OPTICAL INSTRUMENTS

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INTRODUCTION

An understanding of the optics of basic optical instruments is important since the applications are to be found in many different clinical instruments as well as the therapeutic devices that are used by practicing optometrists.

THE CAMERA

CONSTRUCTION

The single-lens photographic camera is a simple optical instrument. It consists of a light-tight box, a converging lens that produces a real image, and a film behind the lens to receive the image. Unlike the eye, this type of camera lens has a fixed focal length. Focusing is accomplished (where possible) by varying the distance between lens and film. For proper focusing, which leads to sharp images, the lens-to-film distance will depend on the object distance as well as on the focal length of the lens.

The shutter, located behind the lens, is a mechanical device that is opened for selected time intervals. To take a photograph, you first adjust the lens position so that a real, inverted image of the object is in focus in the plane of the film. Then, when you press a button, the shutter momentarily opens and an image forms on the film. This image is stored in the light-sensitive material for later chemical processing, yielding a reproduction of the scene. Digital cameras replace the photographic film with an electronic sensor array, the sensitivity of which can be adjusted to resemble the response of film.

The effective lens opening is controlled by an iris diaphragm, the size of which can be varied. It is given this name because it performs a similar function to the iris of the eye. In some cameras, the iris diaphragm also acts as the shutter; while normally closed, the iris opens to a pre-determined size in order to exposure the film.

CONTROL OF LIGHT IN THE CAMERA

With modern photographic films and with adequate lighting, the shutter only needs to be open for a small fraction of a second to successfully record an image on film. Many cameras have a range of available ***shutter speeds*** - that is, lengths of time during which the shutter is open. Shutter speeds of 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000, and 1/2000 second are standard. Note that each of these is approximately half as long (or, in photographic terminology, "twice as fast") as the preceding one. The faster the shutter speed is, the faster the object can be moving and still produce a sharp image.

With this arrangement, moving objects can be photographed with the use of short exposure times, and dark scenes (low light levels) with the use of long exposure times. Without this control, it would be impossible to take stop-action photographs. For example, a speeding race car would move far enough while the shutter was open to produce a blurred image. Stationary objects can be shot with a shutter speed of 1/60 s since there is no chance of motion blurring, although the camera must be held steady. Older cameras had semi-circular shutters, but later models usually had diaphragm shutters.
The amount of light reaching the film must be carefully controlled to avoid **underexposure** (too little light for any but the brightest objects to show up) or **overexposure** (too much light, so that all bright objects look the same, with a consequent lack of contrast). To control the exposure, a "stop" or iris diaphragm, whose opening is of variable diameter, is placed behind the lens. The size of the opening is varied to compensate for different lighting conditions, the sensitivity of the film used, and for different shutter speeds.

Getting the "correct exposure" in a photograph corresponds to allowing the appropriate amount of light to strike the film. Therefore "correct exposure" means the **correct luminous energy per unit area** of the film. This amount is different for different types of film. <u>The amount of light that strikes the film is determined not only by how long the shutter stays open, but also by how large the effective lens opening is</u>. Thus it is analogous to the amount of water flowing from a tap, which depends on both the length of time the tap stays open and the cross-sectional area of the opening. We can deduce a relationship between "amount of light" and camera parameters as follows: (See the photometry section of chapter 8 for detail on terms used here.)

1. **The amount of luminous power falling on the image in a camera is proportional to the area of the lens aperture, or to d^2, where d is the diameter of the aperture.** This follows from the fact that the area of a circle is given by πr^2 ($\pi d^2/4$).

2. **The area of the image formed is proportional to f^2, where f is the focal length of the lens**, since the length of the image formed is proportional to the focal length.

It therefore follows that the luminous power per unit area of the image, or ***illuminance*** of the image, is proportional to d^2/f^2. The time of exposure (shutter speed), **t**, for activating the chemicals on the given negative is inversely proportional to the illuminance (the greater the amount of light falling on unit area per unit time, the less time will be needed to get the "correct amount of light" onto the film). Hence:

$$t \propto f^2/d^2 \quad \text{OR } t \propto (f/d)^2$$

The size of the lens opening, (often referred to as the aperture or relative aperture), is usually measured by what is called the f-value, f-stop or **f-number.**

$$\text{f - number} \equiv \frac{\text{focal length of lens}}{\text{diameter of lens}} = \frac{\text{f}}{\text{d}}$$

For example, a lens with a diameter one half its focal length has an f-number of 2, which is written f-2. The variable-diameter iris diaphragm can be adjusted to decrease the effective lens opening and therefore increase the f-number. Thus, the larger the f-number, the smaller the aperture is, and the smaller the amount of light reaching the film. The f-stop regulates how much light is allowed through the lens by varying the area of the hole the light comes through.

If the aperture is given as f-4*,* this means that the diameter ***d*** of the aperture is f/4*,* where f is the focal length of the lens. An aperture of f-8 means a diameter ***d*** equal to f/8, which is a smaller aperture than f/4*.*

The standard full-stop f-numbers are: 0.7 1.0 1.4 2.0 2.8 4 5.6 8 11 16 22.

Notice that the values of successive f-stops differ by a factor of approximately √2. Thus, if you change the f-number of a lens from f-4 to f-5.6, you reduce the diameter of the aperture by a factor of 1/√2.The area of the aperture decreases by the square of this factor. So, if the shutter speed remains constant, the amount of light passing through the lens opening is cut in half. A change in aperture equivalent to going from one f-stop to the next successive one is known as a **change of one full stop**.

An **increase** of one f-stop will **decrease the amount of light passing through the lens by a factor of 2**. (It will halve.)

A change from one f-stop to the **next lower one** will **increase the amount of light passing through the lens by a factor of 2**. (It will double.)

Since the time of exposure, t, is proportional to f^2/d^2, it follows that the **shutter speed** required with an aperture f-8 (**d**= f/8) is **16 times greater** than that required with an aperture f-2 (**d**= f/2). (Note that we have moved FOUR stops from f-2 to f-8.)

Conversely, the **luminous power** passing through the lens is simultaneously **16 times smaller**.

Here's a table of the aperture areas for the common f-stops for a 50mm lens:

f-stop	Diameter of aperture (mm)	Radius of aperture (mm)	Area of aperture (mm^2)
f-1.0	50.0	25.0	1963
f-1.4	35.7	17.9	1002
f-2.0	25.0	12.5	491
f-2.8	17.9	8.9	250
f-4	12.5	6.3	123
f-5.6	8.9	4.5	63
f-8	6.3	3.1	31
f-11	4.5	2.3	16
f-16	3.1	1.6	8
f-22	2.3	1.1	4
(As shown on lens)	*(50mm divided by f/stop)*	*(1/2 the diameter)*	*(pi X the radius squared)*

Table 9.1: *Aperture areas for the common f-stops for a 50 mm lens*

At this point it may be useful to summarize some of the relationships we have encountered:

- shutter speed $\propto$ (f-number)^2
- lens aperture $\propto$ 1/f-number
- successive f-numbers differ by $\sqrt{2}$

  (Thus exposure time will differ by a factor of 2 for successive f-numbers)
- the amount of light passing through the lens is inversely proportional to (f-stop)^2. (Thus luminous power will differ by a factor of 2 for successive f-numbers.)

