused on a screen.
Real Images are formed in image space.

Virtual Images

Virtual Images are formed by diverging light rays.
Virtual Images cannot be focused on a screen.
Virtual Images are formed in object space.

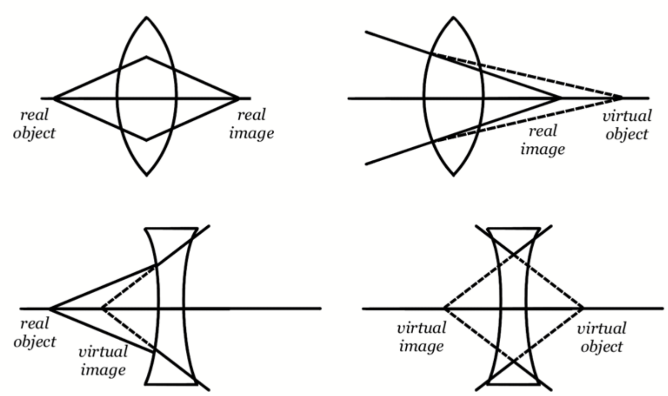


Figure 4 Image – Object Relationships (general)

Apparent Depth

When viewing an object that is suspended in or beneath a refractive medium with an index greater than the medium where the observer is located the object will appear to be closer and therefore larger than it is. The relationship between indices and the object and image distances can be expressed as:

$$\frac{n}{l} = \frac{n'}{l'}$$

where n is the index of the medium where object is located and n' is medium where observation is made

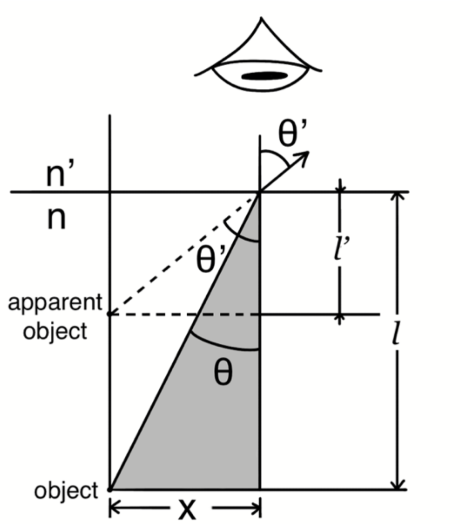


Figure 5 Apparent Depth

Note: if the index of refraction is greater on the observer side of the interface, the image of the object will appear smaller and farther away than the actual object.

Nodal Points & Nodal Rays

Nodal Points

The points on the principal axis of a lens system such that a ray of light directed towards the first nodal point (N), emerges from the system as if from the second nodal point (N'), and in a direction parallel to the incident ray. In other words, the ray (Nodal Ray) is undeviated by the system.

Lateral & Angular Magnification

Lateral Magnification

The ratio of the image size to the object size.

$$\frac{h'}{h} = \frac{l'}{l} = \frac{L}{L'}$$

Angular Magnification
The ratio of the angle subtended by the image with the lens or lens system to the angle subtended by the object without the lens or lens system.

$$M = \frac{Angle\ subtended\ by\ the\ magnified\ image}{Angle\ subtended\ by\ the\ object\ viewed\ directly}$$

$M = \frac{w'}{w}$, or $\frac{F}{4}$

Snell's Law of Refraction
Snell's Law quantifies the refraction that occurs at a surface

$$n \sin\theta = n' \sin\theta'$$

Where:
- n = index of refraction of primary medium
- n' = index of refraction of secondary medium
- Θ = angle of incidence
- Θ' = angle of refraction

B. Thin Lenses

Thin lens are those lenses in which thickness is negligible and therefore can be ignored.
The power of a thin lens is the sum of the two surface powers (aka nominal power).

Vergence: dioptric and effective power
F = F1 + F2 (Power of Thin Lens) (Nominal Power, Approximate Power)
Each surface power is found using the equation F = (n'-n) / r

Effective Power
The effective power of a lens changes as the distance from the eye changes.
A minus lens becomes more powerful moved closer to the eye and less powerful moved away from the eye.
The opposite effect occurs with a plus powered lens.
Due to effective power, myopes require less power for contact lenses and hyperopes require more power.

$$F_X = \frac{F}{1 - dF}$$

where:

- F_X = power of lens at point X (effective power)
- F = lens power
- d = distance from original position X

Compensating Power
For a spectacle Rx greater than 4.00D:
Myopes need less power for Contact Lenses
Hyperopes need more power for Contact Lenses

Object-Image Relationships

Use the relationship L + F = L' to determine L: the Incident (object) vergence or L': the Emergent (image) vergence for a thin lens.

For a Plus Lens

Image formation by Converging Lens

1. When the object is outside the primary focal point of the lens (image distance in image space is greater than the primary focal length, the image is real, inverted, and minified.
2. When the object is at the primary focal point of the lens, the image is formed at infinity.
3. When the object is inside the primary focal point (image distance in image space less than primary focal length) the image is virtual, erect, and magnified.
4. When the object is at infinity, the image is real, inverted, and at F' (secondary focal point).

Object	Image	Type	Size
At Infinity	At F'	Real, Inverted	
Infinity – 2f	f' – 2f	Real, Inverted	Minified
At 2f	At 2f'	Real, Inverted	Same
2f - f	2f' - Infinity	Real, Inverted	Magnified
At F	At Infinity		
F - O	Same side as object	Virtual, erect	Magnified

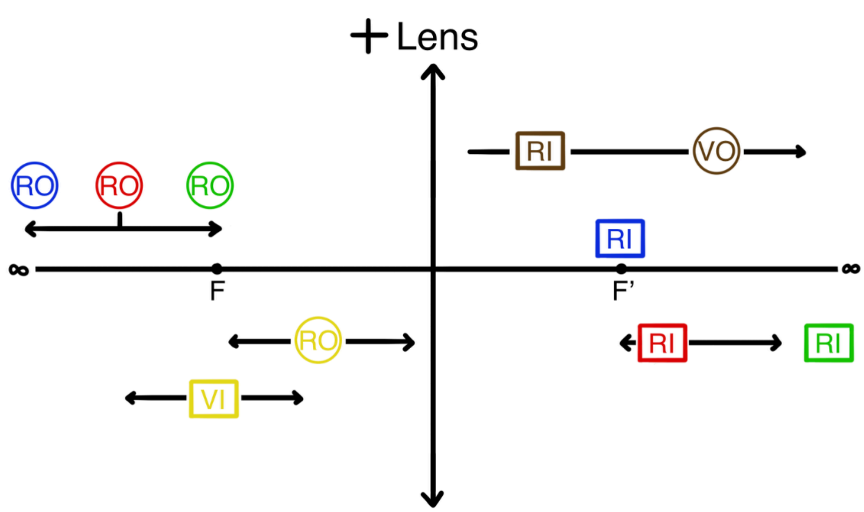


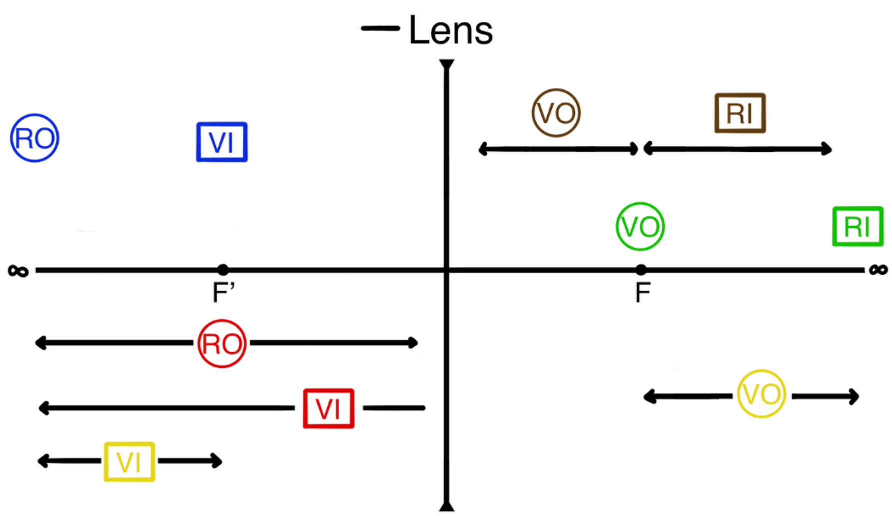
Figure 6 Object / Image Relationship: Plus Lens

For a Minus Lens

Image formation by Diverging Lens

1. For a real object, the image is always virtual, erect, minified, and located between object and lens.
2. When object is at infinity the image is virtual at F'.

