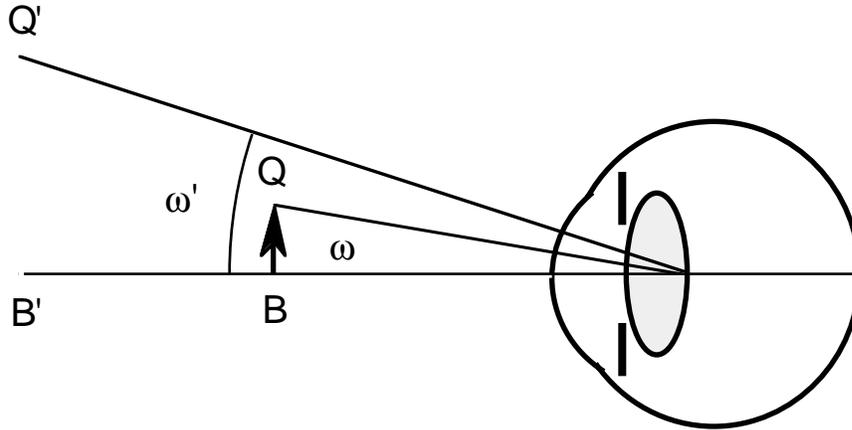


OPTICAL INSTRUMENTS

Microscopes

In discussing conjugate imagery we discussed lateral magnification, m . Another kind of magnification is angular magnification, M . Suppose we have a device that forms an image $B'Q'$ of object BQ , as below:



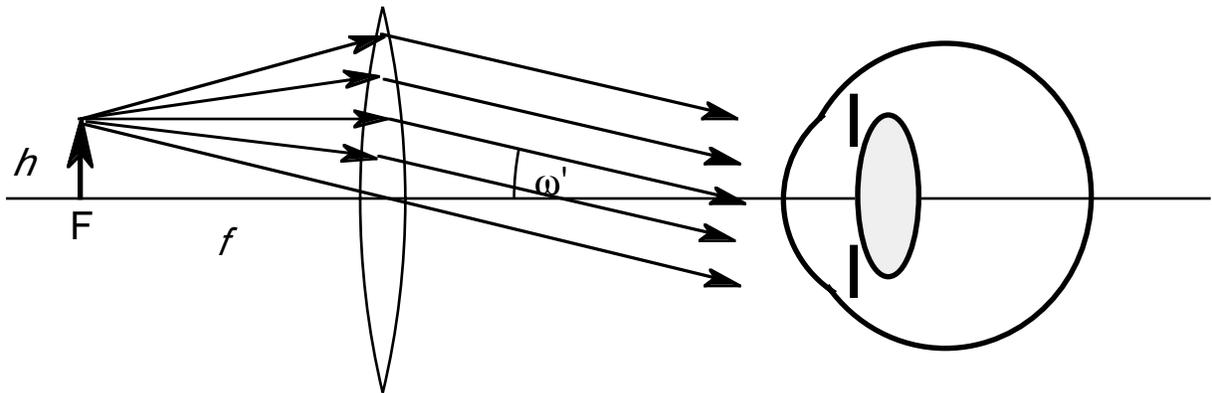
The image is viewed by an observer. If the object subtends angle ω at the observer and the image subtends angle ω' at the observer, then

$$\text{angular magnification} = M = \omega' / \omega.$$

Suppose the observer holds an object of height h a distance q in front of his unaided eye. The angular subtense of the object is $\omega = h / (-q)$. Now suppose he places the object at the primary focus of a simple lens of focal length f' . The image now subtends angle $\omega' = h / f'$. The angular magnification is $M = -q / f'$. By convention, $-q$ is taken to be 25cm so

$$M = -q / f' = 0.25 / f' = F/4.$$

This is the famous $F/4$ formula.

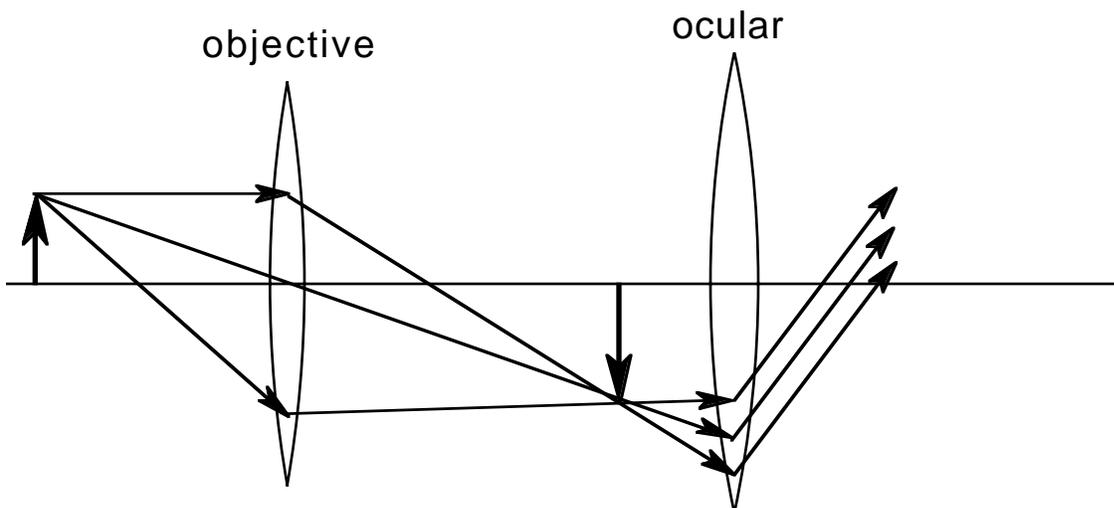


Example: What is the power of an 8X magnifier?

Solution: $F=4M=4 \times 8 = +32D$.

Note that the power in the $F/4$ equation is the equivalent power of the system, not the front or back vertex power.

The single converging lens is a simple microscope. A compound microscope consists of two converging lenses. The first forms a real magnified image of the object while the second is a simple magnifier used to view the image from the first lens.



