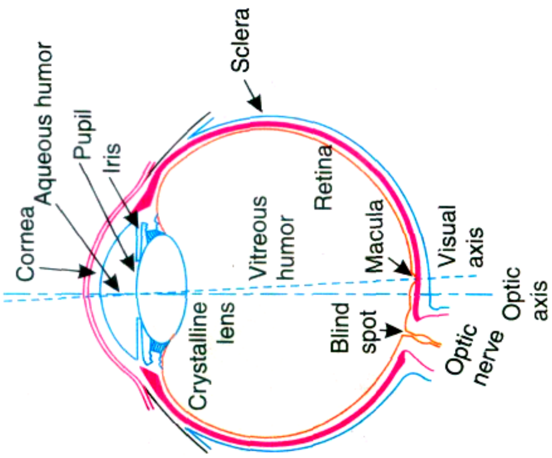
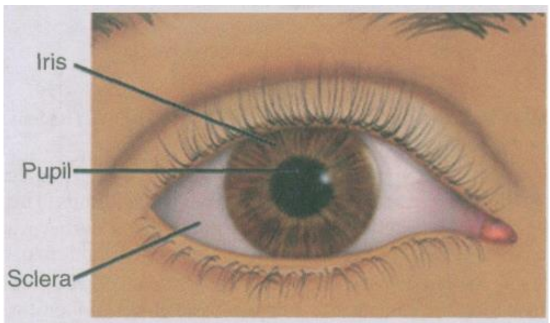
Optical Instruments

1.1 Introduction

The optical instruments can be broadly divided into two groups. One group forms ***real images*** of an object, which is projected onto a screen or photographic plate. The image can be viewed simultaneously by many observers. Projectors belong to this category. The other group forms ***virtual images*** of an object and only one observer can see the image. The virtual image formed by the instrument is transformed by the eye into a real image. The spectacles, microscopes and telescopes belong to this group.

1.2 The Eye





The observer's eye is an essential part of all optical instruments. It is nearly spherical in shape and about 2.5 cm in diameter. It has a tough outer skin called ***sclera***, which protects the eye and gives the necessary stiffness. The sclera is lined inside with vascular tissue, which consists of blood vessels feeding the eye. At the front of the eye, the sclera extends into a thin convex transparent membrane called the ***cornea***, which acts as an entrance lens for the eye. The back of the cornea is the ***iris***, which is a pigmented muscular ring. The iris can be of different colours, which explains why people have blue, green, brown or black eyes. The iris contains an aperture with a variable diameter called the ***pupil***, which opens and closes to adapt to changing light intensity. Behind the iris is a ***crystalline lens***, which is a biconvex lens made by Nature herself. The lens contains a fibrous jelly, hard at the centre and progressively softer at the outer portions. The crystalline lens is held in place by ligaments that attach it to the ciliary muscle, which encircles it.

The chamber in front of the lens and behind the cornea contains a liquid called

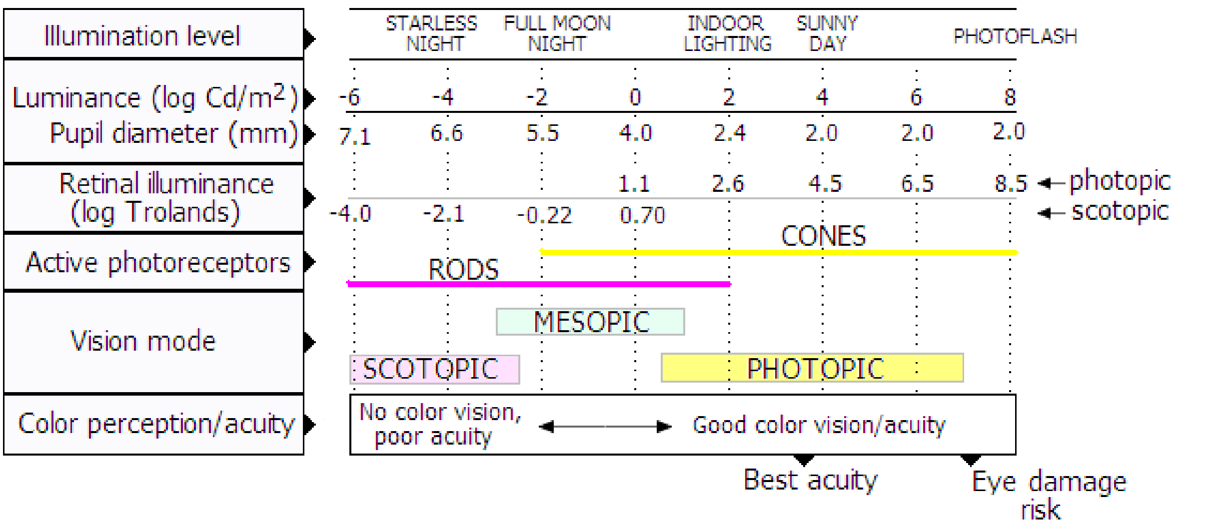
aqueous humor. Behind the lens, the eye is filled with a thin water jelly called ***vitreous humor***. The indices of refraction of both the aqueous humor and vitreous humor are about **1.336**. The crystalline lens, while not homogeneous, has an average index of **1.437**. Most of the refraction of light entering the eye occurs at the outer surface of the cornea. The chamber holding the vitreous humor is lined with a sensory layer called the ***retina***. The retina has the shape of a hemisphere and contains light receptors called ***rods* and *cones***. The human eye has a total of **125 million rods and 6.5 million cones**. They sense the image and transmit it via the ***optic nerve*** to the brain. At the point where the optic nerve enters the eye, there are no rods or cones and this portion of the retina is called the ***blind spot.*** In contrast, vision is most acute in a small central region at the axis of the eyeball called ***the fovea centralis***. Here, cones responsible for colour vision are concentrated. The remaining areas of the retina are occupied mainly by rods.