By being able to adjust both shutter speed and f-number, the photographer can give the proper exposure to the film while still having the option of using a particular shutter speed or a particular lens opening. For example, the same amount of light reaches the film of a camera during exposures of 1/50 s at f-8; 1/100 s at f-5.6; and 1/200 s at f-4.
If we now return to what is meant by **"correct exposure"**, we noted earlier that it was the **luminous energy per unit area.** We showed that this quantity can be obtained from:

correct exposure = illuminance x exposure time

We need a combination of the f–number with shutter speed that will give the correct exposure. More than one combination is possible. For situations where we need to change from one such combination to another, the following relationship allows this to be done easily.

$$f_1^2 \times \frac{1}{t_1} = f_2^2 \times \frac{1}{t_2}$$

a)

For example, if we meter a scene and it tells us that 1/125 s at f-8 is the correct exposure, any of the following combinations would work:

Shutter Speed(s)	1/4	1/8	1/15	1/30	1/60	**1/125**	1/250	1/500	1/1000	1/2000
f/stop	f-45	f-32	f-22	f-16	f-11	**f-8**	f-5.6	f-4	f-2.8	f-2

(**Test your understanding by verifying a few of these combinations.)**

SPEED OF A CAMERA LENS

The **rate at which a photographic image is formed**, or the ***speed*** of the camera lens, is related to previously encountered quantities:

$$\textbf{speed of lens} \propto [d^2/f^2 = 1/(\textbf{f-number})^2]$$

For most purposes, the speed of the lens depends only on the f-number and is independent of the particular focal length. The speed of a lens indicates its light-gathering power and thus the f-number is also a measure of the light-concentrating power of a lens. A fast lens has a small f-number and therefore has a relatively short focal length and a large diameter.

DEPTH OF FIELD

If the lens is focused on a nearby object, a sharp image of it will be formed. But then the rays from a point on an object far away will be out of focus. They will form a blur spot on the film. The distant object will thus produce an image consisting of overlapping spots and will be blurred. These circles are called **circles of confusion.** If you want to have near and distant objects sharp at the same time, you can try setting the lens focus at an intermediate position. Neither near nor distant objects will then be perfectly sharp, but the circles of confusion may be small enough that the blurriness is not too noticeable. For a given distance setting, there is a **range of object distances over which** the circles of confusion will be small enough that **the images will be reasonably sharp**. This is called the **depth of field.**

The depth of field is affected by the following factors:

- the aperture of the lens
- the focal length of the lens
- the distance from the camera to the main subject

For a particular circle of confusion diameter (typically taken to be 0.03 mm for 35-mm cameras), the depth of field depends on the lens opening. If the lens opening is smaller, the circles of confusion will be smaller, since only rays through the central part of the lens are accepted, and these form a smaller circle of confusion. Hence, **at smaller lens openings, the depth of field is greater**.

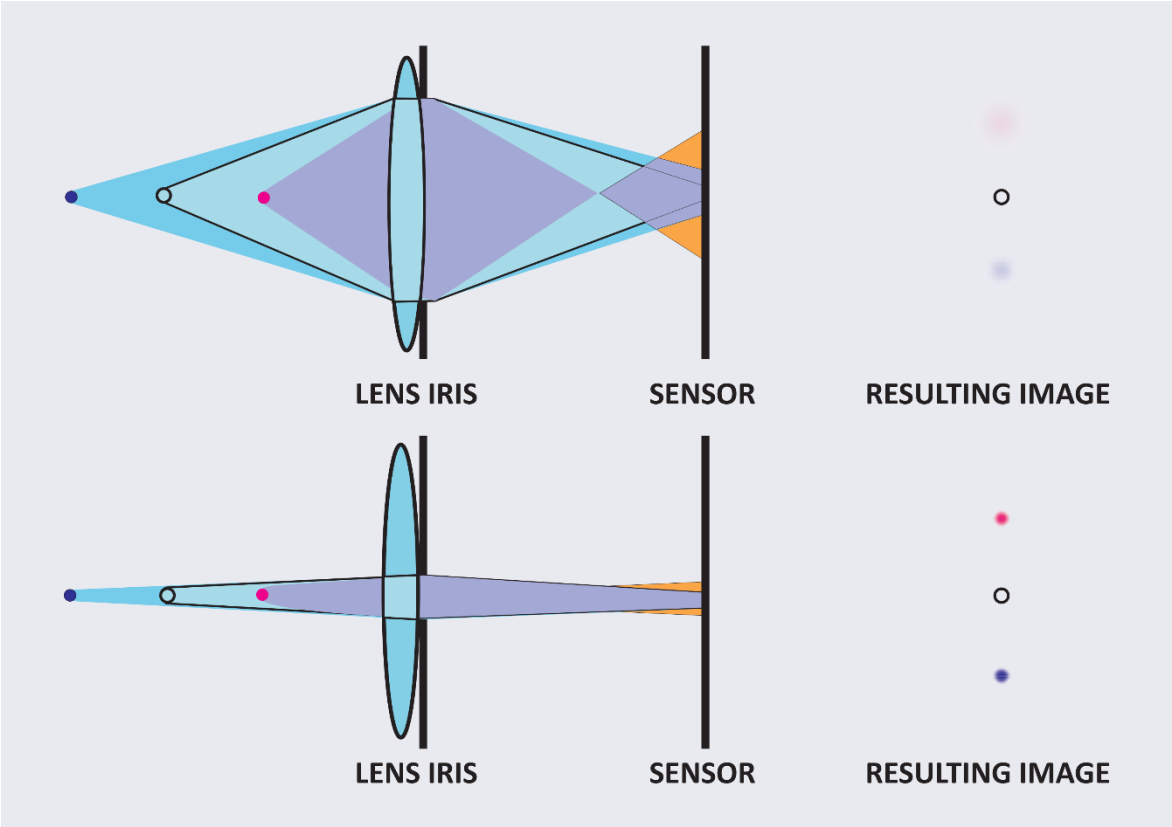

Figure 9.1: *Representation of the depth of field and its effect on the focus of different images*

Another way to change the depth of field is to use a different focal length. As you **increase the focal length of the lens, the depth of field decreases**. This is why focusing is so critical on long lenses.

COMPARISON OF THE CAMERA TO THE EYE

The eye is infinitely more delicate and complicated than the finest camera. But, since in principle they are both imaging systems, there are a number of aspects on which a comparison can be based.

In the camera, there is a simple converging lens, or a system of lenses, which acts like the converging crystalline lens in the eye. However, a camera lens has the same medium on each side, while the lens of the eye has media of different refractive indices on either side. The sensitized film inside the camera corresponds to the light-sensitive retina in the back of the eye, and both receive inverted, real images, which are smaller than the object. The diaphragm regulates the amount of light that enters the camera; the iris regulates the amount of light that enters the eye.

The interior of a camera is blackened so that the walls will absorb any stray light rays. The interior of the eye is similarly surrounded by a black coat that also absorbs light. The film gives us a lasting picture with all details of the object, whereas the image in the eye persists for only about 1/16 of a second before another distinct image is recorded.