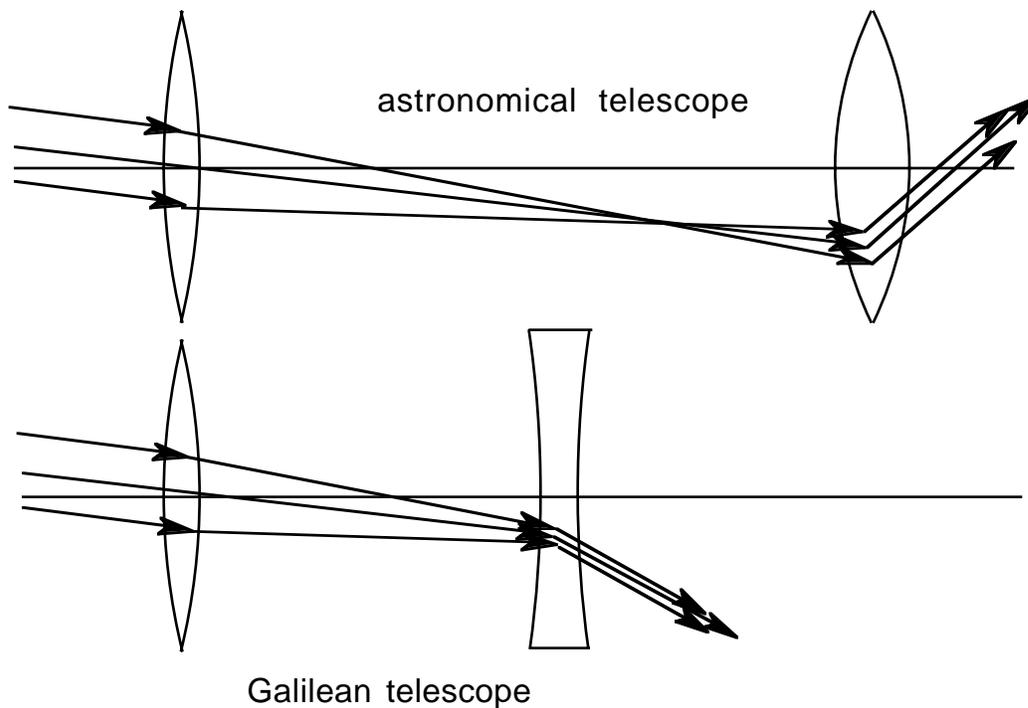
The angular magnification of the microscope is the product of the lateral magnification of the objective times the angular magnification of the ocular as calculated from the $F/4$ formula.

A stereo viewer such as the Keystone telebinocular consists of two

simple microscopes which allow the viewer to see two close-up targets as if they were infinitely far away. A dissecting microscope consists of two compound microscopes used similarly.

Telescopes

While microscopes give angular magnification of near objects, telescopes give angular magnification of distant objects. Telescopes consist of two lenses (in practice two optical systems) mounted such that the secondary focal point of the objective coincides with the primary focal point of the ocular. The objective lens is a converging lens and the ocular lens can be positive or negative. If the ocular is positive it is a Keplerian or astronomical telescope, if it is negative it is a Galilean telescope. Astronomical telescopes produce inverted images and Galilean telescopes produce erect images. Image formation is shown in the diagrams below.



The angular magnification of either kind of telescope can be calculated from the equation

$$M = -F_{\text{ocular}}/F_{\text{objective}} = \rho_E/\rho_{E'}$$

where F_{ocular} and $F_{\text{objective}}$ are the powers of the ocular and objective lenses and ρ_E and $\rho_{E'}$ are the radii of the telescope's entrance and exit pupils.

Example: A telescope has objective of +5.00D power and ocular of -10.00D power. What is its magnification?

Solution: $M = -(-10)/(5) = +2$. The telescope is Galilean with 2X magnification.

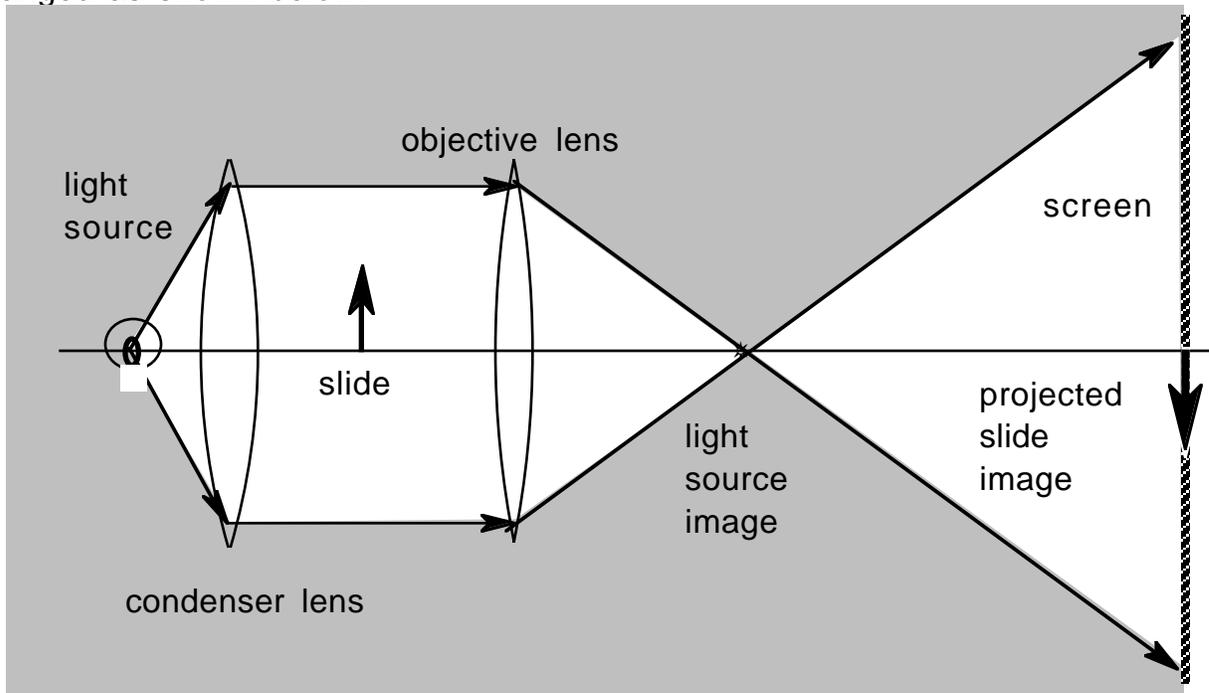
Example: A telescope has entrance pupil 9mm in diameter and exit pupil 6mm in diameter. What is its magnification?

Solution: $M = (9\text{mm})/(6\text{mm}) = 1.5X$.

Taking the ratio of the entrance pupil to exit pupil diameter is, incidentally, a useful way to measure the power of clinically used telescopes.

Projection Systems

A projection system is used to form the image of a slide or aperture. It consists of a light source, and two lenses, the condenser and objective arranged as shown below.