Refraction at the cornea and the surfaces of the lens produces a real and inverted image of the object on the retina. The optic nerve sends a signal to the brain, which makes the corrections necessary for us to see objects in their natural positions.

For an object to be seen sharply, the image must be formed exactly at the location of the retina. The eye adjusts to different object distances by changing the focal length of its lens; the lens-to-retina distance does not change. The focal length of the eye is adjusted by varying the radii of curvature of the crystalline lens, with the help of ciliary muscle. This process is called ***accommodation.***

The eye accommodates involuntarily, but its ability to accommodate is not unlimited. We describe the limited ability of the eye in terms of ***the far point* and the *near point*** of the eye. The far point of a normal eye is infinity. The ciliary muscle is fully relaxed in this position. The nearest point on which the eye is focused with the ciliary muscle fully contracted is the near point of the eye. The minimum distance at which an eye can see objects distinctly and without getting tired is called the ***normal viewing distance or normal distance of distinct vision* (NDDV); it is 25 cm for a normal eye**. The range of accommodation gradually diminishes with age because the crystalline lens grows through a person's life and the ciliary muscles are less able to distort a larger lens.

ILLUMINANCE AND VISUAL FUNCTION



The Eye – Focusing

✓ **The eye can focus on a distant object**

- The ciliary muscle is relaxed
- This causes the lens to flatten, increasing its focal length
- For an object at infinity, the focal length of the eye is equal to the fixed distance between the lens and the retina. This is about 1.7 cm

✓ **The eye can focus on near objects**

- The ciliary muscles tense
- The lens bulges a bit and the focal length decreases
- The image is focused on the retina

The Eye – Near and Far Points

- The *near point* is the closest distance for which the lens can accommodate focus light on the retina
  - Typically, at age 10, this is about 18 cm
  - It increases with age
- The *far point* of the eye represents the largest distance for which the lens of the relaxed eye can focus light on the retina
  - Normal vision has a far point of infinity

Eyes may be:

Farsighted:

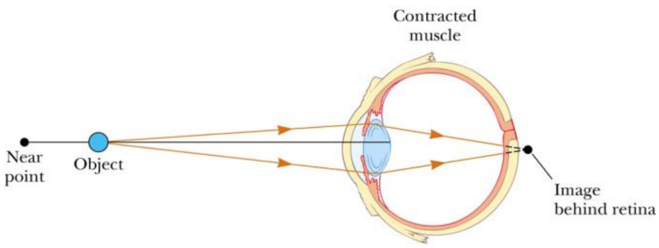
- Light rays reach the retina before they converge to form an image

Nearsighted:

- A person can focus on nearby objects but not those far away

Farsightedness:

- Also called hyperopia
- The image focuses behind the retina
- Can usually see far away objects clearly, but not nearby objects

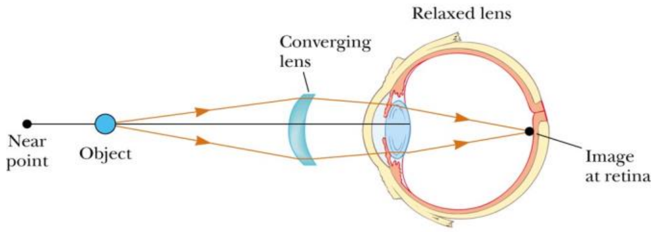


© 2003 Thomson - Brooks Cole (a)

Correcting Farsightedness

A converging lens placed in front of the eye can correct it.