The eye does not have a counterpart to the camera's shutter. While both the camera and the eye focus, the accommodation of the eye is completely different to the focus mechanism of the camera. Recall that the eye changes the shape of its lens while in the camera the distance between the lens and the film is changed.

LENS ABERRATIONS

In your previous studies, image formation by a thin lens was presented. We found, for example, that all rays from each point on an object are brought to a single point as the image point. These, and other results, were based on approximations such as that all rays make small angles with one another. Because these approximations are not valid (to varying extents), we expect deviations from the simple theory in practice. These deviations are referred to as lens aberrations. They decrease the quality of the image and may even shift the image position.

Some aberrations are due to the lens material (its refractive index). An example is chromatic aberration. This effect is not observed when monochromatic light is used.

Other aberrations are a result of the form the lens has, and vary as the form changes. Examples are coma and spherical aberration.

SPHERICAL ABERRATION

This problem is present whenever spherical surfaces are used. Consider a point object on the axis of a lens. **Rays** from this point **that pass through the outer regions of the lens are brought to a focus at a different point than those that pass through the centre of the lens.** This is called spherical aberration, and is shown exaggerated in the figure. Consequently, the image seen on a piece of film (for example) will not be a point but a tiny circular patch of light. If the film is placed at the point **C,** as indicated, the circle will have its smallest diameter, which is referred to as the circle of least confusion.

Sometimes a camera lens uncorrected for spherical aberration is deliberately used in order to give a soft-focus (halo) effect.

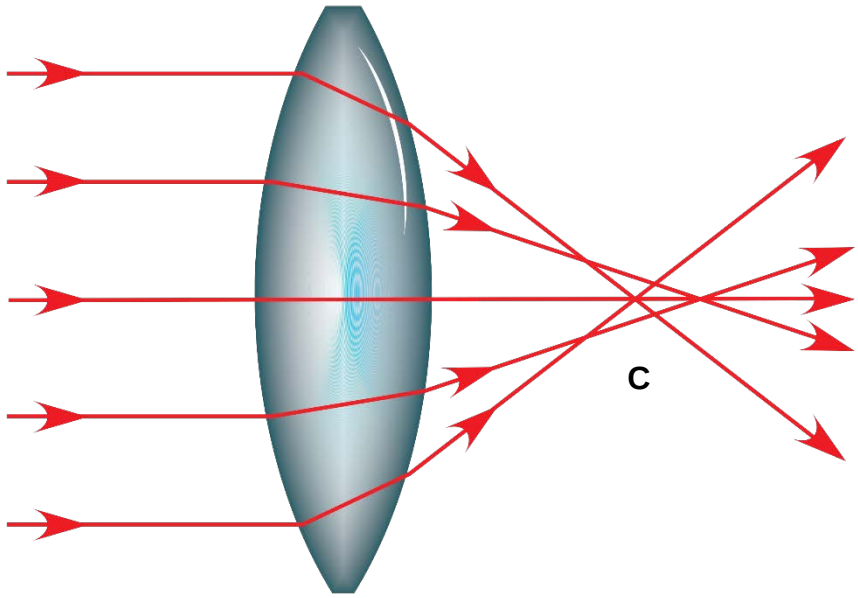

Figure 9.2: *Spherical aberration*

Aberrations may be:

- reduced by surrounding the lens with an opaque disc having a hole in the middle, so that **light is incident only on the middle of the lens**. However, this method reduces the illuminance of the image since it limits the amount of light passing through the lens. (On a camera this would entail using larger f-stops.)

- corrected by using nonspherical lens surfaces, but to grind such lenses is very expensive. (This also applies to mirrors.)

CHROMATIC ABERRATION

The image of an object formed by a single lens is distorted from a variety of causes. The main defect of the lens is the colouring of the image it produces, which is known as *chromatic aberration.*

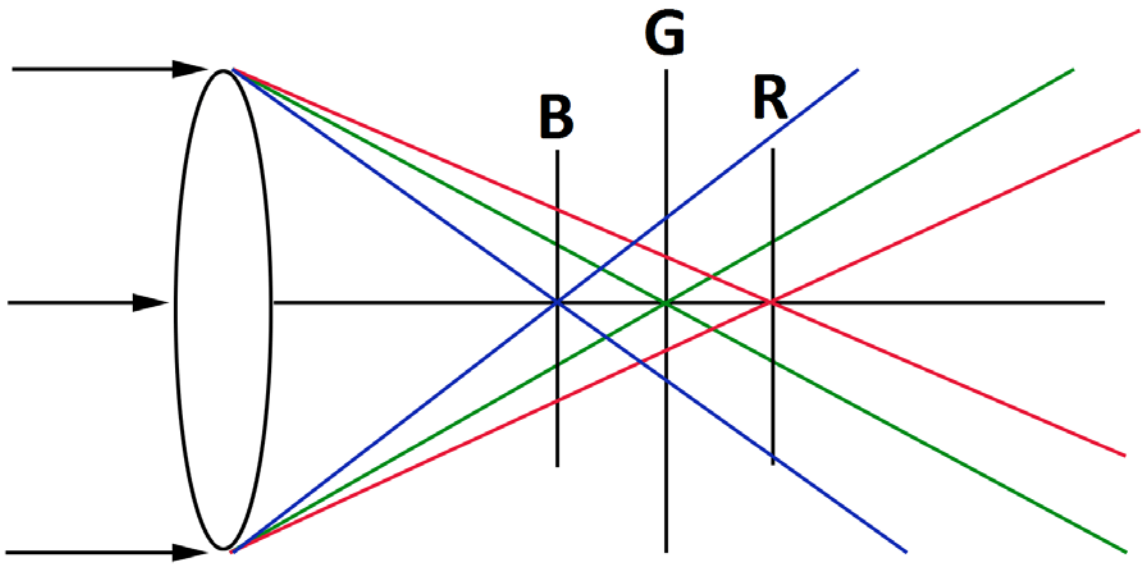

Figure 9.3: *Chromatic aberration*

Experiment shows that if a parallel beam of white light is incident on a converging lens, the red rays in the light are brought to a focus at **R**, and the blue rays are brought to a slightly nearer focus at **B**. (See figure 9.3.) [Recall that the refractive index of a lens increases with decreasing wavelength. Therefore the refractive index for red light will be greater for blue light, focusing it closer to the lens.] Thus a single lens produces coloured images of an object which are at slightly different positions. Because he did not know how to eliminate these chromatic aberrations, Newton eventually decided to abandon the use of lenses for large telescopes.

Achromatic Combination of Lenses

A converging lens deviates an incident ray towards its principal axis. A diverging lens, however, deviates a ray away from its principal axis (see figure 9.4 below).

The dispersion between two colours produced by a converging lens can thus be annulled by placing a suitable diverging lens beside it. The following figure illustrates an achromatic lens combination, known as an *achromatic doublet.* The converging lens is made of crown glass, while the diverging lens is made of flint glass. In various forms the diverging lens is typically plano-concave or biconcave, while the converging lens is biconvex or plano-convex. So that the lenses can be cemented together with Canada balsam, the radius of curvature of the curved surface of the concave lens is made numerically the same as that of one surface of the converging lens. The achromatic combination acts as a converging lens when used as the objective lens in a telescope or microscope since the positive crown lens is paired with a weaker flint lens. It should be noted that chromatic aberration would occur if the diverging and converging lenses were made of the *same* material, as the two lenses together would then constitute a single thick lens of one material.