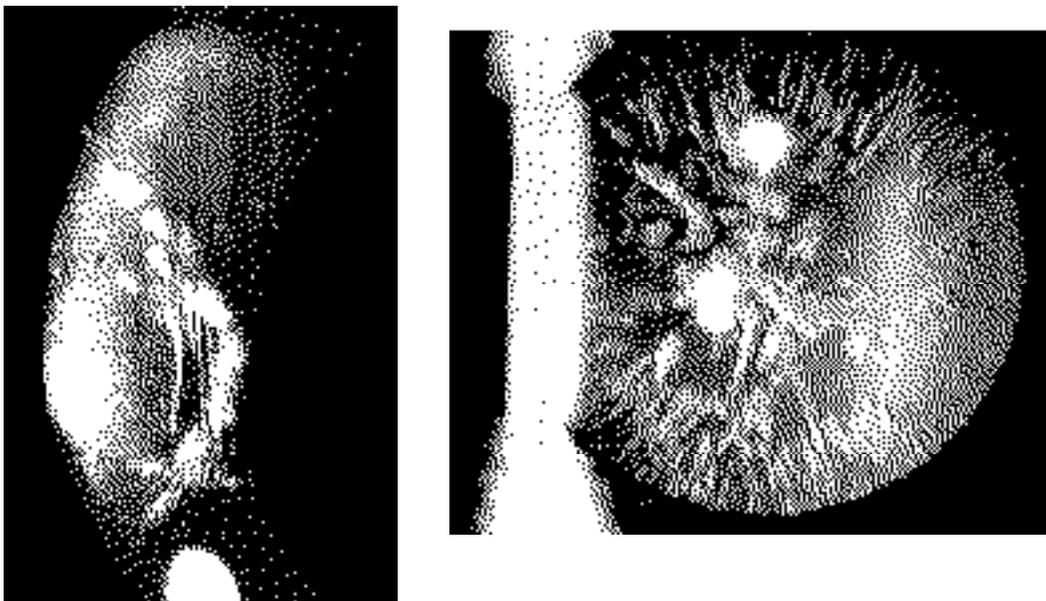


As the illustration shows, the light source is placed at the primary focus of the condenser lens. A beam of light passes through the slide to the

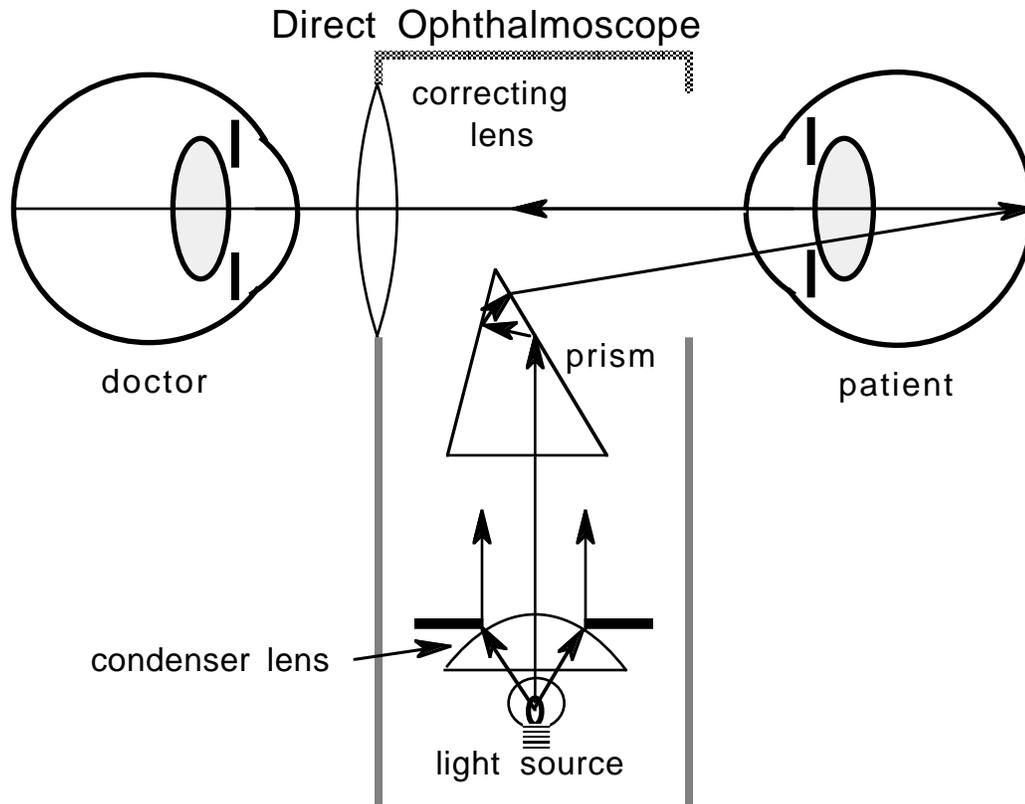
objective lens. The image of the light source (the filament) is formed in front of the objective lens and light from the source goes on to illuminate the whole screen. Light passing around the slide forms the image of the slide on the screen. To find the image of the slide, use the usual paraxial equations with the distance from and power of the objective lens. To form a sharp image, the objective lens must have good optics. The condenser lens, on the other hand, serves only to spread the light from the source and need not have excellent optics.

Biomicroscope

A biomicroscope is a combination of short focus projector and microscope. The projector forms the image of an aperture, usually a slit and the microscope is focused so that the observer's retina is conjugate to the slit. This kind of illumination and observation system have proved very useful in clinical practice.



The pictures above show a scarred cornea illuminated with a slit (left) and a cataract illuminated from behind by slit light entering the left of the pupil and reflecting off the retina.



The diagram above shows how a direct ophthalmoscope works. For the doctor to see the patient's retina clearly, the power of the correcting lens must be the algebraic sum of the ametropias of the doctor's and patient's eyes minus the dioptric amount of their accommodation. Here is what the doctor sees.

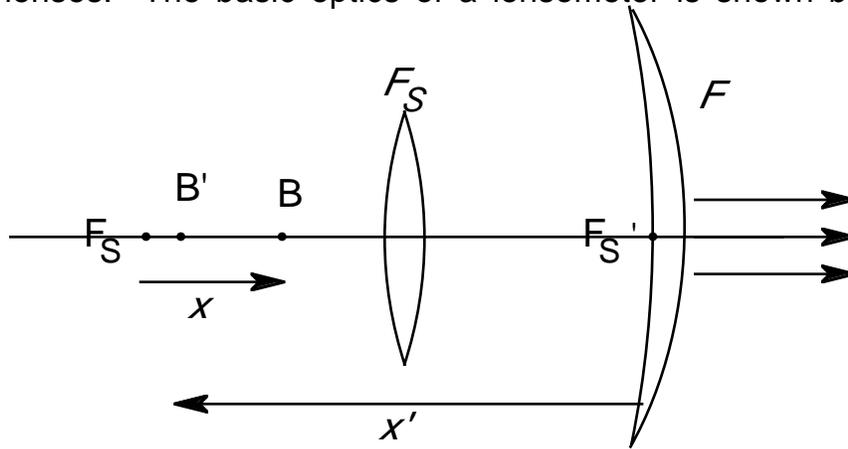


Example: A doctor who is a four diopter myope accommodates one diopter while looking at the retina of an absolute presbyope. If the correcting lens in the ophthalmoscope that gives a clear view of the retina is -3 diopters, what is the patient's approximate spectacle prescription?

Solution: $F_{spectacles} + (-4-1)=-3$ so $F_{spectacles} = +2$.

Lensometer

A lensometer or vertometer measures the back vertex power of spectacle or contact lenses. The basic optics of a lensometer is shown below.