Object	Image	Type	Size
At Infinity	At F'	Virtual	
Infinity – O	F' - O	Virtual, Erect	Minified



(note: any RO creates VI)

Figure 7 Object / Image Relationship: Minus Lens

Lateral (translinear) and Angular Magnification

Lateral Magnification

The ratio of image size to object size (due to image distance)

$$\frac{h'}{h} = \frac{l'}{l} = \frac{L}{L'}$$

Angular Magnification

$$M = \frac{\textit{Angle subtended by the magnified image}}{\textit{Angle subtended by the object viewed directly}}$$

$M = \frac{w\prime}{w}$, or $\frac{F}{4}$

Thin Lens Systems

The simplest multiple lens systems is two thin lenses that are assumed to have no significant separation between them, the power of the lens system is the addition of the two lens powers.
If the is a significant separation between the lenses, this can an effect on the power of the system. If the lenses are separated by air then the index can be ignored.

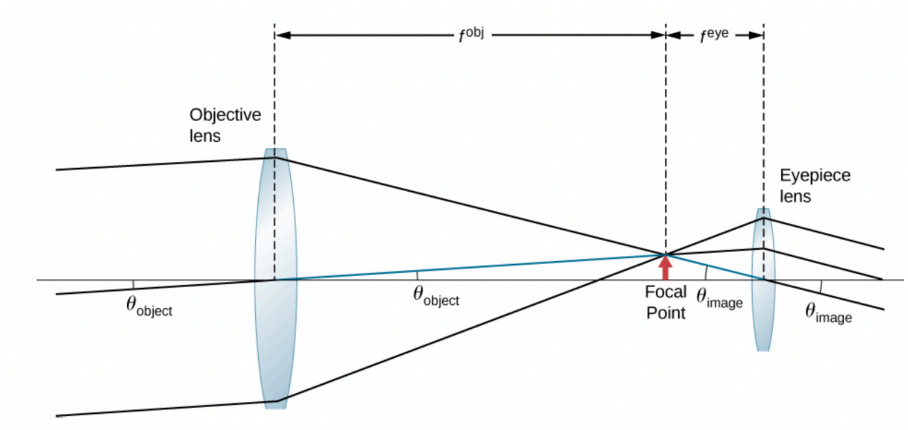


Figure 8 Thin Lens System Optics (Credit: Ling, Sanny, & Moebs (UCF))

For the lens system in the figure above:

Object for Lens 1 at infinity
Image for Lens 1 is Object for Lens 2
F' for Lens 1 = F for Lens 2
Emergent Vergence for system is 0

Equivalent power of a thin lens system

$$F_E = F1 + F2 \ - dF1F2$$

Prismatic Effect (Prentice's Rule & Prism Effectivity)

Prentice's Rule

The prismatic effect at any point on a spherical lens is equal to the distance of the point from the pole (optical center) of the lens, in centimeters, multiplied by the power of the lens.

Δ = dP

- Δ = prismatic power
- d = distance from lens pole
- P = refracting power of the lens

Prism Effectivity

Changing the distance of a prism from the spectacle plane changes its effective power.
Prism effect decreases as vertex distance increases.
The decrease in prismatic effect only applies to near objects.
The reference point for prism effectivity is the center of rotation of the eye.

$$\Delta_e = \frac{\Delta}{1 - \frac{s}{u}}$$

Where:
s = the distance from prism to center of rotation of the eye
u = the distance from prism to near object

Ray Tracing, Optical Center, and Optic Axis

Optical Center
The point where an undeviated ray intersects the optic axis.

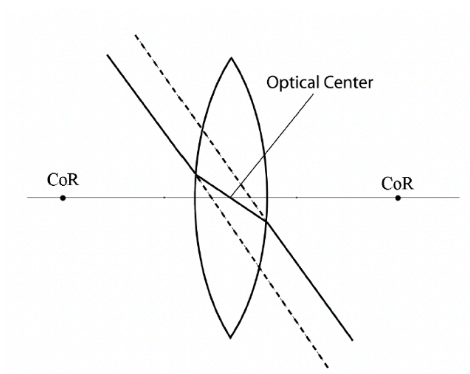


Figure 9 Optical Center

Optic Axis
A line that connects the centers of rotation of a lens.

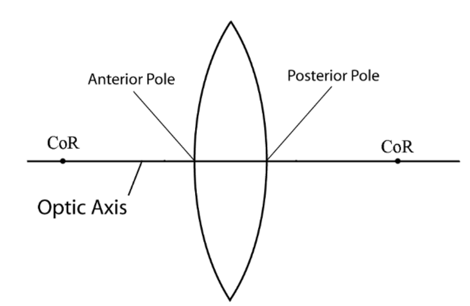


Figure 10 Optic Axis

C. Thick Lenses

Thick Lenses are those lenses where the center thickness cannot be ignored.
The total power of a thick lens does not equal the sum of its surface powers (nominal power).

Cardinal Points

The two Principal Foci (F & F')
The two Principal Points (P & P')
The two Nodal Points (N & N')

Cardinal Points & Distances

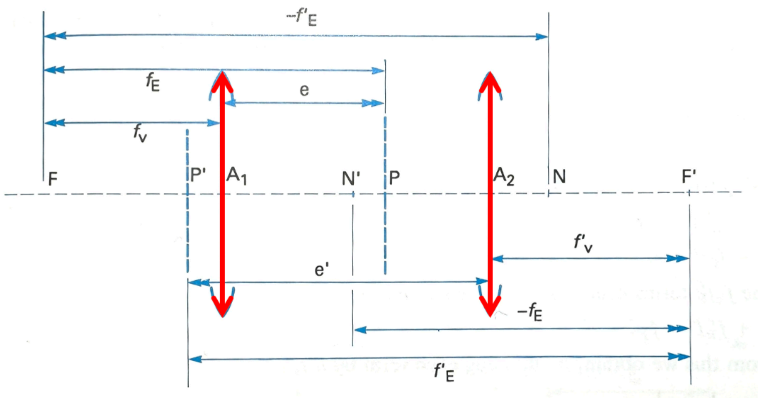


Figure 11 Cardinal Points & Distances (credit Freeman 1990)

Principal Foci & Principal Points

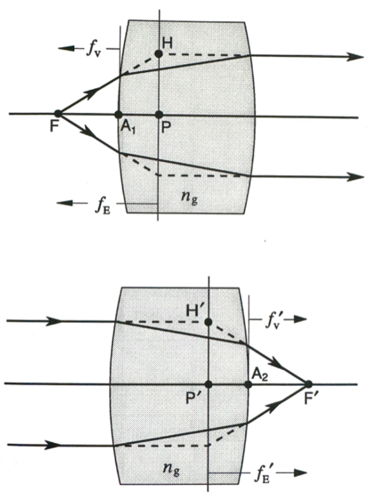


Figure 12 Principal Foci & Principal Points (credit Tunnacliffe & Hirst 1996)

Focal Points

Primary Focal Point (F)
Secondary Focal Point (F')

Principal Points

Found on Principal Planes (H & H')
Where optic axis intersects H & H'
First Principal Point (P)
Second Principal Point (P')

Nodal Points

A ray that passes undeviated through a thick lens passes through the nodal points.
The first and second nodal points lie along the optic axis of the lens.
The nodal ray crosses the optic axis at the optical center.