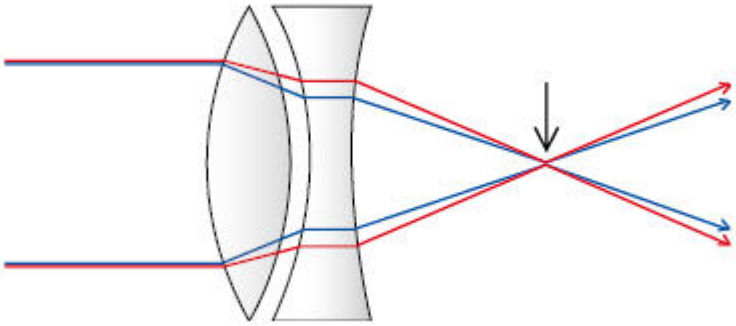

Figure 9.4: Eliminating chromatic aberration with a combination of lenses

Chromatic aberration can be countered by

- Changing the refractive index of the lens
- Changing the shape of the lens
- Decreasing the aperture size (results in fewer marginal rays). (However please remember that chromatic aberrations are firstly due to the glass refractive index changing with wavelength and not the geometry of the lens itself).

(The amount of spherical aberration increases as the square of the aperture.)

COMA

Another type of aberration is coma, which derives its name from the comet-like appearance of the aberrated image. An off-axis object point is not a sharp image point, but it appears as a characteristic comet-like flare because the image is a series of circles that form a comet shape. Coma is an aberration which causes rays from an off-axis point of light in the object plane to create a trailing "comet-like" blur. Coma may be defined as **the inability of a lens to render point sources of light that are away from the optical axis as circular**.

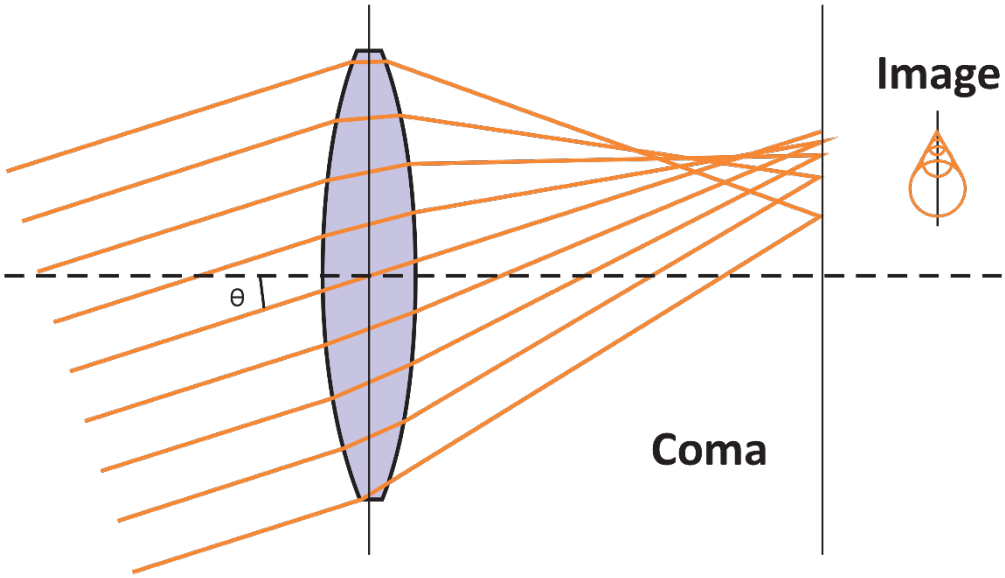

Figure 9.5: *Coma aberration*

Coma occurs when an object off the optical axis of the lens is imaged, where rays pass through the lens at an angle to the axis θ. Rays which pass through the centre of the lens of focal length f are focused at a point with distance f tan θ

from the axis. This is essentially spherical aberration with the object being off-axis in this case. Rays passing through the outer margins of the lens (peripheral rays) are focused at different points. Therefore, even if spherical aberration is corrected and the lens brings all rays to a sharp focus on axis, a lens may still exhibit coma off axis. Such a lens may produce a sharp image in the centre of the field, but become increasingly blurred toward the edges.

In general, a bundle of parallel rays passing through the lens at a fixed distance from the centre of the lens are focused to a ring-shaped image in the focal plane, known as a *comatic circle*. This causes blurring in the image plane (surface) of off-axis object points. The sum of all these circles results in a V-shaped or comet-like flare. As with spherical aberration, coma can be minimised (and in some cases eliminated) by choosing the curvature of the two lens surfaces to match the application. Lenses in which both spherical aberration and coma are minimised are called *bestform* lenses.

For a single lens, coma can be partially corrected by bending the lens.

Since this aberration is due to peripheral rays, it is primarily a problem for large aperture optical systems and can be ignored in spectacles because of the limited affect of the pupil. If we increase the aperture size, we have more coma. (The amount of coma increases as the square of the aperture size.) Shorter objects exhibit less coma. Objects further off axis have more coma. Lens shape will minimize spherical aberration, but not totally eliminate coma. When the aperture is closer to the lens, greater coma occurs.

As with spherical aberration, correction can be achieved by using multiple surfaces. Alternatively, a sharper image may be produced by judiciously placing an aperture, or stop, in an optical system to eliminate the more marginal rays.

The term aplanatic system is used to refer to an optical system free of spherical aberration and coma.

THE SIMPLE MAGNIFIER

The simple magnifier (simple microscope) is one of the most basic of all optical instruments because it consists only of a single converging lens. As the name implies, this device is used to increase the apparent size of an object.

ANGULAR MAGNIFICATION

The size of the image on the retina of the observer depends on

(i) the real size of the object, **h**

(ii) the distance of the object from the observer, **u**.

These two factors (**h** and **u**), determine the size of the angle subtended at the eye by the object (α in the diagrams below).

The apparent size of an object is proportional to this angle.