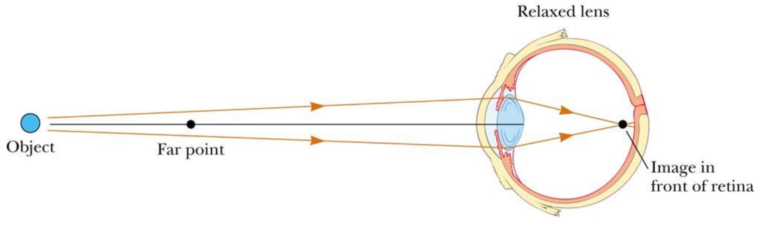
The lens refracts the incoming rays more toward the principle axis before entering the eye.



© 2003 Thomson - Brooks Cole (b)

Nearsightedness

- Also called **myopia**
- In *myopia* the nearsightedness is caused by the lens being too far from the retina

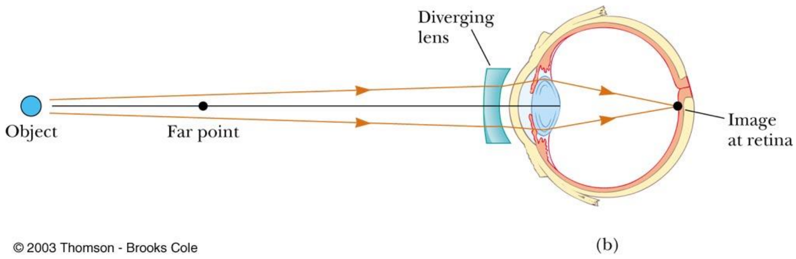


© 2003 Thomson - Brooks Cole (a)

Correcting Nearsightedness

A diverging lens can be used to correct the condition

The lens refracts the rays away from the principle axis before they enter the eye



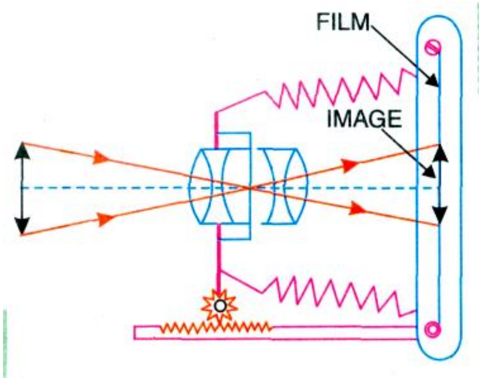
Presbyopia

Presbyopia ("**old-age vision**") is due to a reduction in accommodation ability

- The cornea and lens do not have sufficient focusing power to bring nearby objects into focus on the retina (=farsightedness)
- Condition can be corrected with converging lenses

1.3 Camera

A photographic camera is optically very similar to the human eye. It consists of a convex lens, a light-tight box, a light-sensitive film to record an image and a shutter to let the light from the lens strike the film for a prescribed length of time. The lens forms a reduced real image of the object on the photographic film.



In order to record the image properly on the film, the total light energy per unit area reaching the film must fall within certain limits. This is controlled by the shutter and the lens aperture. The shutter controls the time interval during which light enters the lens. This is usually adjustable in steps corresponding to factors of about two, often from 1sec to 1/1000sec.

With a convex lens, the image distance decreases as the object distance increases. Hence in focusing the camera, the lens is moved closer to the film for a distant object and farther from the film for a nearby object.

1.3.1. Camera Lenses

The simplest type of camera lens is the ***biconvex*** lens. It suffers from every type of aberration. It was used in the earliest stages. With the advancement in technology, lens combinations are used. They are classified as normal, wide-angle, telephoto, zoom etc.

1- The ***normal lens*** has a large aperture to reduce exposure time, an angular field of view of about 50° and produces an undistorted image.

2- A ***telephoto lens*** has a long focal length, gives a small angle of view and a large image of distant object,

3- A ***wide-angle lens*** is a lens of short focal length and gives a small image and a wide angle of view.

4- A ***zoom lens*** consists of a large number of individual lenses to decrease aberrations. The focal length of an ordinary camera may be increased up to six times without moving the image out of focus.