When the index on each side of the lens is the same, the Nodal Points (N, N') coincide with the Principal Points (P, P').
When the index to the right of the lens is greater than the index to the left of the lens, the Secondary Nodal Point (N') will be to the right of the lens in image space.

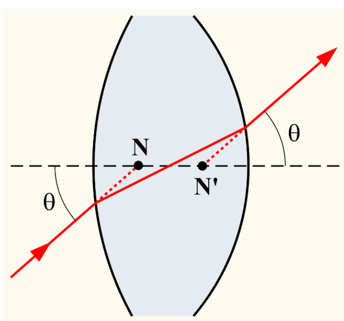


Figure 13 Nodal Points

Equivalent Power

For thick lenses it is important to consider the impact of the center thickness of the lens on lens power. This can be done using Front and Back Vertex power as well as Equivalent power.

Reduced Thickness

The reduced thickness of a thick lens is found using:
$t' = t_{lens} / n_{lens}$

Equivalent Lens Power

The equivalent lens is a theoretical lens that replaces the optical elements of an optical system or of a thick lens. With a thick lens, all refraction is assumed to take place at the principal planes of the lens. Once equivalent lens power has been determined, the index of the lens can be ignored as we used the reduced thickness in calculating the equivalent lens power.

Equivalent lens power is found using:

$Fe = F1 + F2 - t' (F1)(F2)$

Primary Equivalent Focal Length (fe):
focal length measured from the Primary Equivalent Focal Point to Primary Focal Point

Primary Focal Power:
Fe = -n/fe = n'/fe' where fe is the distance between H and F
Measured from P

Secondary Focal Power:
Measured from P'
Lateral & Angular Magnification

D. Aberrations

Monochromatic Aberrations
When a spherical wavefront is incident on a spherical interface, the exiting wavefront is no longer spherical. These are also known as Seidel Aberrations or third order aberrations.

Spherical Aberration
Spherical aberration is a problem for optical systems with large apertures. Spherical aberration can be an issue for spectacle lenses with high plus power, especially those used for correction of aphakia. Spherical aberration can be reduced by using aspheric surfaces.

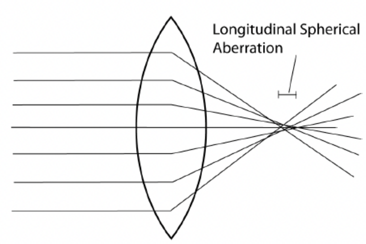


Figure 14 Spherical Aberration

Coma
Coma occurs when oblique or off axis rays are refracted by a large aperture optical system. Like spherical aberration the problem is that the lens has a different focal length in the periphery than the center of the lens. The image formed by the lens is comet shaped. Coma is typically ignored in the design of spectacle lenses.

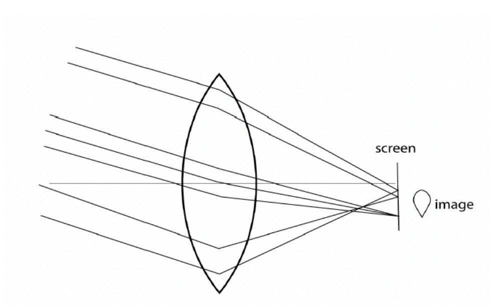


Figure 15 Coma

Oblique Astigmatism

Oblique astigmatism, also called marginal or radial astigmatism, occurs when a small pencil of light from an object passes obliquely through a lens and rather than forming a point focus it forms an interval of Sturm with two line foci and a circle of least confusion. The amount of oblique astigmatism is the dioptric separation of the two line foci (the tangential focus and the sagittal focus).

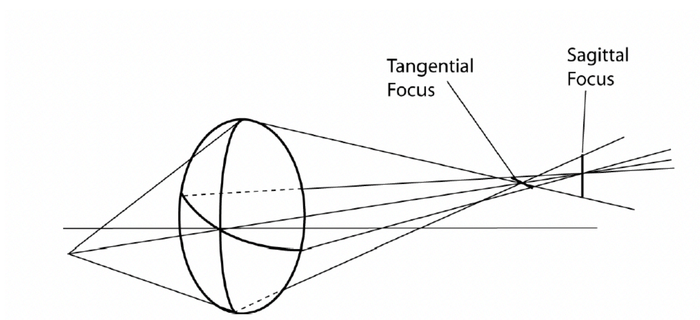


Figure 16 Oblique Astigmatism

Oblique astigmatism is significant for spectacle lenses and lenses are designed to minimize oblique astigmatism. Lenses are designed that bring the two foci closer together. This involves solving a quadratic equation (Jalie's equation) and choosing the flatter base curve given the back vertex power. Jalie's equation produces and ellipse and the flatter curve (Ostwalt's curve) provides the base curve that eliminates oblique astigmatism.

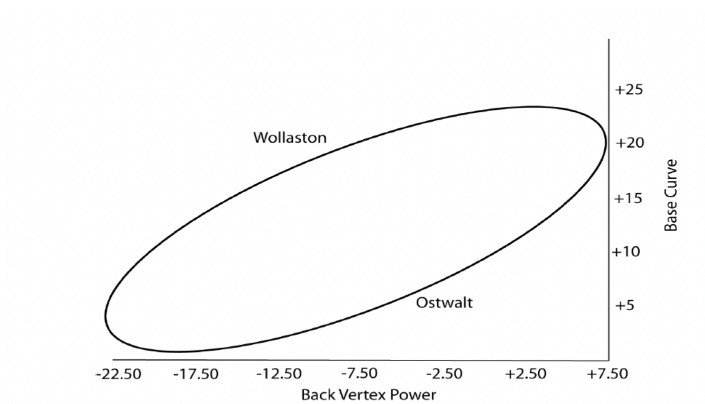


Figure 17 Tscherning's ellipse

Curvature of Field

An ophthalmic lens does not form a plane image for a plane object but rather forms a curved image. This curved image is known as the Petzval surface. For a converging lens, the off axis image is closer to the object point than the axial image point. For a diverging lens, the image curves so that the off axis point is farther from the object point than the axial image point.

When the Petzval surface varies from the far point sphere, Curvature of Field occurs. Curvature of Field is controlled using base curve selection. Base curves that minimize Oblique Astigmatism will also reduce Curvature of Field.

Distortion
Unlike other Seidel monochromatic aberrations, distortion is not a problem of image defocus but rather a problem of image shape. Distortion occurs because the magnification of the extended image varies with the distance of the corresponding object point from the optic axis. In plus powered lenses, magnification increases away from the optic axis, and this results in pincushion distortion of the image. For minus lenses powered lenses, magnification decreases away from the optic axis, and this causes barrel distortion of the image.