A movable target B backlit by a light source and condenser lens (not shown) is moved in front of a converging standard lens of power F_S . A spectacle lens of power F is placed with its back vertex at the secondary focal point of the standard lens. The position of the target B is adjusted until image B' falls on the focal point of the spectacle lens so that collimated light leaves the system. The observer uses a telescopic system or screen focusing system to guarantee collimated light leaving the spectacle lens. Now, from Newton's relation, $xx' = f_S f_S'$. When collimated light leaves the spectacle lens, $x' = -f_V'$, the back focal length of the lens when it sits before the eye. Recall that $F_S = -1/f_S = 1/f_S'$ and $F_V = 1/f_V'$. Combining all this gives

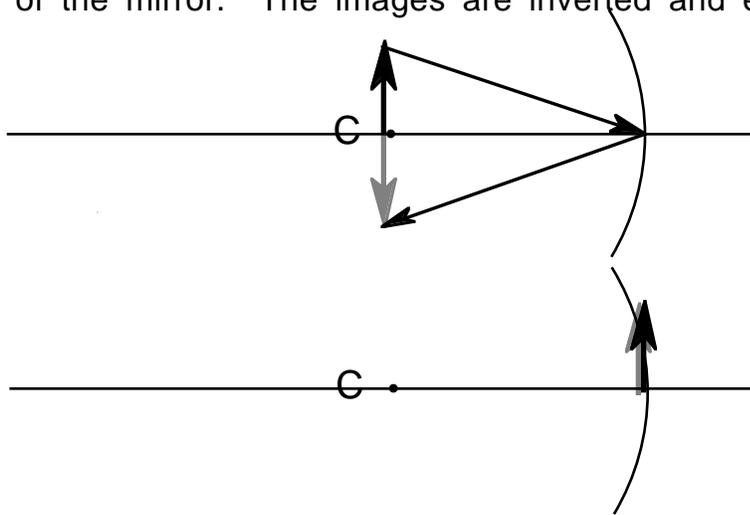
$$x = F_V / F_S^2.$$

Example: A lensometer has a standard lens of +22.00D power. How much must the target move from the zero position in measuring a lens of power -3.00D?

Solution: Substituting in the equation above, $x = -3/22^2 = -6.2\text{mm}$.

Radiuscope

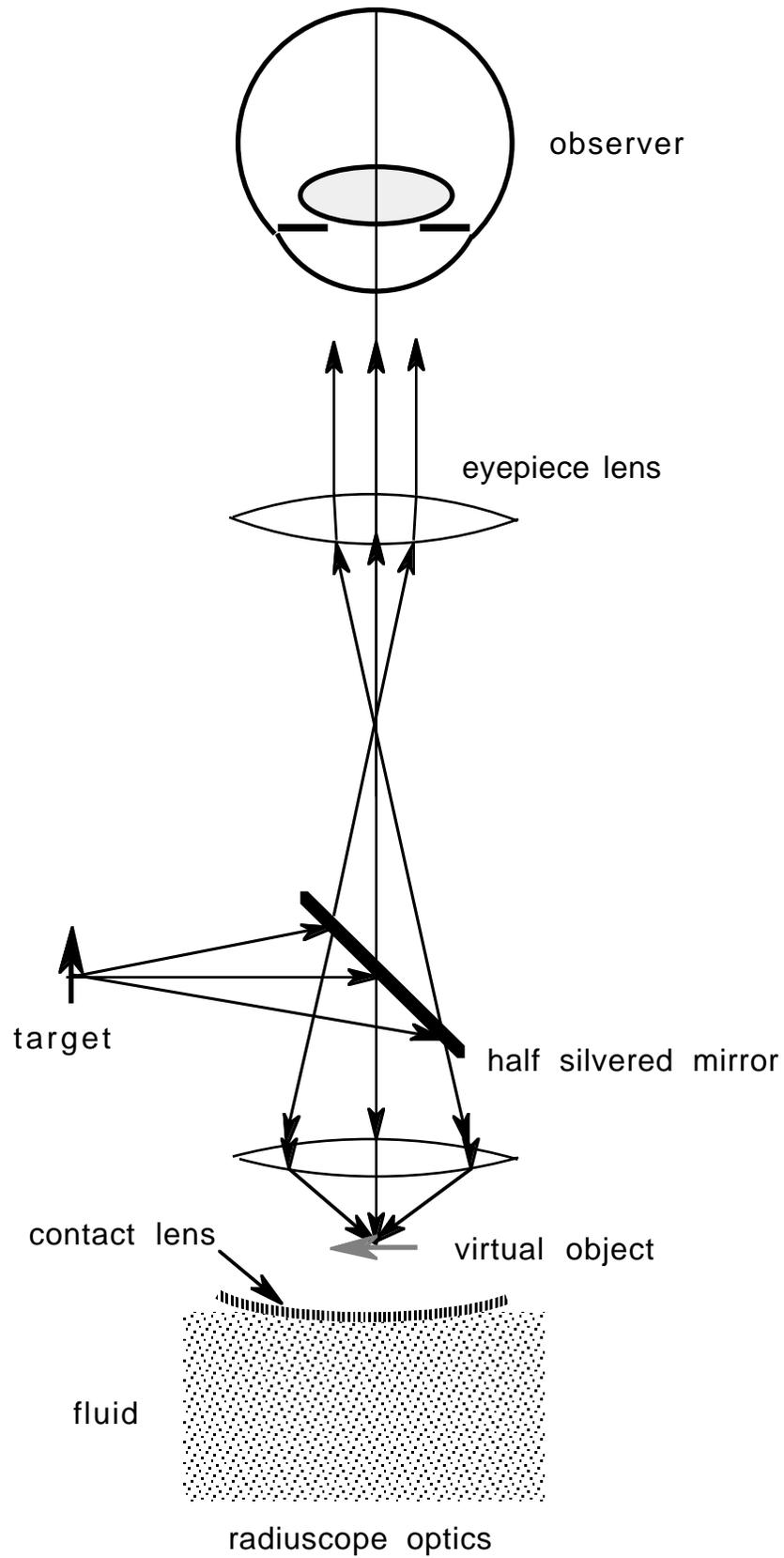
A radiuscope is used to measure the radius of curvature of a contact lens. It uses the fact that there are two positions in which the object and image coincide for a curved mirror; at the center of curvature of the mirror and at the surface of the mirror. The images are inverted and erect, respectively.



A radiuscope produces a virtual object conjugate to the eye of the observer. The observer adjusts the instrument up and down until he finds two different positions at which he can see the image of that object clearly. The radius of curvature of the surface is the physical distance the instrument moves between the two positions of image focus.