Main Similarity and Difference between Eye and Camera:

The Similarities are:

1- Both the human eye and a camera use something called a lens. In fact, they both use the same type of lens - a converging lens

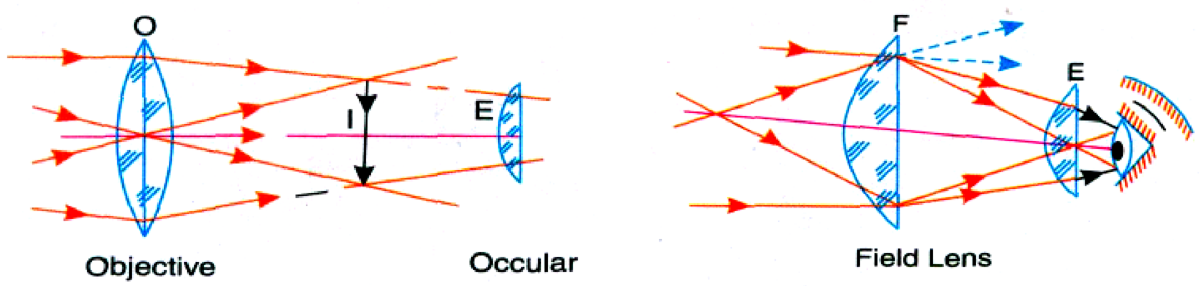
2- Both the human eye and a camera can focus on things that are close to you or far from you.

The Differences are:

1. Eye is a live organ for sight whereas a camera is an equipment to capture images.
2. Eye uses live cells to detect light while the camera uses a diaphragm to detect light and capture images.
3. Stereoscopic vision of eyes allows 3 dimensional images while camera captures only 2 dimensional images.
4. The pupil adjusts the size while focusing while in a camera lens moves to change focus.
5. Eyes have blind spots while cameras do not.

1.4 Objective and Eyepiece

To increase the magnifying power, two separate lenses are used. The lens near the object is called the **objective,** which forms a real image of an object under examination. The lens used to enlarge this image further to form a final image and which is then viewed by the eye is called an **eyepiece** or **ocular.**



An optical instrument is required to produce a magnified image free from aberrations and a bright image covering a wide field of view. If a single lens is used as an eyepiece, the final image will suffer from spherical and chromatic aberrations. Another drawback is the small field of view, which becomes lesser and lesser as the magnification of the instrument is increased. The field of view will progressively decrease as the distance between the objective and ocular is increased. The distance is varied in order to increase the magnification. It becomes therefore expedient to place an additional lens in the eyepiece to cause all the rays from the image to enter the eye lens. This extra lens is called a **field lens.** The function of the field lens is to gather in more of the rays from the objective toward the axis of the eyepiece. The two lenses are made and kept in such a way that their combination is achromatic and free from spherical aberrations. Two common eyepieces are the Huygens and the Ramsden types.

1.4.1 Kellner's Eyepiece

Construction:

It consists of two Plano-convex lenses of equal focal lengths. The distance between the two lenses is equal to the focal length of either lens. The convex surfaces of both lenses face the incident light.

***(i)* Condition for achromatism:** The distance between the two lenses for achromatism is

$$d = \frac{f_1 + f_2}{2}$$

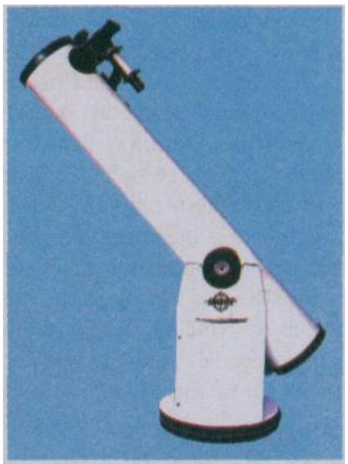
In the present case $f_1 = f_2 = f\ (say)$

$$\therefore \quad d = \frac{f + f}{2} = f$$

This is true for Kellner eyepiece. Thus, Kellner eyepiece satisfies the condition of achromatism.

(ii) **Condition of minimum spherical aberration:** The distance between the two lenses for minimum spherical aberration is:

$$d = f_1 - f_2 \qquad as\ f_1 = f_2 \quad then \quad d = 0$$



Kellner's eyepiece.

But the distance between the two lenses in Kellner eyepiece is ***f***. Thus, the eyepiece does not satisfy the condition of minimum spherical aberration.

(iii) **Equivalent focal length:** The equivalent focal length of the eyepiece is given by

$$F = \frac{f_1 f_2}{f_1 + f_2 - d} = \frac{f\,f}{f + f - f} = f$$

(iv) **Position of cross-wires:** The cross-wire placed on the plane surface of the field lens.

Merits and demerits:

1. The field of view of the eyepiece is very large. Therefore, it may be used in the microscope and high power telescopes.