Distortion is a problem for higher powered spectacle lenses. Distortion is generally ignored in spectacle lens design. In theory distortion can be reduced using steeper back surfaces.

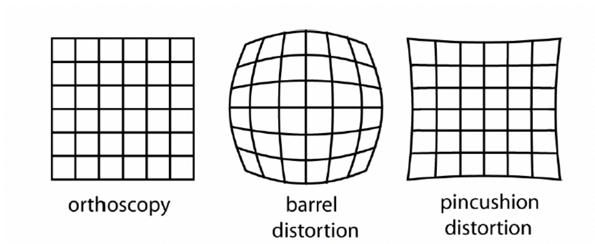


Figure 18 Distortion

Chromatic Aberration
The refractive index of a lens material wavelength dependent. For most materials the refractive index is higher for shorter (blue) wavelengths than for longer (red) wavelengths. This means lenses display different refractive powers for different wavelengths of light. Chromatic aberration are a function of lens material and not affected by lens shape.

Due to light source containing multiple wavelengths instead of being monochromatic.
Different wavelengths of light are refracted differently by the medium.
Chromatic aberrations can be Longitudinal or Lateral.

Longitudinal (Axial) Chromatic Aberration (LCA)

Each wavelength of light focuses on a different point along the optic axis.

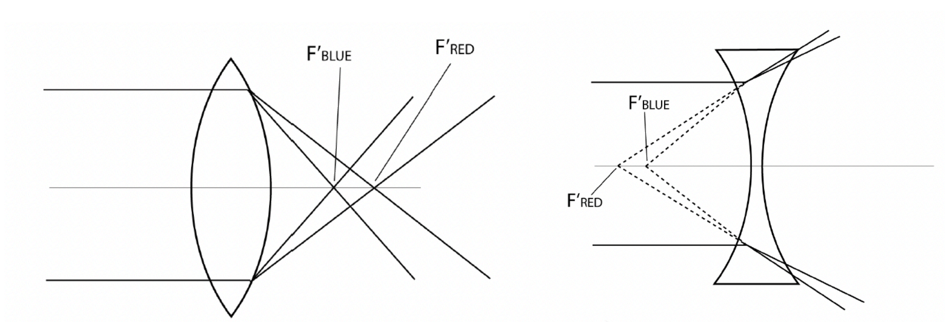


Figure 19 Longitudinal Chromatic Aberration

A plus lens creates positive longitudinal chromatic aberration (red focus to the right of blue focus) and a negative lens creates negative longitudinal chromatic aberration (red focus to the left of the blue focus).

Lateral (Transverse) Aberration

Transverse or Lateral chromatic aberration is due to the difference in image size for different wavelengths of light originating from off axis points. The image from shorter wavelengths is smaller than the image from longer wavelengths. Transverse chromatic aberration can be measured in terms of either linear or angular differences in image size.

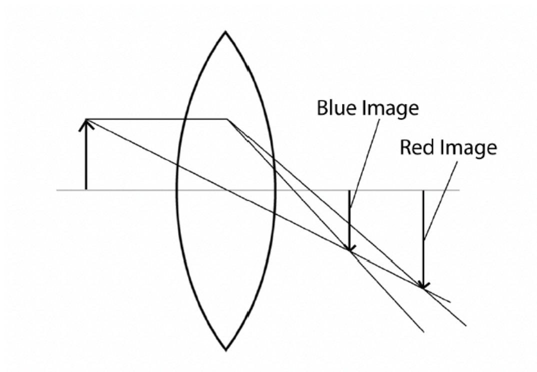


Figure 20 Lateral Aberration

Correction of Chromatic Aberration

Longitudinal chromatic aberration can be eliminated by using an achromatic doublet. This is a lens constructed by adding together concave and convex lenses of different Abbe values. If the lens is constructed so that the refracting power for blue and red wavelengths are equal, longitudinal chromatic aberration is minimized or eliminated. Doublets are not used for correcting refractive errors. However, they are important in the construction of some ophthalmic instruments. It is important to note that even with longitudinal chromatic aberration eliminated transverse chromatic aberration may be present. Chromatic aberration is not a significant problem with most spectacle lenses.

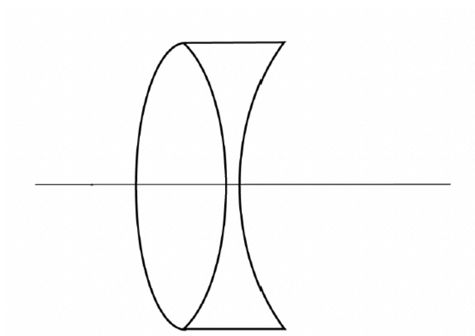


Figure 21 An Achromatic Doublet

Design of an Achromatic Doublet
An achromatic doublet can minimize chromatic aberration by combining a positive and negative lens of different materials (with different index of rection). The LCA of the plus lens will cancel out the LCA of the minus lens.

The Lens Powers are additive: F = (F1) + (F2)
Chromatic Aberration is additive: LCA + LCA1 + LCA2

E. Stops, Pupils, & Ports

Control of Light Through and Optical Systems

The functions of stops in optical systems

- Control aberrations of the image
- The depth of focus and depth of field
- The illuminance of the image
- The resolving power of the instrument
- The field of view

Aperture & Field Stops

Aperture Stop

The aperture stop is the physical component that limits the amount of light reaching the image and therefore controls the illuminance (brightness) of the image. The aperture stop can be located in front of, behind, or within the lens system. One of the lenses may serve as the aperture stop. The aperture stop depends on the location of the object.

Field Stop

The field stop determines the extent of the object that will be represented in the image (the field of view).

Entrance & Exit Pupils

Entrance Pupil: the image of the aperture stop as seen from the object.
Exit Pupil: the image of the aperture stop as seen from image space.

Entrance & Exit Ports (Windows)

Entrance Window: the image of the field stop as seen from object space.
Exit Window: the image of the field stop as seen from the image space.

Depth of Focus, Depth of Field, Hyperfocal Distance

Field of View and Half Illumination

The maximum observable dimensions of an extended object or the angular extent of the object measured relative to a particular point on the optic axis. The Field Stop is the physical component that determines the Field of View (FOV) by limiting the angle of the principal (chief) rays from oi axis points that can pass through the optical system.

Principal Ray: passes through the center of the entrance pupil and after refraction, passes through the center of the exit pupil.

The FOV can be quantified as the angle subtended at the Entrance Pupil by the edges of the Entrance Window (in degrees).

Field of Half Illumination

The edge of the field of view where . of the light passes through the optical system. The Principal Ray defines the boundary of the Field of Half Illumination.

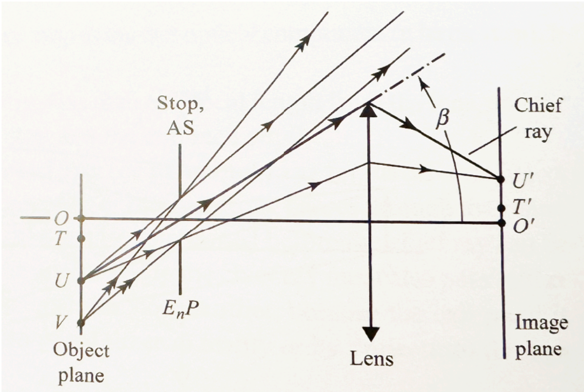


Figure 22 Field of Half Illumination (credit Pedrottis 2025)

Field of View Calculation

$$FOV\ (\alpha) = 2\theta$$

$$tan\theta = \frac{radius\ of\ EnW}{distance\ of\ EnP\ to\ EnW}$$

Where:
EnW is the Entrance Window
EnP is the Entrance Pupil

Depth of Field & Depth of Focus

Depth of Field
The total axial range (along the optic axis) over which the object can be moved without noticeable deterioration in the image quality given a fixed image plane.