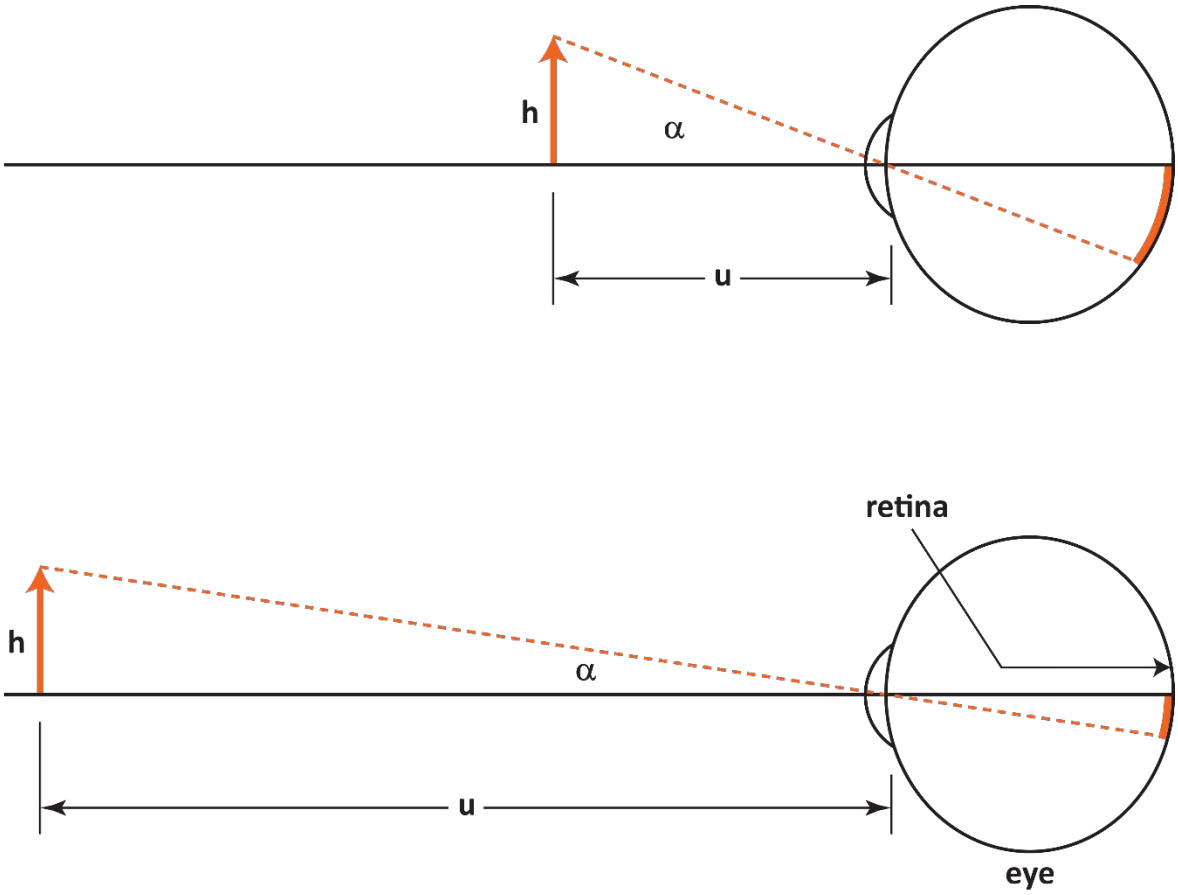

Figure 9.6: *Angular magnification*

Smaller α, smaller image on retina

Optical instruments provide magnification by increasing the size of the angle subtended at the eye.

Suppose an object is viewed at some distance from the eye. Clearly, the size of the image formed at the retina depends on the angle, θ, subtended by the object at the eye. As the object moves closer to the eye, θ increases and a larger image is observed. However, a normal eye cannot focus on an object closer than about 25 cm, the near point. Therefore, **θ is a maximum at the near point**.

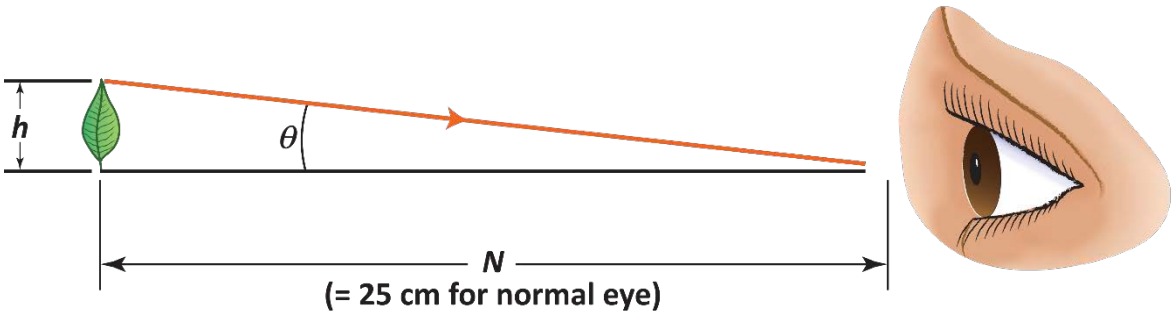

Figure 9.7: *Angular magnification in a human eye*

To further increase the apparent angular size of an object, a converging lens can be placed in front of the eye. The magnifier is held so that the object is positioned just inside the focal point of the lens. At this location, the lens forms a virtual, erect image that is enlarged as much as possible.

The lens thus increases the angular size of the object. To produce such an image, the object is placed at the focal point or just within it. If the eye is relaxed, the image will be at infinity, and in this case the object is exactly at the focal point. If the eye accommodates, the image is at the near point and the object is just within the focal point. (You make this slight adjustment yourself when you "focus" on the object by moving the magnifying glass.)

It should be noted that in the theory of optical instruments, we are concerned with visual angles and not with the physical sizes of the object and the image obtained.

We define the **angular magnification, or magnifying power, M,** of the lens as the ratio of the angle subtended at the eye by the image formed by an optical instrument (angle θ' in the figure) to the angle subtended at the eye by the object being viewed (angle θ in the figure).

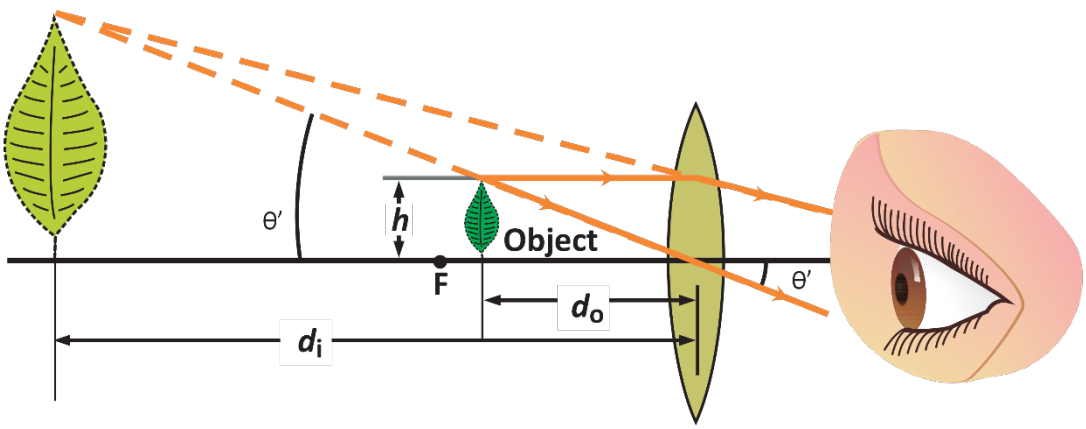

Figure 9.8: *Magnifying power*

$$\mathbf{M} = \frac{\boldsymbol{\theta}'}{\boldsymbol{\theta}}$$

The angular magnification is a maximum when the image formed by the lens is at the near point of the eye; that is, when $d_i = -25$ cm. The object distance that corresponds to this image distance can be calculated from the thin-lens equation:

$$\frac{1}{d_o} + \frac{1}{-25} = \frac{1}{f}$$

where f is the focal length in centimetres.