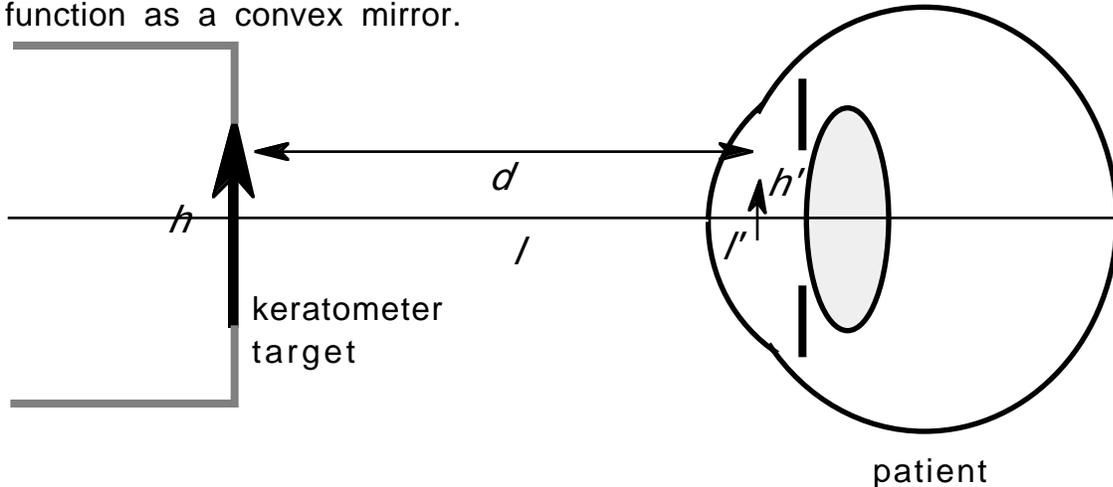
The diagram on the next page shows the optical principal of the radiuscope. An object is imaged through a half silvered mirror and a lens to form a virtual object. In practice the object is back lit by a lens-condenser system (not shown). When light from the image, now a virtual object, reaches the contact lens, it is reflected back toward through the half-silvered mirror to the observer's eye. The eyepiece is adjusted to make the observer's retina conjugate to the virtual object.

The contact lens rests below the radiuscope with its convex side downward floating on fluid such as wetting solution. The fluid is to minimize reflections from the front surface of the lens.



Keratometer

The keratometer is used to measure the curvature of the anterior corneal surface by measuring the size of an image reflected from the cornea function as a convex mirror.

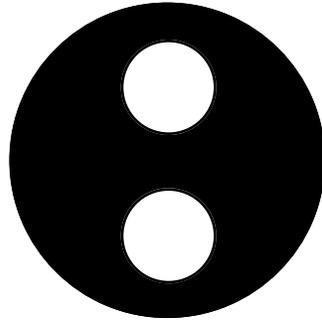


The keratometer is constructed with a target or keratometer mire at the front of the instrument. The image of the target is viewed through the microscope optics of the instrument and brought into focus by moving the instrument back and forth. Thus there is a fixed distance $d = l' - l$ between the target and the image formed in the cornea. The magnification of the image is given from the usual paraxial equation by $m = -l'/l = -l'/(l' - d) \cong l'/d$ since $l' \ll d$. From the fundamental paraxial equation for a mirror $1/l + 1/l' = 2/r$ where r is the radius of curvature of the cornea. Since $|l| \gg l'$, the fundamental paraxial equation becomes $1/l' \cong 2/r$. Eliminating l' , we get for the radius of curvature of the cornea

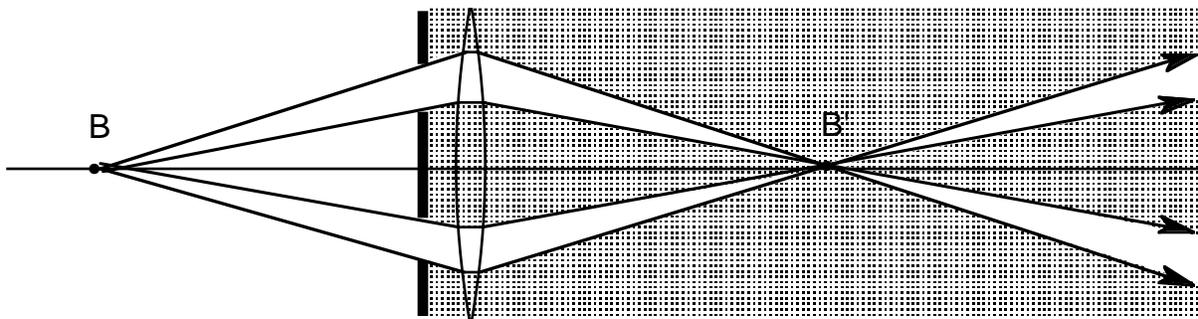
$$r = 2md = 2dh'/h.$$

Thus knowing the distance d , a constant of the instrument, the size of the mire h , we can measure the radius of the cornea by measuring the size of the corneal image h' .

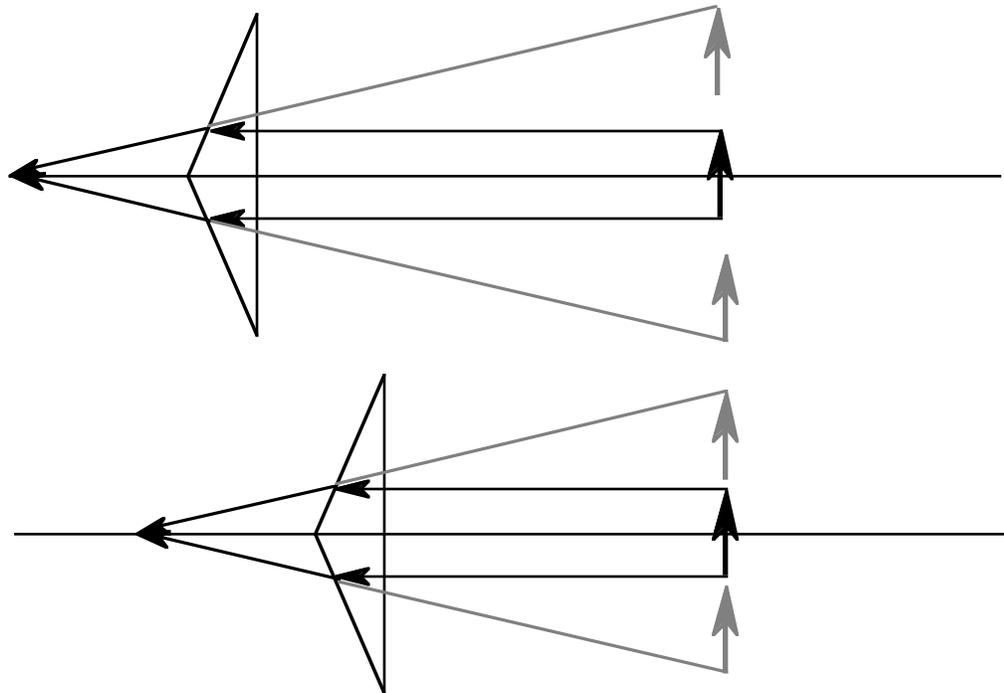
Even at the high magnification the keratometer's optics provide, it can be difficult to tell when the image of the mire is in focus. To help with this, keratometers usually use a Scheiner disk in the optical pathway. The disk is a barrier with a couple of apertures, like that below.



As the optical diagram below shows, a Scheiner disk in a light beam produces a **doubled and blurred** image outside the plane of focus, and that's easier to recognize than an image which is merely blurred.