Depth of Focus
The total axial range (along the optic axis) over which the image plane can be moved without noticeable deterioration in the image quality given a fixed object.
Depth of Field & Depth of Focus are dependent on aperture size.

This illustration shows the extent of depth of field (object space) and depth of focus (image space). Both can be specified as linear distances or dioptric equivalents.

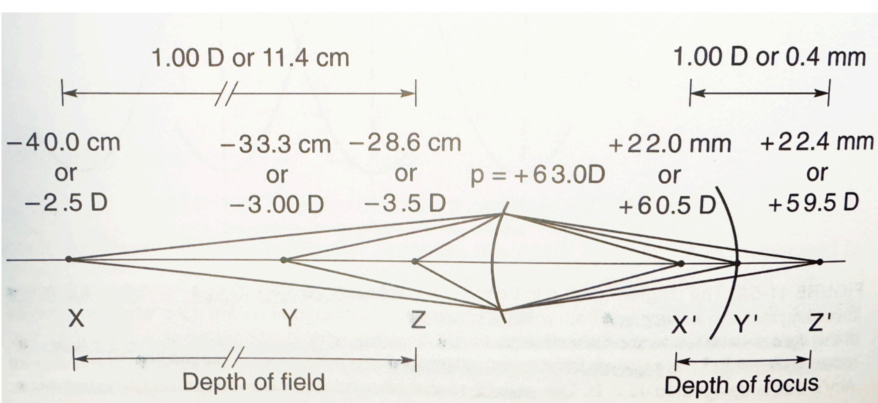


Figure 23 Depth of Field & Depth of Focus (credit Schwartz 2002)

Hyperfocal Distance

When a lens is focused at infinity (emergent vergence is 0), the closest object point to the lens that yields a clear image is the Hyperfocal distance.

When a lens is focused at the Hyperfocal distance all object point up to ½ the hyperfocal distance will produce clear images.

F. Spherocylindrical Lenses

Location of foci, image planes, principal meridians, and circle of least confusion

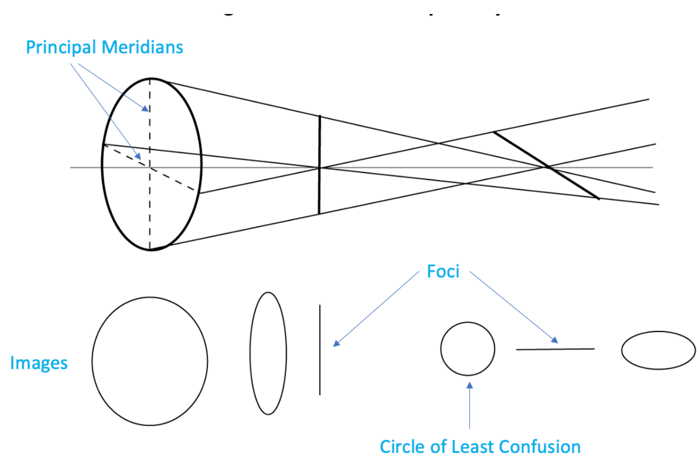


Figure 24 Spherocylindrical Lens Optics

Principal Meridians
Contain the maximum and minimum curvatures of the lens
The principal meridians are perpendicular
Axis Meridian: the meridian of least curvature

Circle of Least Confusion
The position on the pencil of light with the smallest cross sectional dimension
The circle of least confusion is not linearly centered, but rather dioptrically centered between the two principal meridians

Obliquely Crossed Cylinders

Two Spherocylinder lenses are added together in a manner where cylinder axes are not 090 degrees apart.

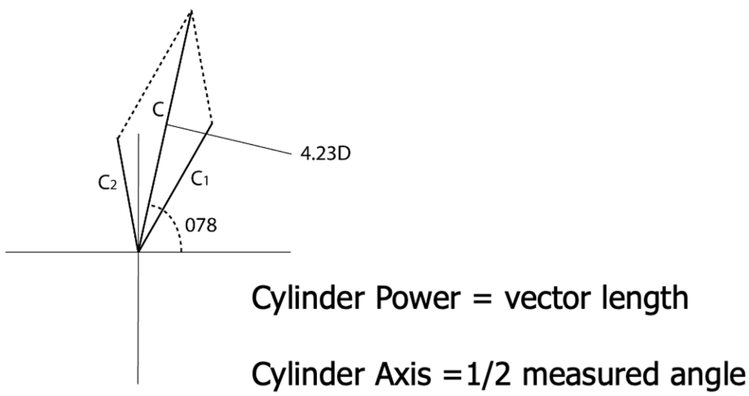


Figure 25 Vector Addition: Obliquely Crossed Cylinders

Clinical Application of Obliquely Crossed Cylinders

Used when fitting toric contact lenses.
Use with SCOR (Sphero Cylinder Over Refraction)
Combine CL power (trial lens) with over refraction to determine resultant power.
This provides the CL power to be ordered for the patient.

Transposition

Cylinder Transposition has three steps:

1. Add the sphere power and the cylinder power algebraically to obtain the new sphere power.
2. Change the sign of the cylinder.
3. Rotate the cylinder axis 090 degrees

Prismatic Effect

Prismatic effects with Spherocylinder lenses

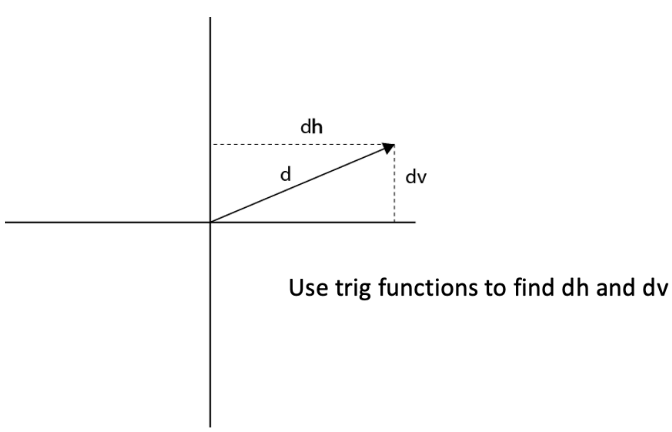


Figure 26 Prismatic Effect with Spherocylinder Lenses

G. Thin Prisms

Unit of Measure (Prism Diopter)

A prism diopter is 1cmm of deviation at a distance of 1meter.