If we apply the small-angle approximation, it gives:

$$\tan\theta_0 \approx \theta_0 \approx \frac{h}{25} \qquad \text{and} \qquad \tan\theta \approx \theta \approx \frac{h}{d_o}$$

Thus, the magnification becomes:

$$M = \frac{\theta'}{\theta} = \frac{h/d_o}{h/25} = \frac{25}{d_o} = \frac{25}{25f/(25+f)}$$

Simplifying this equation gives:

$$M = 1 + \frac{25\text{ cm}}{f}$$

In optometric practice, lenses are normally specified by back vertex power, while some magnifying lenses may be specified by equivalent power. In these cases, the magnification equation can be written as:

$$M = 1 + \frac{F}{4}$$

The angular magnification given by the above equation is once again the ratio of the angular size seen with the lens to the angular size seen without the lens, with the object at the near point of the eye. **The eye** can actually focus on an image formed anywhere between the near point and infinity, and **is most relaxed when the image is at infinity.**

YOU ARE NOT REQUIRED TO KNOW THESE DERIVATIONS.
In order for the image formed by the magnifying lens to appear at infinity, the object must be placed at the focal point of the lens; that is, $d_o = f$. In this case, the small-angle approximation gives:

$$\theta_0 \approx \frac{h}{25} \quad \text{and} \quad \theta \approx \frac{h}{f}$$

The angular magnification is then:

$$M = \frac{\theta'}{\theta} = \frac{25\text{ cm}}{f}$$

When lens powers are specified:

$$M = \frac{F}{4}$$

With a single lens, it is possible to achieve angular magnifications up to about 4 without serious aberrations. We see that the magnification is slightly greater when the eye is focused at its near point than when relaxed. It can also be seen that the shorter the focal length of the lens, the greater the magnification. It is up to you whether you relax your eye or not when using a magnifier.

THE COMPOUND MICROSCOPE

A microscope is an instrument for viewing small objects. We noted that the magnification of a simple magnifier can be increased by using a lens of shorter focal length. It is impractical to decrease f beyond a certain limit. Firstly, there are mechanical difficulties associated with grinding a lens of short focal length (great curvature). Secondly, lens aberrations increase to such an extent that the image becomes one of poor quality.

To increase the magnification over that possible with a simple magnifier, two separated lenses can be used to obtain a high angular magnification, and constitute a **compound microscope**. In this case the magnifying lens is referred to as the ***eyepiece lens*** (or ocular) and the added lens as the ***objective lens***. The objective typically has a focal length ($\mathbf{f_o}$) of approximately 1 cm while the eyepiece has a focal length ($\mathbf{f_e}$) of a few centimetres. The two lenses are separated by a distance **L**, which is much greater than either $\mathbf{f_o}$ or $\mathbf{f_e}$.

The object is placed just outside the focal point $\mathbf{F_o}$ of the objective lens. This lens forms an enlarged real image which is at or just inside the focal point of the eyepiece. The eyepiece then acts as a simple magnifier and produces a greatly enlarged virtual image at infinity of the real image formed by the objective lens. This image is inverted, since

the image formed by the objective lens is inverted. This virtual image becomes the object for the eye itself, which forms the final real image on the retina, as shown.

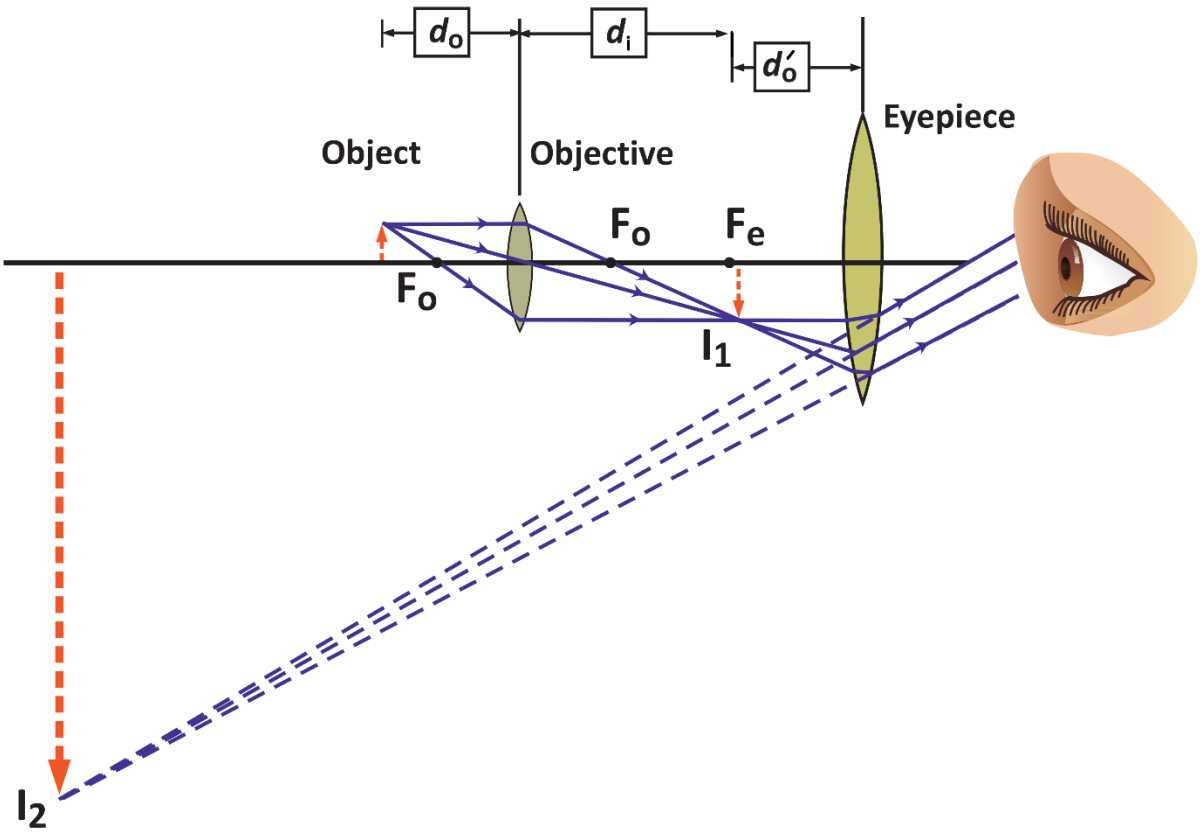

Figure 9.9: *The compound microscope: the objective lens produces a real magnified image I_1, which is then further magnified by the eyepiece.*

The magnification of a compound microscope is simply the product of the magnifications produced by each of the two lenses. The lateral magnification, M_o, of the first image is $-d_i/d_o$. Note from the figure that $\mathbf{d_i}$ is approximately equal to **L**. This occurs because the object is placed close to the focal point of the objective lens, which ensures that the image formed will be far from the objective lens. Furthermore, because the object is very close to the focal point of the objective lens, $\mathbf{d_o \approx f_o}$.