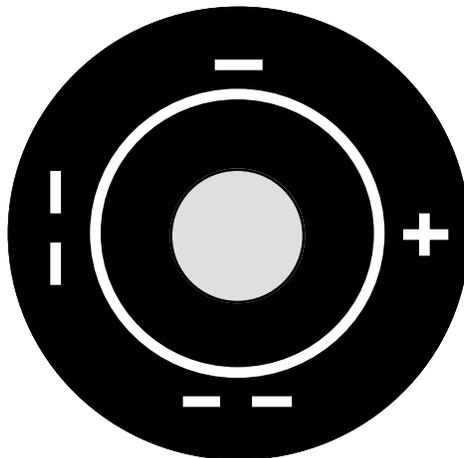


Because the image in the cornea is small, it is examined at high magnification. At such magnification, the normal oscillations of the eye make it impossible to compare the image height with any reticle scale. To measure the image size, then, clinical keratometers use a prismatic doubling system. The doubling system is inside the keratometer somewhere in the path of the light returning from the cornea to the doctor and it divides the light pencil from the image into two pencils. Thus the doctor sees two images. His job is to adjust the instrument until the images are separated a fixed distance. The mechanism that does this is calibrated to give a measure of h' which may be converted to a corneal curvature.

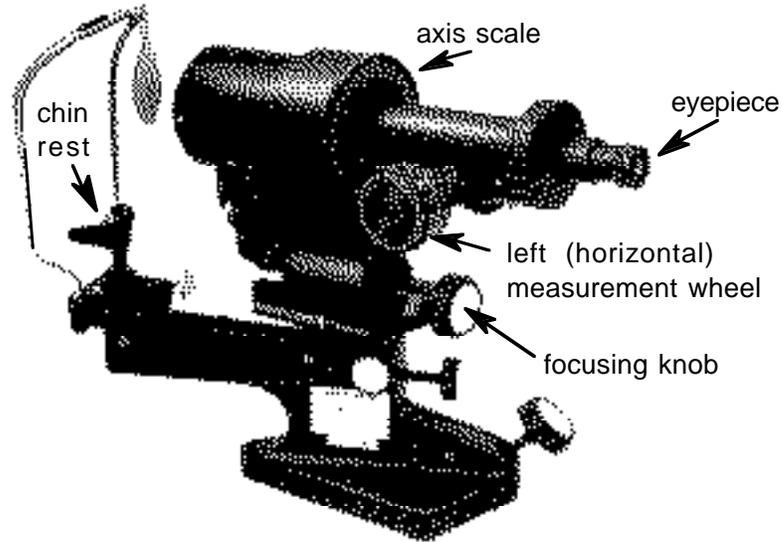


The most commonly used doubling system is a prism doubling system in which a pair of prisms is moved back and forth until the pair of images are tangent. The two diagrams above show how varying the position of a biprism changes the position of the pair of images formed.

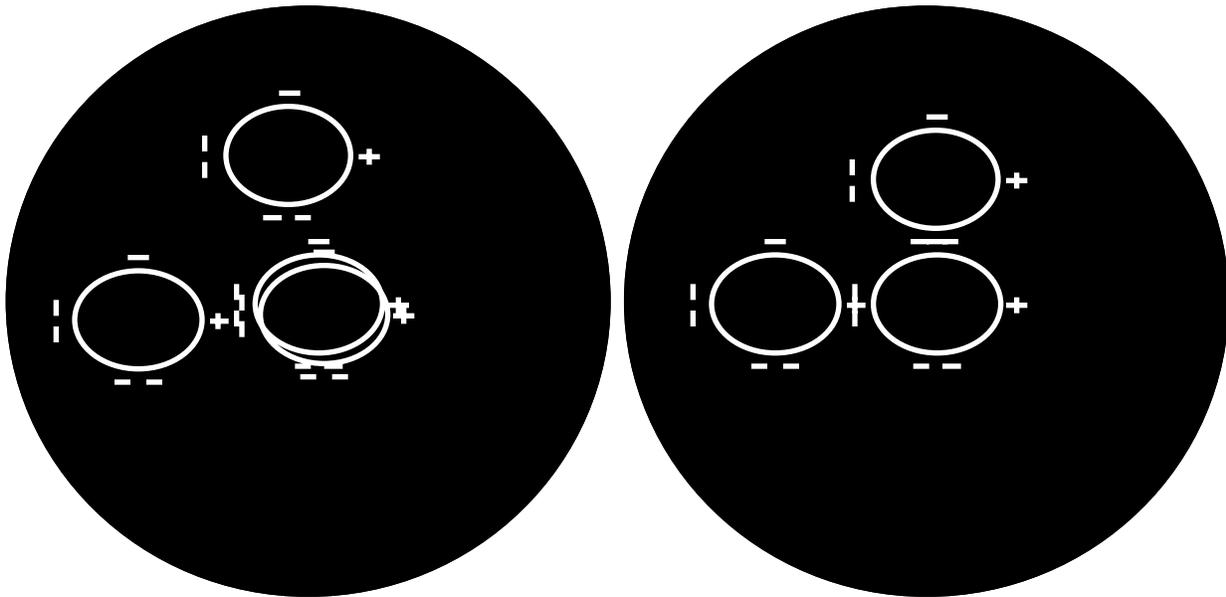
Keratometer mires are circular so that an astigmatic cornea makes them somewhat elliptical. The mires of many keratometers look like the figure below.



The picture below shows a typical keratometer. In use, the patient sits with his chin in the chin rest while the doctor adjusts the instrument and takes measurements.



The doctor's view through the eyepiece is initially like the left picture below. The image of the circular mire is somewhat elliptical (with the rule corneal astigmatism in this case). The Scheiner's disk arrangement causes the central mire to be doubled instead of blurred when the mire is out of focus. Doubled images of the mire appear above and to the left of the central mire.