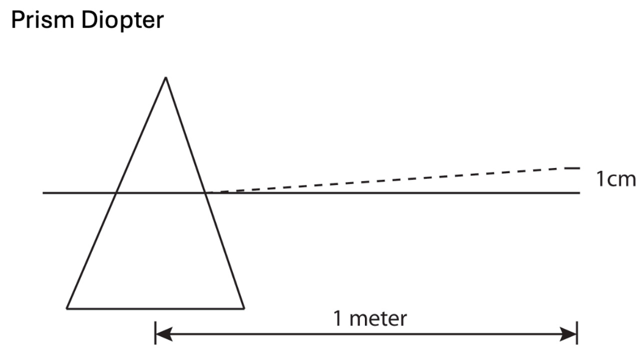


Figure 27 Prism Diopter

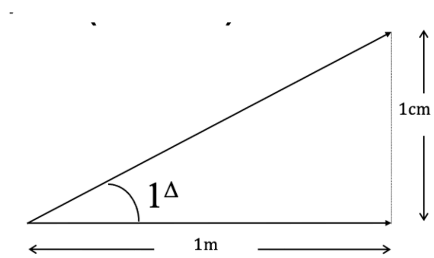


Figure 28 Prism Diopter

Prism Deviation

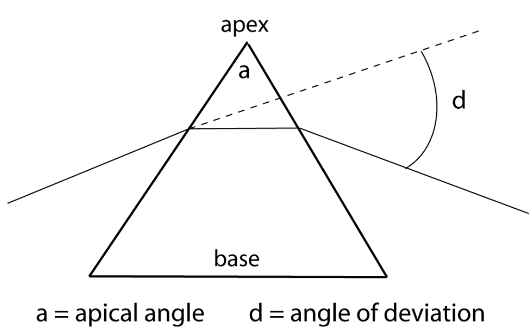


Figure 29 Prism Deviation

Objects viewed through a prism appear to be displaced toward the apex of the prism.

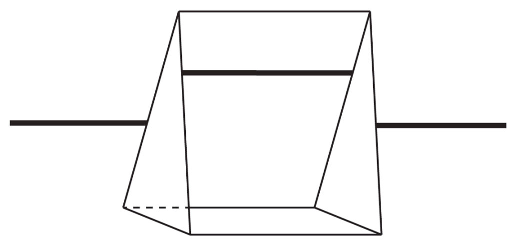


Figure 30 Prism Deviation

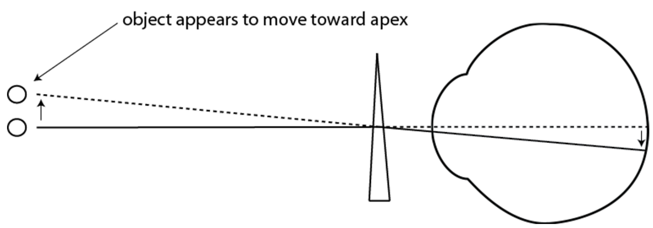


Figure 31 Prism Deviation

Combination of Thin Lenses
Combining multiple prisms into one "equivalent" prism.
Combining prisms (binocularly):
Same Bases = Subtract Prism Powers
Opposite Bases = Add Prism Powers

Resolution of Oblique Prisms
Resolving a prism into horizontal and vertical components.
Use Pythagorean Theorem to find the horizontal and vertical prism powers.

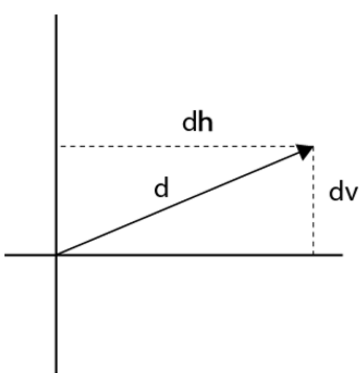


Figure 32 Resolving Oblique Prism

Total Internal Reflection
As light passes from air into a medium, the angle of refraction is less than the angle of the incidence (deviated toward the normal).

Critical Angle
When light passes from a denser to a less dense medium, light is deviated away from the normal.
When the angle is increased until no light is refracted and all light is internally reflected, this angle is called the Critical Angle.

$$\sin\theta_c = \frac{n'}{n}$$

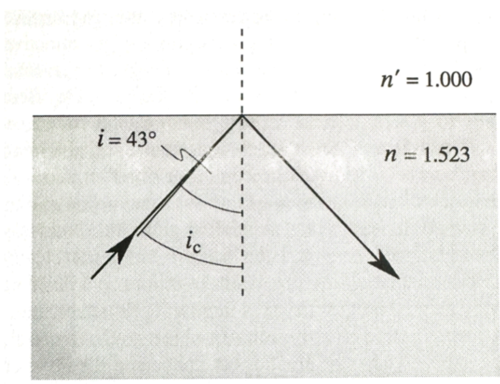


Figure 33 Critical Angle

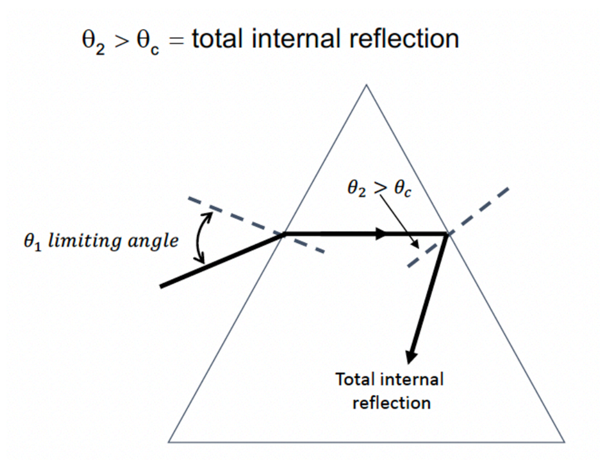


Figure 34 Total Internal Reflection (Credit Loshin)

H. Optical & Ophthalmic Instruments

Review of Ports(windows) & Pupils

It is important to be able to identify the limits of light and field of view with lens systems. Optical Instruments are common examples of optical lens systems.

Aperture Stop: the element that limits the amount of light passing through the system.
Entrance Pupil: the image of the Aperture Stop from object space.
Exit Pupil: the image of the Aperture Stop from image space.
Field Stop: the element that limits the field of view (field of half illumination) for the system.
Entrance Window: image of the Field Stop from object space.
Exit Window: image of the Field Stop from image space.

Simple Magnifiers

A simple magnifier can be created with a single plus powered lens.
The simple magnifier provides angular magnification which is measured by comparing the angle subtended by the image with and without the lens. This can be thought of as the ratio of the "modified" size of an image to the "original" size of the image. This requires a standard reference distance for comparison.
The reference distance for simple magnifiers is 25cm (the minimum distance of distinct vision).
When an object is placed at the primary focal point of the magnifier, no accommodation is required to obtain a clear image and the distance between the eye and magnifier is not important.

With an object at primary focal point of the lens:
M = F/4 where F is lens power and 4 is 1/reference distance in meters.

When the object is not at the primary focal point, accommodation is required (1/image distance) and **M = F/4+1**.