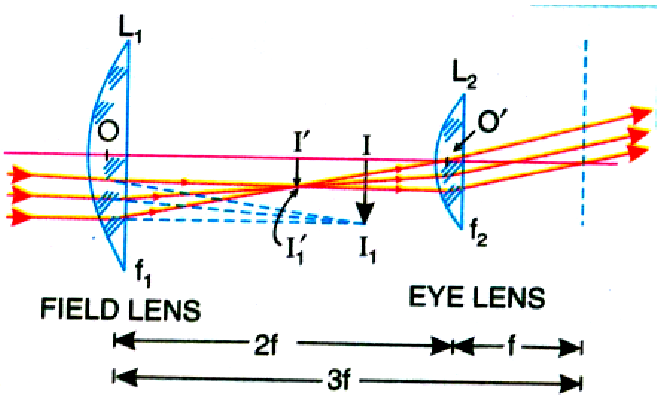
2. As the eyepiece does not satisfy the condition of minimum spherical aberration, the defect is present.

3. The cross-wires are permanently marked on the field lens. Any scratch or dust particle present on the field lens also come into sharp focus and as a result the final image is spoiled.

4. The defect of distortion is produced.

1.4.2 Huygens Eyepiece

Construction:



Huygens' eyepiece consists of two lenses having focal lengths in the ratio 3:1 and the distance between them is equal to the difference in their focal lengths. The focal lengths and the positions of the two lenses are such that each lens produces an equal deviation of the ray and the system is achromatic. This eyepiece is free from chromatic as well as spherical aberrations as it satisfies the two conditions simultaneously.

(i) The lens combination acts as an achromatic system if $D = \frac{f_1 + f_2}{2}$.

(ii) The lenses produce equal deviation of the incident ray when the distance between the two lenses is equal to $(f_1 - f_2)$.

The field and the eye lenses used are Plano-convex and are placed with their convex surfaces towards the incident ray. In this way, the total deviation due to the combination is divided into four parts which makes the combination to have minimum spherical aberration. If spherical and chromatic aberrations are to be minimized simultaneously, the following condition is to be satisfied.

$$D = \frac{f_1 + f_2}{2} \qquad \text{Chromatic aberration}$$

$$D = f_1 - f_2 \qquad \text{Spherical aberration}$$

Combining the two conditions, we obtain

$$\frac{f_1 + f_2}{2} = f_2 - f_1$$

or
$$f_2 = 3f_1$$

$\therefore$
$$D = 3f_1 - f_1 = 2f_1$$

To satisfy the conditions for minimum chromatic and spherical aberrations, the focal length of the field lens should be three times the focal length of the eye lens and the distance between them should be equal to twice the focal length of the eye lens.

***(iii)* Equivalent Focal Length:**

The equivalent focal length of the eyepiece can be found as follows. If F is the equivalent focal length of the eyepiece, then it is given by

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{d}{f_1 f_2}$$

$$\frac{1}{F}=\frac{1}{f}+\frac{1}{3f}-\frac{2f}{3f^2}=\frac{2}{3f}$$

$$\therefore \qquad F=3f/2$$

The equivalent lens lies behind field lens at a distance of

$$x=\frac{d\times F}{f}=\frac{2f\times 3f/2}{f}=3f$$

In other words, the equivalent lens is at a distance of $3f-2f=f$ behind the eye lens.

***(vi)* Position of Cross-wires:** The Position of Cross-wires lies midway between the two lenses. Hence the image and the scale would not be magnified equally and so the measurements will not be reliable. The image of the cross-wire or scale would have all the defects of an image formed by a single lens. Hence in instruments using Huygens' eyepieces, scale is not used except when magnification is low.

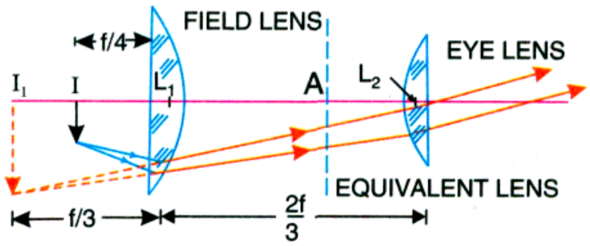
Merits and Demerits:

1- The Huygens' eyepiece is fully free from chromatic aberration because the distance between the lenses is equal to half the sum of their focal lengths.

2- Spherical aberration is also minimum because the distance between the two lenses is equal to the difference of their focal lengths.

3- The field of view of this eyepiece is smaller than that of Ramsden's eyepiece.

1.4.3 Ramsden Eyepiece



Ramsden's eyepiece consists of two Plano-convex lenses each of focal length separated by a distance equal to ***(2/3) f***. The lenses are kept with their curved surfaces facing each other to reduce spherical aberration. The field lens is a little larger than the intermediate image and is placed close to this image to allow as much light as possible to pass through it. The eye lens has a smaller diameter but carries out the actual magnification.