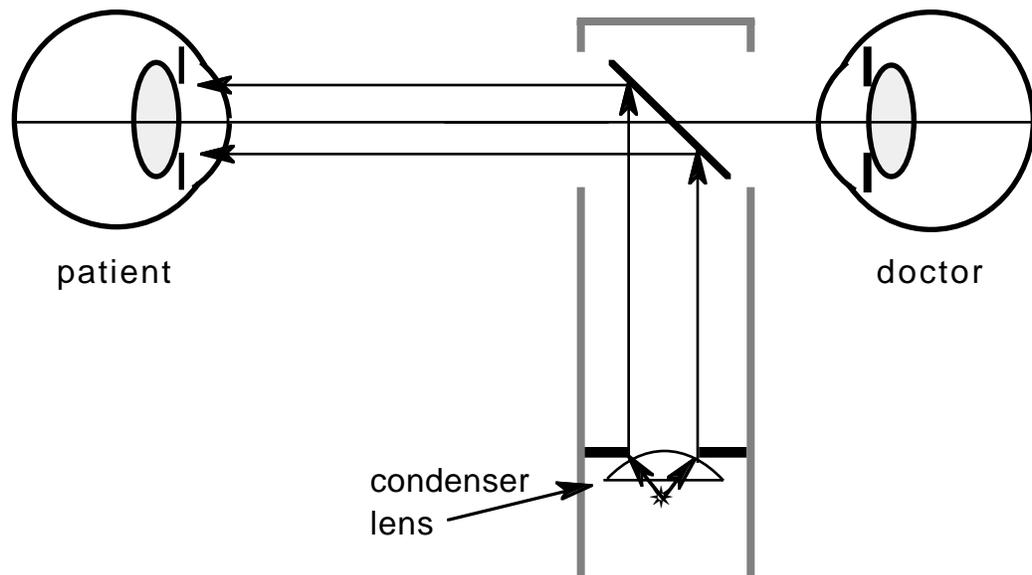


Retinoscope

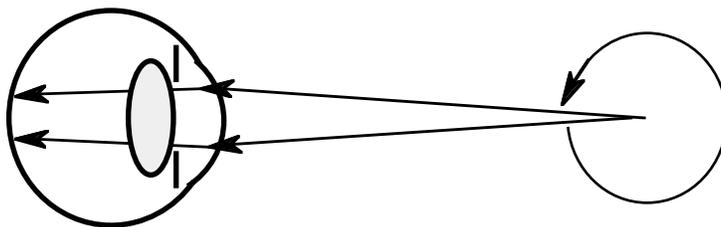
The retinoscope permits an "objective" estimate of a patient's refraction in which no subjective responses are required of the patient. The doctor shines the retinoscope's light into the patient's eye and then wiggles the light beam while watching the red reflex from the patient's retina in the patient's pupil. If the reflex moves in the same direction as the doctor's wiggles it is called "with" motion of the reflex, and if it moves in the opposite direction it is called "against" motion. Lenses in the phoropter are changed until the motion speeds up and finally reverses direction. Neutrality is reached with the lens that produces the transition in direction.

The retinoscope can be analysed by considering it as two optical systems; the illumination system which sends light toward the retina and the observation system which observes the light reflex.

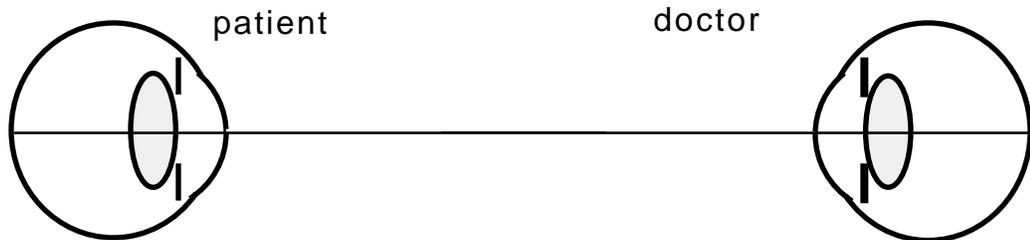
The optics of the illumination system is shown schematically below.



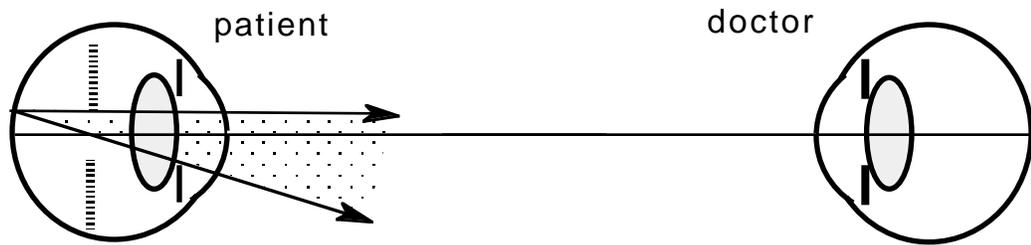
The illumination system is very similar to that of an ophthalmoscope. Now consider what happens when the illumination system is wiggled down ward.



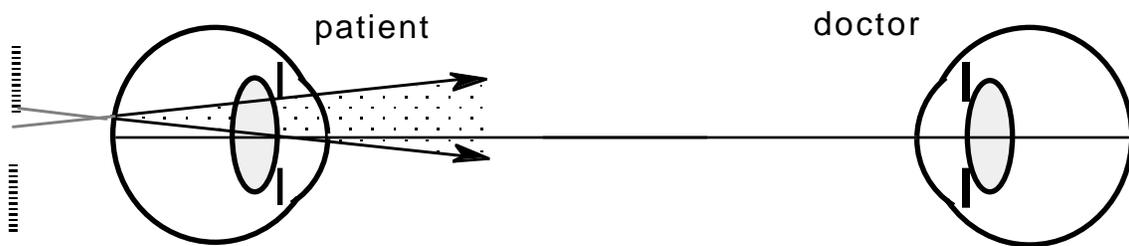
As the diagram shows, as the beam is rotated downward, an illuminated patch moves down the retina. The retina acts as a matte reflector, so that patch becomes a secondary light source. Light from that illuminated patch travels through the patient's pupil and the doctor's pupil to the doctor's retina. Let's look at the observation system.



For an object at the patient's retina, the iris of the doctor is the aperture stop and its image through the doctor's cornea and the patient's eye is the entrance pupil. The patient's pupil is the field stop and its image through the patient's crystalline lens is the entrance port. That pupil will be in front of, behind, or at the patient's retina.



Suppose the entrance pupil is in front of the retina (the patient is relatively myopic compared to the observer's position). As the diagram above shows, when the lit patch moves down the retina, the beam leaving the eye moves up. Now let the doctor's pupil be imagined behind the patient's retina (the patient is relatively myopic compared to the observer's position) as in the diagram below. The diagram shows that as the lit patch moves down the retina, the beam leaving the eye moves down.



So let's get the sequence down:



As the light beam moves down, if the doctor's iris is imaged **behind** the patient's retina, the light beam leaving the eye moves **up**, hence we get **against** motion.

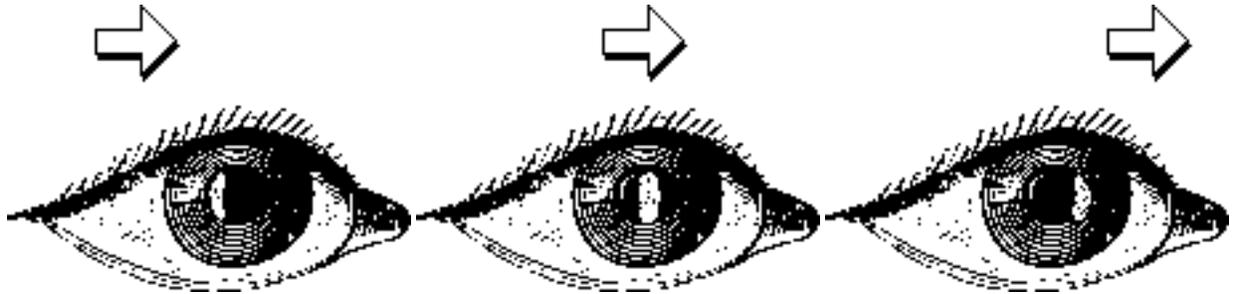


As the light beam moves down, if the doctor's iris is imaged **behind** the patient's retina, the light beam leaving the eye moves **down**, hence we get **with** motion.