Angular Magnification with a Simple Magnifier

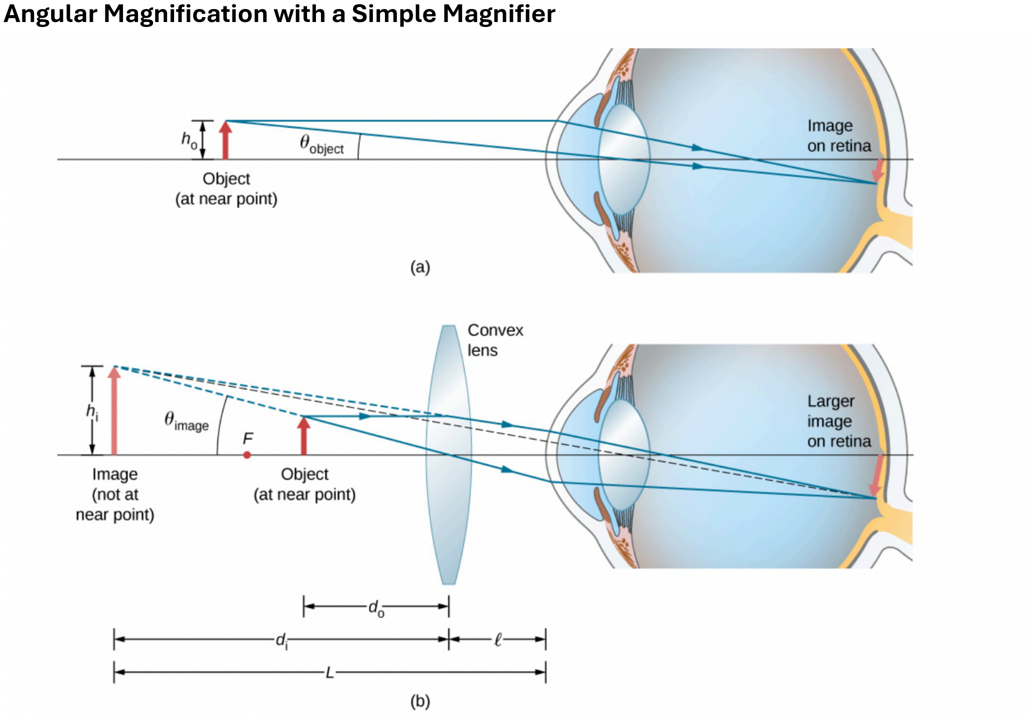


Figure 35 Angular Magnification with Simple Magnifier (credit: Ling, Sanny, & Moebs: UCF Physics)

Telescopes (Afocal)

An afocal telescope produces magnification for distant objects without a change in the vergence of light. When used by an emmetrope or an ametrope corrected for distance no accommodation is required. Two types of afocal telescopes are used as aids by low vision patients (Keplerian & Galilean). Both types produce angular magnification of distant objects.

General Characteristics

Simple afocal telescopes are systems of two lenses: an objective lens and an eyepiece lens. The eyepiece is always higher powered than the objective lens. The aperture of the objective lens is the aperture stop and the entrance pupil for both types of afocal telescope. For the Galilean telescope the aperture of the eyepiece is the field stop and exit window for the system. For a Keplerian telescope an aperture can be placed at the secondary focal point of the objective lens to create the field stop (resulting in a sharper image). Without this aperture the aperture of the eyepiece serves as the field stop. The exit pupil for is behind the eyepiece for a Keplerian TS and between the lenses of a Galilean TS.

Keplerian (astronomical) Telescope

The Keplerian telescope utilizes a positive powered objective lens and a positive powered eyepiece lens. This combination creates an image that is inverted. By adding a third lens to the system an erect image can be produced.

Keplerian Telescope Optics

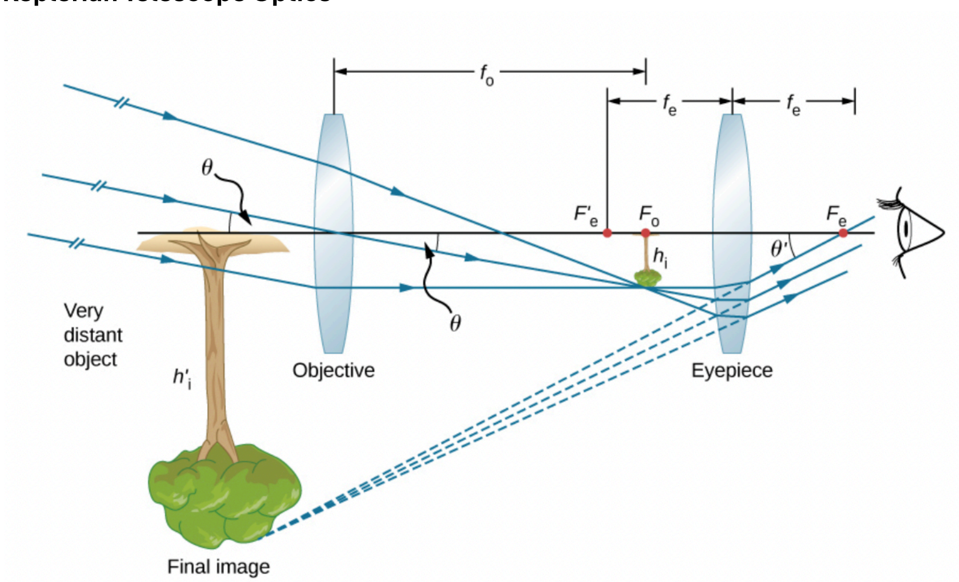


Figure 36 Keplerian (Astronomical) Telescope Optics (Credit: Ling, Sanny, Moebs UCF Physics)

Galilean (terrestrial) Telescope

The Galilean telescope utilizes a positive powered objective lens and a negative powered eyepiece lens. The combination creates an erect image.

Galilean Telescope Optics

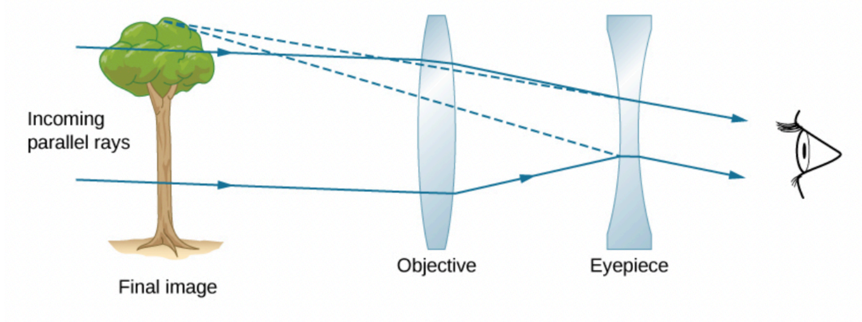


Figure 37 Galilean Telescope Optics (Credit: Ling, Sanny, Moebs UCF Physics)

Telescope Magnification

Afocal telescopes create angular magnification which can be determined with the following formula:

$$Magnification = \frac{-F_{eyepiece}}{F_{objective}}$$

Telescope Length (tube length)

$$\text{telescope length} = f'_o - f_e$$

F' of the objective lens coincides with F of the eyepiece.
For a given magnification (same objective and eyepiece powers) a Galilean telescope is shorter than a Keplerian telescope.

Telescope Effective Magnification

If a telescope is being used by an uncorrected ametrope, the user will have to adjust the telescope length (distance between lenses) to obtain a clear image. For either telescope type an uncorrected myope will decrease the separation between the lenses and an uncorrected hyperope will increase the distance between the lenses. With an uncorrected refractive error the magnification will change as follows:

$$M_{\text{Effective}} = M + \frac{dMRE}{M - 1}$$

Where d is the separation between lenses, M is the telescope magnification for emmetropia, and RE is the user's refractive error.

Effective Telescope Magnification for Ametropia

Refractive Error	Galilean TS	Keplerian TS
Myopia	Reduced	Increased
Hyperopia	Increased	Reduced

Telescopes for Reading (low vision)

When used in low vision for near distances, telescopes are fitted with a reading cap (plus lens attached to the front) and the total magnification is the product of angular magnification and relative distance magnification. The reading cap power is the plus powered required for the reading distance. For example, to use a telescope at 33cm would require a reading cap power of +3.00D.

Telemicroscope: Telescope with Reading Cap used for near work

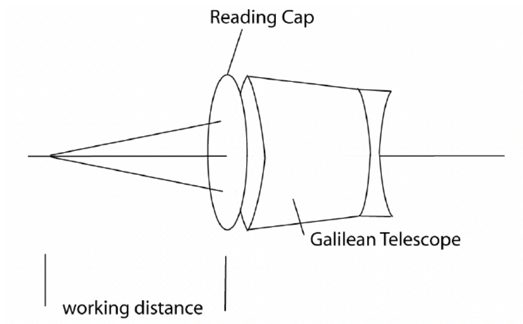


Figure 38 Telemicroscope Optics

Microscopes

The simplest compound microscope is constructed from two convex lenses.
The objective lens is a convex lens that has a short focal length with a magnification typically from 5 to 100.
The eyepiece (ocular) is also a convex lens but has a greater focal length (lower power) than the objective lens.