This gives a lateral magnification of

$$M_o = -\frac{d_i}{d_o} \approx -\frac{L}{f_o}$$

for the objective. The angular magnification of the eyepiece for an object (corresponding to the image at I_1) placed at the focal point is found from the equation derived in the previous section:

$$M_e = \frac{25\text{ cm}}{f_e}$$

The overall magnification of the compound microscope is therefore:

$$M = M_o M_e = -\frac{L}{f_o}\left(\frac{25\text{ cm}}{f_e}\right)$$

Where necessary, assume a standard length (L) of 16 cm. This is used by many manufacturers, but certainly not by all. Another popular length is 18 cm, for example.

The negative sign indicates that the image is inverted with respect to the object. Again, the shorter the focal lengths of the lenses, the greater the magnification. Of course, larger magnifications mean thicker lenses and hence greater lens aberrations. For this reason, most microscope lenses are complex multilens structures designed to reduce aberrations as much as possible.

Opaque objects are generally illuminated by a source placed above them. If the objects to be viewed are transparent, such as cells or tissue, light is normally passed through the object from a source beneath the microscope stage. The illumination system must be carefully designed if maximum sharpness and contrast are to be achieved. Usually, a *condenser* is employed, which is a set of two or three lenses, although inexpensive condensers may be a single lens or curved mirror. The purpose of the condenser is to gather light over a wide angle from the source, and to "condense" it down to a narrow beam that will illuminate the object strongly and uniformly. A number of different designs are employed. The source is often placed in the focal plane of the condenser so that light from each point on the source is parallel when it passes through the object.

THE TELESCOPE

Although the lens system is similar to the previous one, differences arise because the instruments are used for different purposes. In the case of the microscope, object distances are very short. Telescopes, on the other hand, are used to magnify objects that are very far away. In most cases the object can be considered to be at infinity.

REFRACTING TELESCOPE

This telescope uses a combination of lenses to form an image. In this type of telescope, the objective lens has a relatively long focal length (0.5 m upwards) and the object being viewed is far away compared to this focal length. As a result, rays from the object arrive nearly parallel and a real image forms at the focal point of the objective. Note, however, that in this case the image formed by the objective is smaller than the physical size of the object. The objective lens forms a real, inverted image of the distant object, very close to (inside) the focal point of the eyepiece. The eyepiece has a focal length of a few centimetres.

Hence the two lenses are separated by the sum of their focal lengths which corresponds to the length of the telescope tube. The eyepiece finally forms, at I_2, an enlarged, erect image of its object at I_1. $\mathbf{I_2}$, which forms at infinity, is an **enlarged, inverted image of the original object**.

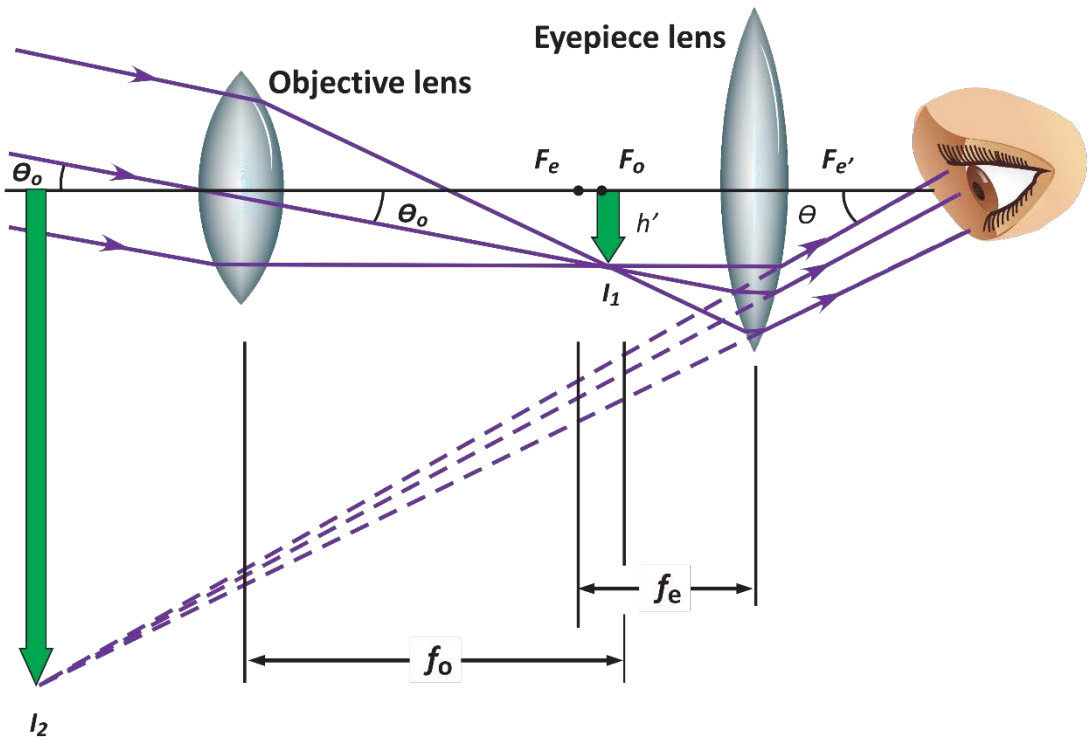

Figure 9.10: *Refracting telescope*

The magnification of such a telescope is given by:

$$M = -\frac{f_o}{f_e}$$

The minus sign again indicates that the image is inverted. To achieve a large magnification, the objective lens should have a long focal length and the eyepiece a short focal length.

REFLECTING TELESCOPE

For an astronomical telescope to produce bright images of faint stars, the objective lens must be large to allow in as much light as possible. Indeed, the diameter of the objective (and hence its ‘‘light-gathering power”) is the most important parameter for an astronomical telescope, which is why the thirty-six largest ones are specified by giving the objective diameter.

However, refracting telescopes with such large objective lenses give rise to a number of problems.

1. They are subject to chromatic aberration. We have seen that this aberration can be reduced by the use of an achromatic lens that corrects for red and blue light, or an apochromatic lens that corrects for at least red, blue, and green.
2. The construction and grinding of large lenses is very difficult.
3. A large lens, which can only be supported at its edges, would sag under its own weight and thus distort the image.
4. They are subject to spherical aberration.

In an attempt to avoid many of these problems, the largest telescopes are **reflecting** telescopes that use a curved mirror as the objective. Although these instruments are also subject to spherical aberration (see below), they have a number of advantages.

A. A mirror has only one surface that needs to be ground.
B. Sagging is avoided because a mirror can be supported along its entire back surface.
  a. Very large mirrors can be locally distorted by actuators at the rear surface to compensate for atmospheric distortions; this is known as adaptive optics. Actuators can also compensate for mirror distortion due to gravity, a process called active optics. Adaptive optics has been applied to the scanning laser ophthalmoscopes to image individual photoreceptors in the living eye.
C. Good quality optical material is not required since the light does not pass through it.
D. Since light does not pass through the mirror, there is no chromatic aberration.
E. The image is also brighter. In the refracting telescope there is some loss of light by reflection at the lens surfaces and by absorption.

The mirrors are polished to a parabolic shape to counter spherical aberration.

The accompanying diagram shows a typical design. Incoming light rays pass down the barrel of the telescope and are reflected by a parabolic mirror at the base. These rays converge towards point **A** in the figure, where an image would be formed on a photographic plate or another detector. However, before this image is formed, a small flat mirror at point **M** reflects the light toward an opening in the side of the tube that passes into an eyepiece.

