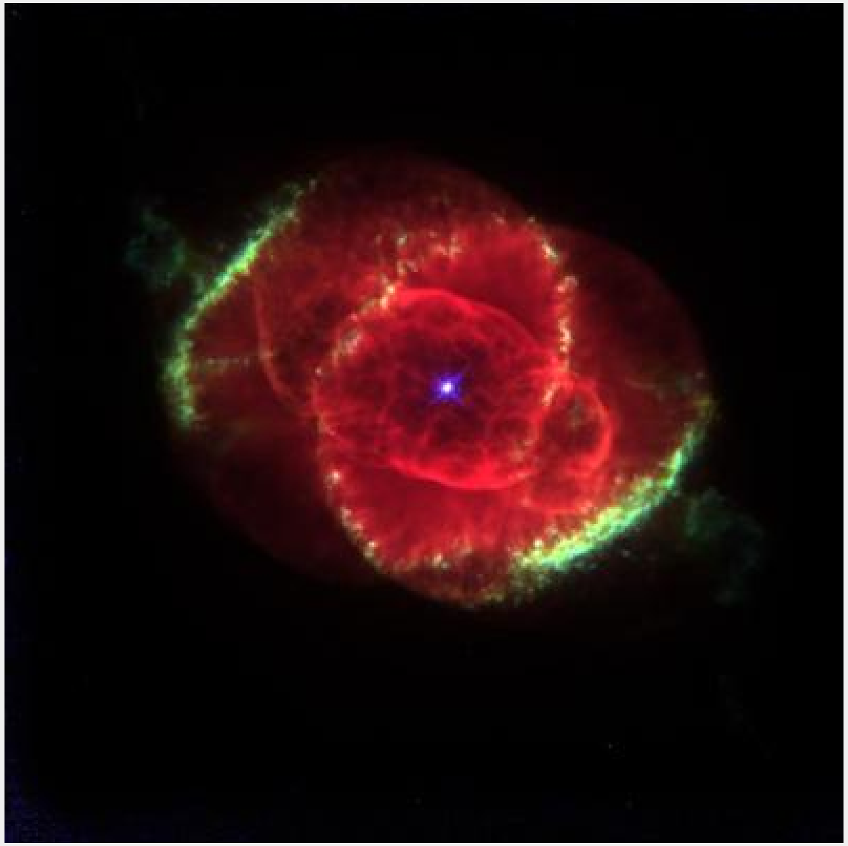
An Eye on the Universe: Image Formation in the Eye and the Telescope



Credit: J.P. Harrington "& K.J. Borkowski (University of Maryland), and NASA

Summary

We have now seen many images of objects, but how do telescopes work to create and focus these images onto CCDs.

In this Activity you will learn how images are formed

- in the eye, and
- in the optical telescope

with particular attention being given to how convex lenses work.

In each case, we start by discussing the eye and then compare it to the telescope.

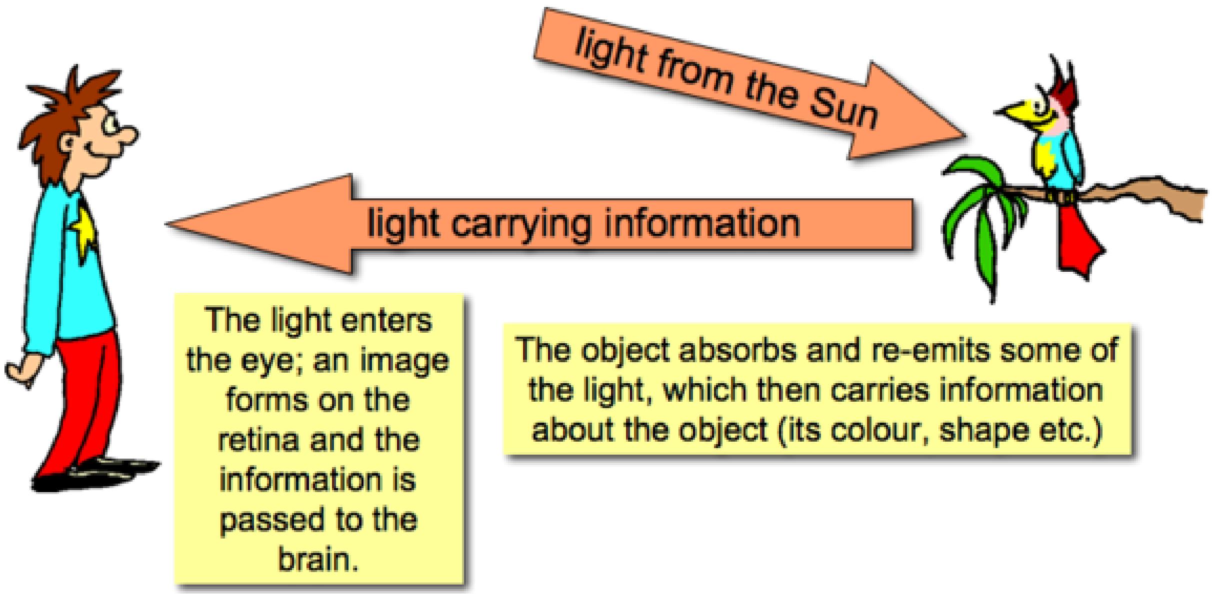
You will also be introduced to the two major types of optical telescopes:

- reflecting telescopes, and
- refracting telescopes.