Equivalent focal length:

The equivalent focal length of the eyepiece can be found as follows:

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{d}{f_1 f_2}$$

$$\frac{1}{F}=\frac{1}{f}+\frac{1}{f}-\frac{(2/3)f}{f^2}$$

$$=\frac{2}{f}-\frac{2}{3f}$$

$$=\frac{4}{3f}$$

The equivalent lens of focal length **(3/4)*f*** must be placed behind the field lens at a distance

Position of the cross-wires:

The cross-wires should be placed at the position of the focal plane of the equivalent lens. Since the scale and image would be magnified equally, the measurement would be trustworthy.

Merits and Demerits:

1- The field of view of this eyepiece is fairly wide.

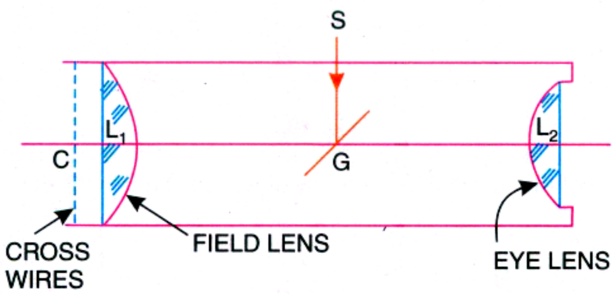
2- It is not entirely free from chromatic aberration since the distance between the two lenses is not equal to half the sum of their focal lengths. However, chromatic aberration is minimized by using an achromatic combination both for the field lens and the eye lens.

3- Spherical aberration is minimized by using two Plano-convex lenses thereby spreading deviation over four surfaces.

Comparison of Ramsden Eyepiece with Huygens Eyepiece

	Ramsden Eyepiece	*Huygens Eyepiece*
1.	Ramsden's eyepiece is a positive eyepiece. The image formed by the objective lies in front of the field lens. Therefore, cross-wires can be used.	Huygens' eyepiece is a negative eyepiece. The image formed by the objective lies in between the two lenses. Therefore, cross-wires cannot be used.
2.	The condition for minimum spherical aberration is not satisfied. But by spreading the deviations over four surfaces, spherical aberration is minimized.	The condition for minimum spherical aberration is satisfied.
3.	It does not satisfy the condition for achromatism but can be made achromatic by using an achromatic doublet as the eye lens.	It satisfies the condition for achromatism.
4.	It is achromatic for only two chosen colours.	It is achromatic for all colours.
5.	The other types of aberrations are better eliminated. Coma is absent and distortion is 5% higher.	Other aberrations like pincushion distortion are not eliminated.
6.	The eye clearance is 5% higher.	The eye clearance is too small and less comfortable.
7.	It is used for quantitative purposes in microscopes and telescopes.	It is used for qualitative purposes in microscopes and telescopes.
8.	Its power is positive.	Its power is positive.

1.4.4 Gauss Eyepiece



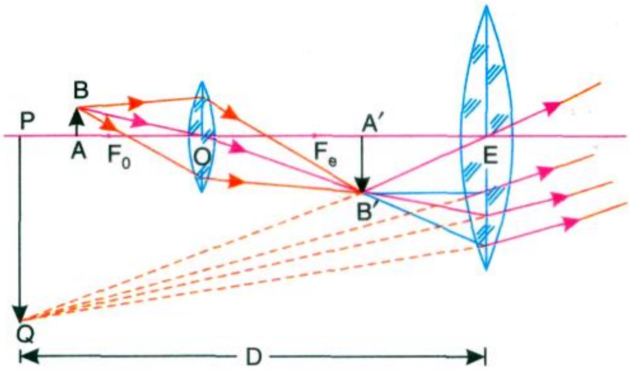
Gauss eyepiece is a modification of Ramsden eyepiece. The field lens and the eye lens are two Plano-convex lenses of equal focal length and separated by a distance equal to two third of the focal length of either. To illuminate the field of view a glass plate **G** is held at an angle of 45° to the axis of the lens system. **S** is a source of light. Light reflected from **G** illuminates the field of view. The cross-wire **C** is kept at a distance ***f*** in front of the field lens.

1.5 Compound Microscope


Compound microscope

A simple magnifying lens is not useful where large magnification is required. A highly magnified image must be produced in two stages. A compound microscope is used for this purpose. Around 1590, Janssen, a Dutch spectacle maker, invented the compound microscope. Galileo announced his invention of the compound microscope in 1610.