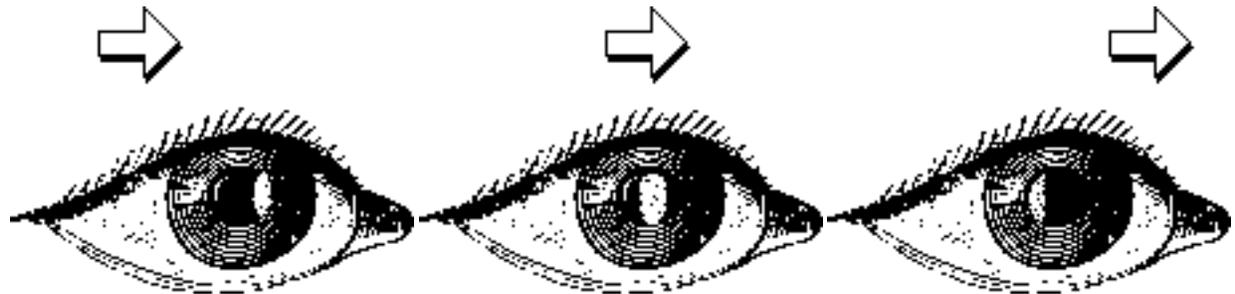


As the light beam moves down, if the doctor's iris is imaged **at** the patient's retina, we are have **neutral** motion.

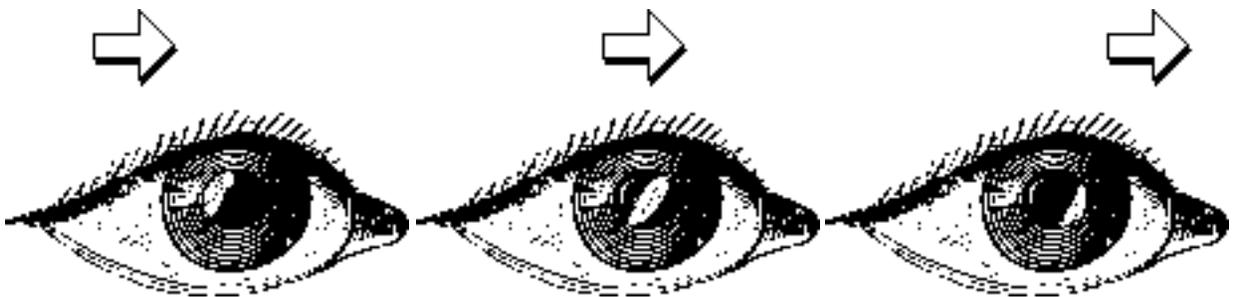
What the doctor sees during retinoscopy is illustrated below for a streak retinoscope which emits light in a narrow strip. The arrows show the direction of motion of the beam and the reflex is shown in the pupil.



with motion--hyperopia



against motion--myopia



oblique motion--astigmatism

The nearer the patient's and doctor's retinas are to conjugacy, the faster the motion of the reflex. The doctor's task is to first rotate the beam to eliminate oblique motion, thus placing his streak in a principal meridian, and then to neutralize each of the principal meridians by changing lenses in front of the patient to achieve very rapid movement and/or reversal of the motion.

Suppose separation of the doctor's and the patient's eyes, the so-called working distance, is d . If the patient's myopia exceeds $1/d$, the entrance pupil will be imaged in front of the patient's retina and the doctor will see **against** motion on retinoscopy. If the patient is hyperopic, emmetropic, or his myopia is less than $1/d$, the entrance pupil will be imaged behind the patient's retina and the doctor will see **with** motion on retinoscopy.

In clinical retinoscopy the doctor places lenses in front of the patient until he reaches neutral motion. The patient's ametropia is the lens that produces neutral motion minus $1/d$, the dioptric equivalent of the working distance.

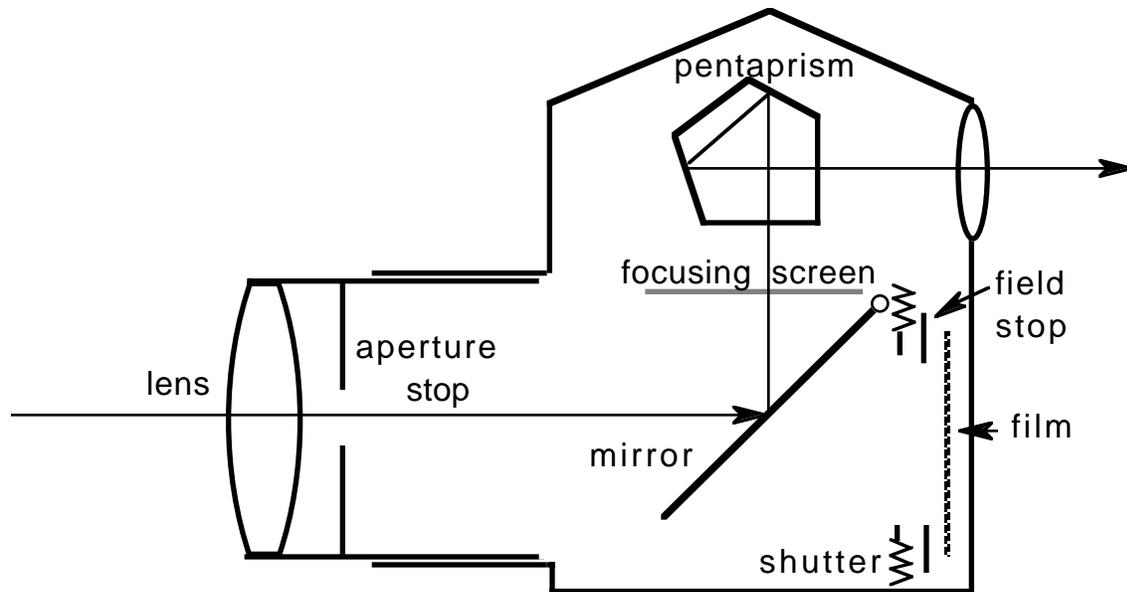
Example: A doctor's working distance in retinoscopy is 67cm. He gets neutral motion when a +5.75D lens is in the phoropter. What is the patient's spectacle prescription?

Solution: The dioptric equivalent of the working distance is $1/67\text{cm}=1.50\text{D}$ so the Rx is $+5.75\text{D}-1.50\text{D}=+4.25\text{D}$.

Interestingly, what the doctor actually sees when he watches the light leaving the patient's pupil is the shadow of his **own** iris.

Single Lens Reflex Camera

The type of camera most popular with professional and serious amateur photographers is the single lens reflex camera or simply reflex camera. The optics of a typical single lens reflex camera is shown schematically in the diagram below.



While the photographer is focusing, light which passes through and is focused by the camera lens is deviated by a hinged mirror to a focusing screen conjugate to the film. The photographer observes the image with the help of a lens and an erecting pentaprism. When the shutter is triggered the mirror flips out of the way and the shutter opens permitting light to go to the film.

In most modern cameras, focusing is done with the aperture stop wide open to give maximum illuminance of the image on the focusing screen along with minimal depth of field to facilitate precise focusing. Such a camera is said to have a coupled aperture.

In real cameras the simple lens of the diagram above is replaced by a photographic objective which consists of several lenses. The design of photographic objectives has been an important problem in the history of optics.