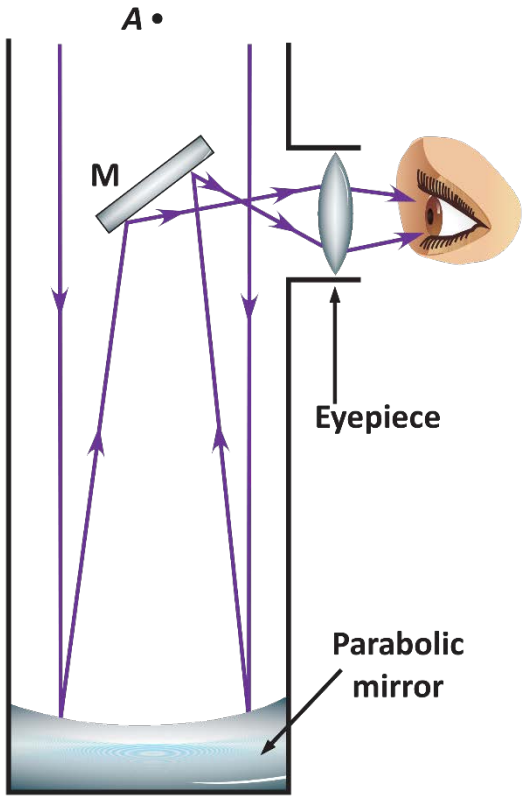

Figure 9.11: *Reflecting telescope*

This design is said to have a Newtonian focus, after its developer. (There are other systems such as the Cassegrainian which use a convex mirror.)

TERRESTRIAL TELESCOPE

A terrestrial telescope (for use in viewing objects on earth), unlike its astronomical counterpart, must provide an upright image. We will consider two ways in which such upright images are obtained.

A. The Galilean type, which Galileo used for his great astronomical discoveries, has a diverging lens as eyepiece. It intercepts the converging rays from the objective lens before they reach a focus, and acts to form a virtual upright image.

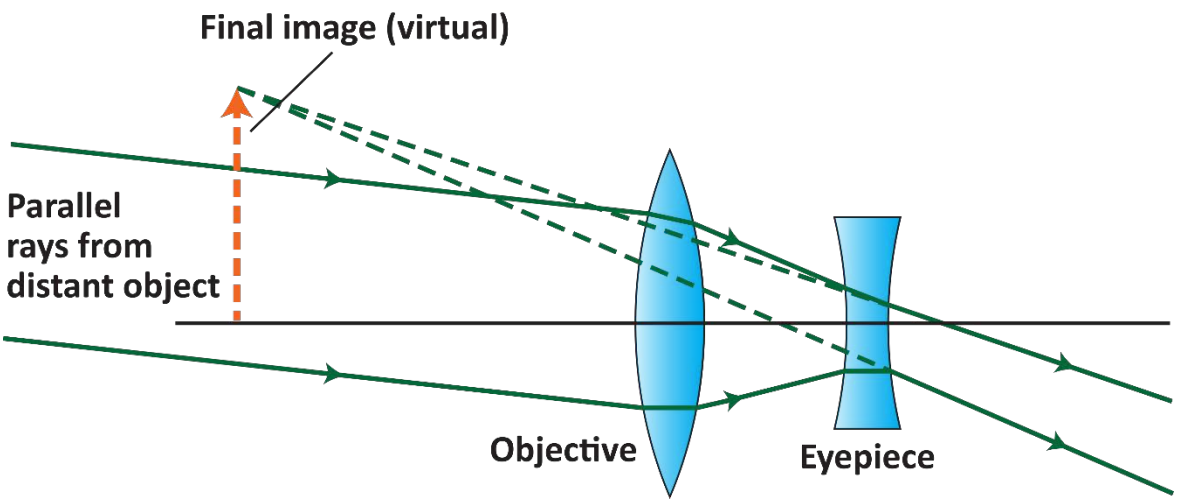

Figure 9.12: *Terrestrial telescope – Galilean type*

The distance between the objective and the eyepiece in the Galilean telescope is (fo-fe) which is much shorter than in the erecting telescope described in the next paragraph. Thus this type of telescope is convenient for use at events such as opera and horse races. A disadvantage is that this instrument has a restricted field of view.

B. Another solution is to place an additional converging lens, L, of focal length f between the objective and the eyepiece. This additional lens is known as the **erecting** or **inverter** or **field** lens. (See figure 9.13 below.) L is placed at a distance 2f in front of the inverted real image I_1 formed by the objective. It can be shown that the image I formed by lens L is (i) inverted, real, and the same size as I_1 and (ii) is also at a distance 2f from L. The only function of L is to invert the image I_1. Since the image I produced by L is the same size as I_1, the presence of L does not affect the magnitude of the angular magnification of the telescope.

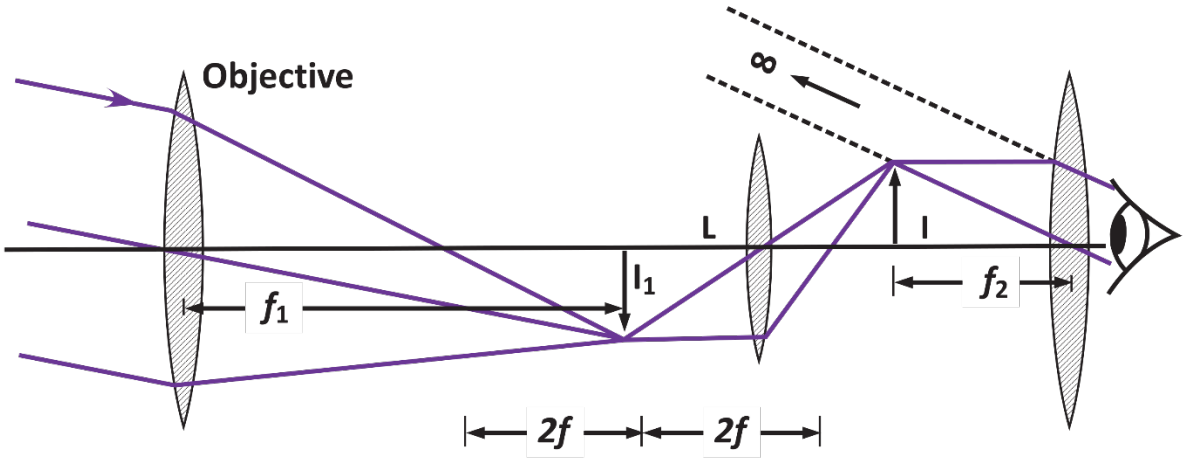

Figure 9.13: *Terrestrial telescope, different type*

Thus the image I is now erect with respect to the distant object. If I is at the focus of the eyepiece (as shown), the final image is formed at infinity and is also erect.

The field lens, however, reduces the intensity of light emerging through the eyepiece, as light is reflected at the lens surfaces and absorbed by the lens material. Yet another disadvantage is the increased length of the telescope. The distance from the objective to the eyepiece is now ($f_o + f_e + 4f$), compared with ($f_o + f_e$) in the astronomical telescope and the even shorter distance in the Galilean telescope.