A compound microscope has two lenses, an objective and an eyepiece. Both the objective and the eyepiece of an actual microscope are highly corrected compound lenses with several optical elements.

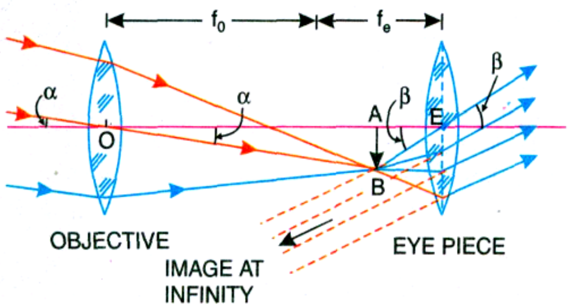


1.6 Telescopes

Jan Lippershey invented the first telescope in 1608. In the year 1609 Galileo designed a telescope with which he made astounding astronomical observations. Newton designed a reflecting telescope because of the difficulty in manufacturing lenses free from chromatic aberrations. An astronomical telescope is used to view heavenly bodies. The telescope that uses a lens as an objective is called a **refracting telescope.**

1.6.1 Refracting Astronomical Telescope

The simple astronomical telescope consists of two lenses. The objective is a convex lens of long focal length and forms a real image of the distant object.



The eyepiece is a convex lens of small focal length. It may be noted that the optical system of a telescope is similar to that of a microscope. The objective lens forms a real and reduced image of the object. The eyepiece enlarges this image and forms a magnified virtual image at infinity. As the object viewed by the telescope lies far away, the first image is formed nearly at the second focal point of the objective lens. If the final image formed by the eyepiece lies at infinity, the first image must also be at the first focal point of the eyepiece.

To calculate the angular magnification **M** of the telescope, it is assumed that the eye is very close to the eyepiece. Moreover, the distance between the objective and the eyepiece is very small compared to the distance of the object from the objective or eyepiece.

$$M = \frac{\beta}{\alpha}$$

In the ΔABE, $\tan\beta = \frac{AB}{AE}$ or $\beta = \frac{AB}{AE}$

In the ΔOAB $\tan\alpha = \frac{AB}{OA}$ or $\alpha = \frac{AB}{OA}$

$$M = \frac{\beta}{\alpha} = -\frac{AB/AE}{AB/OA} = -\frac{OA}{AE} = -\frac{F}{f}$$

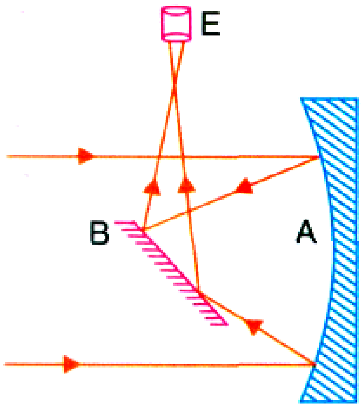
Thus, the magnification is equal to the ratio of the focal length of the objective and the eyepiece. The negative sign shows that the final image is inverted. To increase the magnification of the telescope, the objective should be of large focal length and the eyepiece should be of short focal length.

1.6.2 Reflecting Telescope

In the reflecting telescope, the objective lens is replaced by a concave mirror. In large telescopes, this has many advantages. The objective of the telescope should have a large aperture if fine details and a bright image are required. In the case of a refracting telescope, the objective is a combination of lenses. But the objective of a very large aperture cannot be manufactured. Therefore, in very large telescopes the objective is a parabolic mirror instead of a converging lens. Mirrors are inherently free from chromatic and spherical aberrations. Spherical aberration in the case of a mirror can be avoided by the use of a parabolic mirror. The material of the mirror need not be transparent. Moreover, the mounting of a mirror is easier than that of a lens because the lens can be supported only at the rim. Because the image is formed in a region traversed by incoming rays, this image can be observed directly with an eyepiece by blocking part of the incoming beam. When a telescope is used for photography the eyepiece is removed and photographic film or an electronic detector is placed at the position of the real image. Most of the telescopes for research do not use an eyepiece.

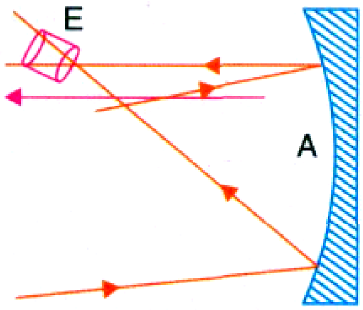
1- Newton's Telescope

The objective is a large concave spherical mirror made of speculum metal (alloy of copper and tin). A Ramsden eyepiece is used with this telescope. The rays from the distant star are reflected from the concave spherical mirror **A** of large aperture and long focal length. Then they are reflected to one side at right angles to the axis, by means of a small plane mirror **B**. The final image is seen through the eyepiece **E**.