The compound microscope is not an afocal system. A microscope produces an enlarged image that is easily viewed (beyond the eye's near point). The object to be viewed is placed just beyond the focal point of the objective lens which produces a magnified, real, inverted image. The image (which is the object for the eyepiece) is located within the focal length of the eyepiece which results in an image that is further magnified. The final image is a virtual image that remains inverted.

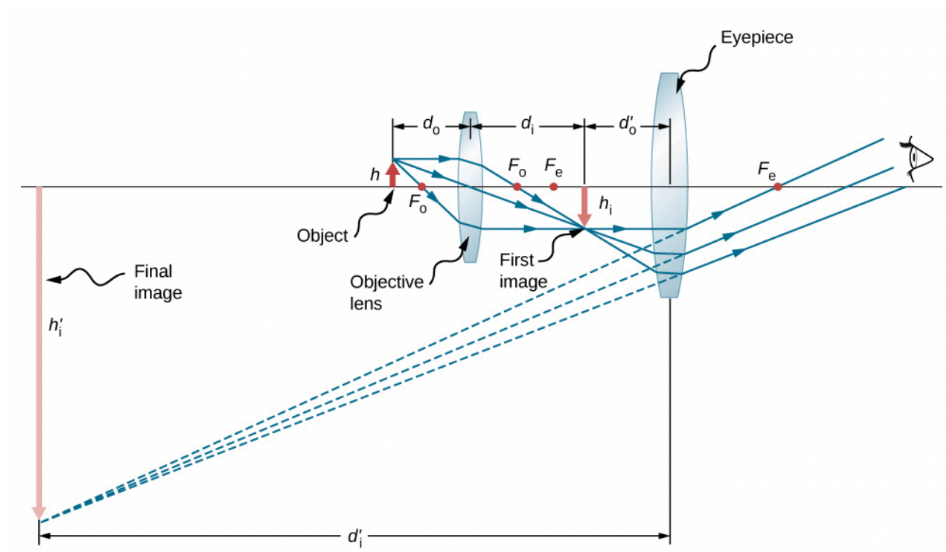


Figure 39 Compound Microscope Optics (Credit: Ling, Sanny, Moebs UCF Physics)

Microscope Magnification

The overall magnification of a compound microscope is the product of:

The linear magnification of the objective lens
The angular magnification of the eyepiece
M_{TOTAL} = LMo x AMe (LMo = Lateral Mag from Objective Lens and AMe = Angular Mag from Eyepiece)
LMo = l'/l (l' = image distance, l = object distance)
AMe = F/4 (F = eyepiece power)

Microscope Tube Length

The tube length is the distance between the focal points F'o and Fe.

Lensometer

The lensometer can be used to determine front and back vertex powers of spectacle and contact lenses.

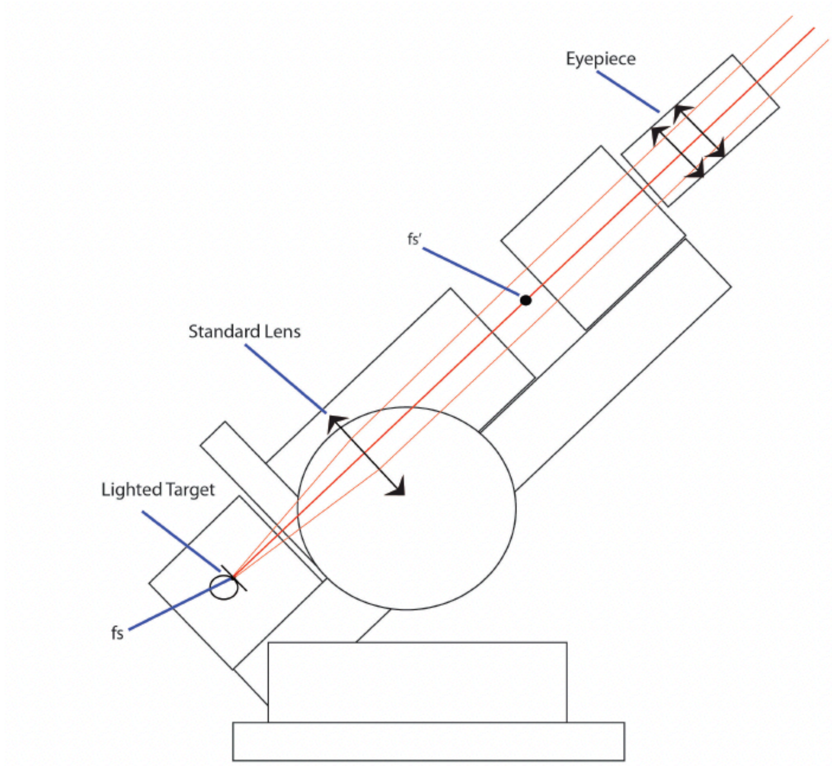


Figure 40 Lensometer Optics

Lensometer Optics: Important Elements

Moveable Target (lighted)
Standard Lens (+20D is typical)
Lens Stop (position of lens to be measured)
Eyepiece (Keplerian Telescope)

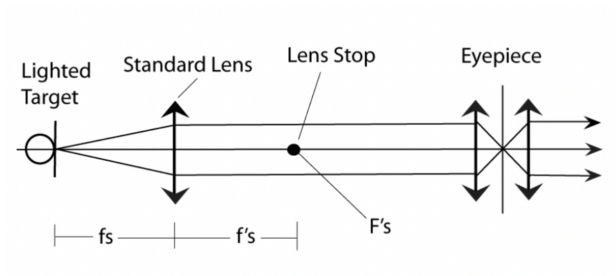


Figure 41 Lensometer Optics

Lensometer Optics

With the lensometer properly calibrated and no test lens in place the lighted target should be located at the primary focal point of the standard lens and parallel light (vergence of 0) should emerge from the eyepiece. The only moving parts of the lensometer are the lighted target and the measuring drum which are linked together. With a test lens at the lens stop (the secondary focal point of the standard lens) the vergence of light emerging from the eyepiece will change and create a blurred image of the lighted target. By rotating the measuring drum the lighted target is relocated to a position where parallel light is once again emerging from the eyepiece. The target must be positioned so that light incident on the test lens is convergent for a negative test lens and divergent for a positive test lens. The distance the target moves from the primary focal point is the extrafocal distance which can be used with Newton's relation to determine the test lens power.

$$x_s = f_s^2 F_v'$$

Where: x_s = target movement fs = standard lens focal length F_v' = back vertex power of test lens

Lensometer Optics: Neutralizing a Plus Powered Test Lens

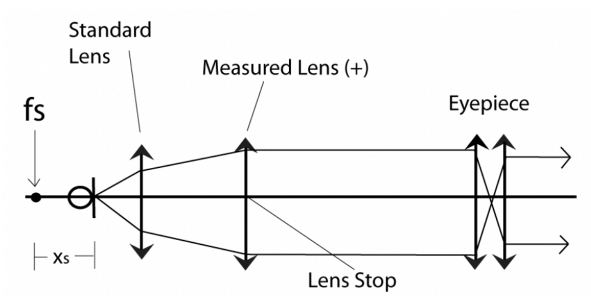


Figure 42 Lensometer Optics with Plus Powered Test Lens