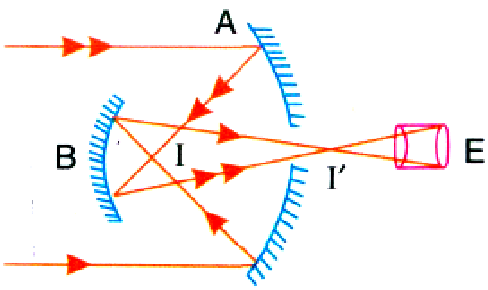
2- Herschel's Telescope

Is similar to the Newton's telescope but the axis of the mirror **A** is inclined to the incident rays from the distant star. This avoids the use of the mirror. The final image is formed on one side and is seen through the eyepiece **E**.

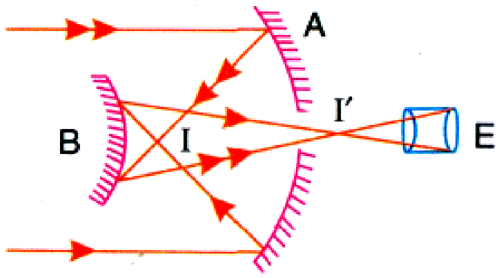


3- Gregory's telescope

The objective **A** has small central aperture. The rays from the distant star are reflected by the objective **A**. These rays form an image **I** at the point which lies between the focus and the centre of curvature of the concave mirror **A**. These rays after reflection from the mirror **B** form the final image **I'** which is viewed by the eyepiece **E**. **I'** is secondary image of **I**.

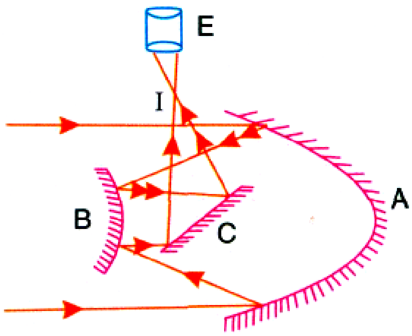


4- Cassegrain's telescope



Has a large spherical mirror **A**, having an aperture in the centre just similar to Gregory's telescope. The rays from the distant star after reflection from the mirror **A** fall on the convex mirror **B** and are allowed to converge at **I**. The final image is formed at **I'**, which can be viewed through the eyepiece. The 500 cm Mount Polomar telescope is Cassegrain type.

5- **Coude's telescope**



Has a large paraboloidal mirror **A**. **B** is a convex mirror and **C** is a plane mirror. The rays from the distant star after reflection from the mirror **A** fall on the convex mirror **B** and after falling on the mirror **C** converge to a point **I**. The final image is formed at **I** which can be viewed through the eyepiece. The telescope is a combination of Newtonian and Cassegrainian telescopes. Moreover, the necessity of the aperture in the centre of the mirror **A** is avoided.

There are many points in favour of reflecting telescopes:

1. There is no absorption of light as in thick lenses.
2. The mirrors are free from chromatic aberration.
3. With parabolic mirror, there is no spherical aberration for beams parallel to the axis.
4. Mirrors can be constructed with considerably large diameters than lenses.
5. Mirrors can be easily mounted whereas lenses can be mounted only on the edges or rim.

QUESTIONS

1- Describe a simple photographic camera.

2- What are the advantages of a compound microscope over a simple microscope?

3- What are the functions of a field lens used in an eyepiece? Give the construction of a Huygens eyepiece and calculate the positions of the cardinal points.

4- What is an eyepiece and what is its advantage over a single lens?

5- Give the construction and working of a Ramsden eyepiece. How are chromatic and spherical aberrations minimized in this eyepiece?

6- Explain the construction of a Huygens eyepiece. Why cannot a cross-wire be used with it?

7- Give the name and construction of the eyepiece, which satisfies the condition for achromatism.

8- Describe and point out the respective merits of Ramsden and Huygens eyepieces.

9- Explain what do you understand by spherical and chromatic aberrations. Describe how these are minimized in a Huygens eyepiece.

10- Give the construction and working of a Ramsden eyepiece. How are chromatic and spherical aberrations minimized in this eyepiece?

11- Explain with the help of a neat diagram the construction and working of a Huygens eyepiece and clearly indicate the positions of its cardinal points. Why is it referred to as a theoretically perfect but a negative eyepiece?

12- Explain why an eyepiece should consist of two lenses?