The eye

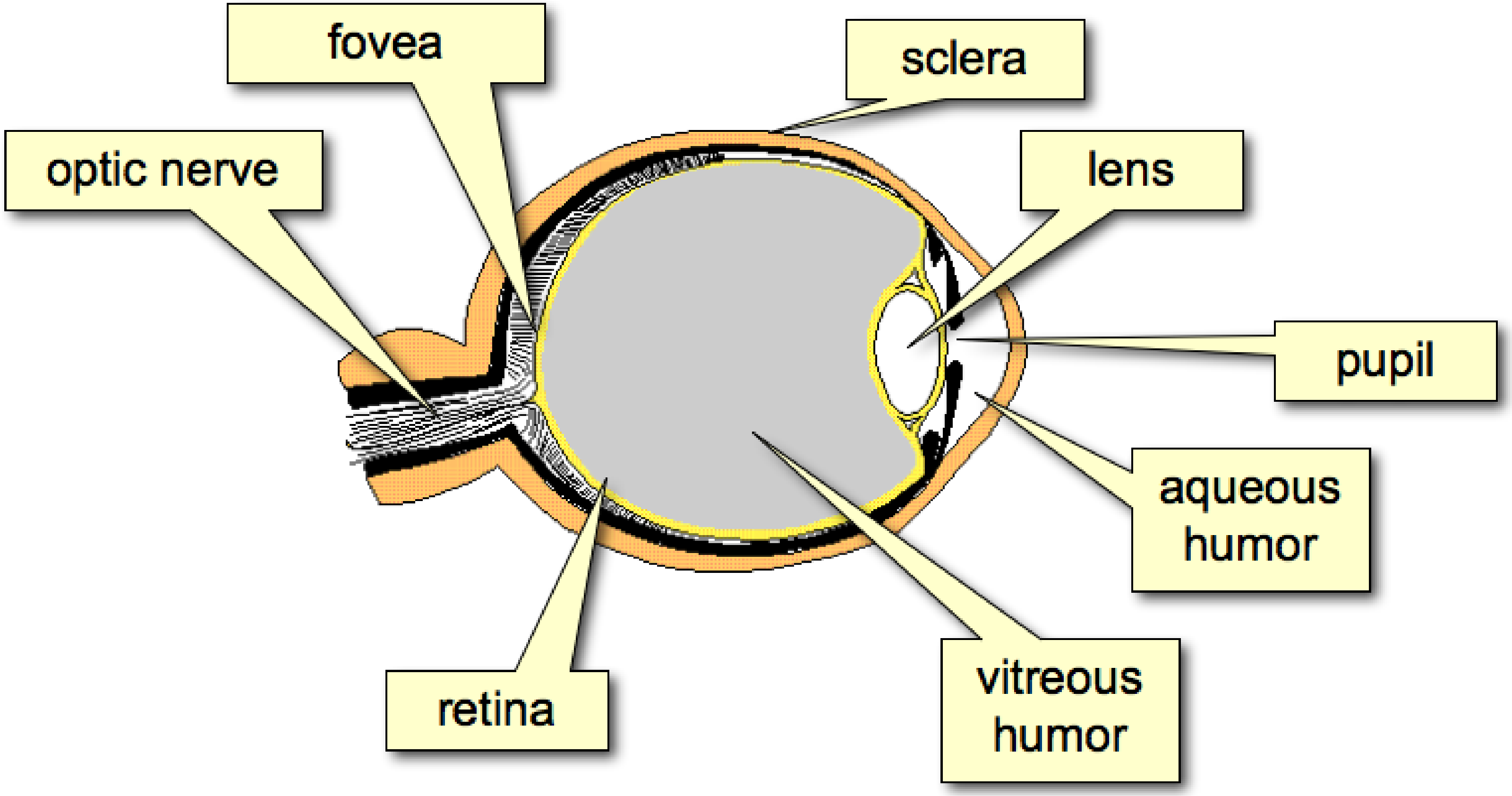
The function of the eye, in almost every creature on Earth, is to collect light transmitted, emitted or reflected by a distant object and form an image of that object for presentation to the brain.

The brain then analyses (and usually recognises) the source of the image, and can decide whether (and how) to respond. What the brain will decide to do in this case depends largely on whether the observer is a cat ("hunt!"), a caterpillar ("hide!") or a birdwatcher ("take photo!"). All observers, however, want the **clearest** image they can get.



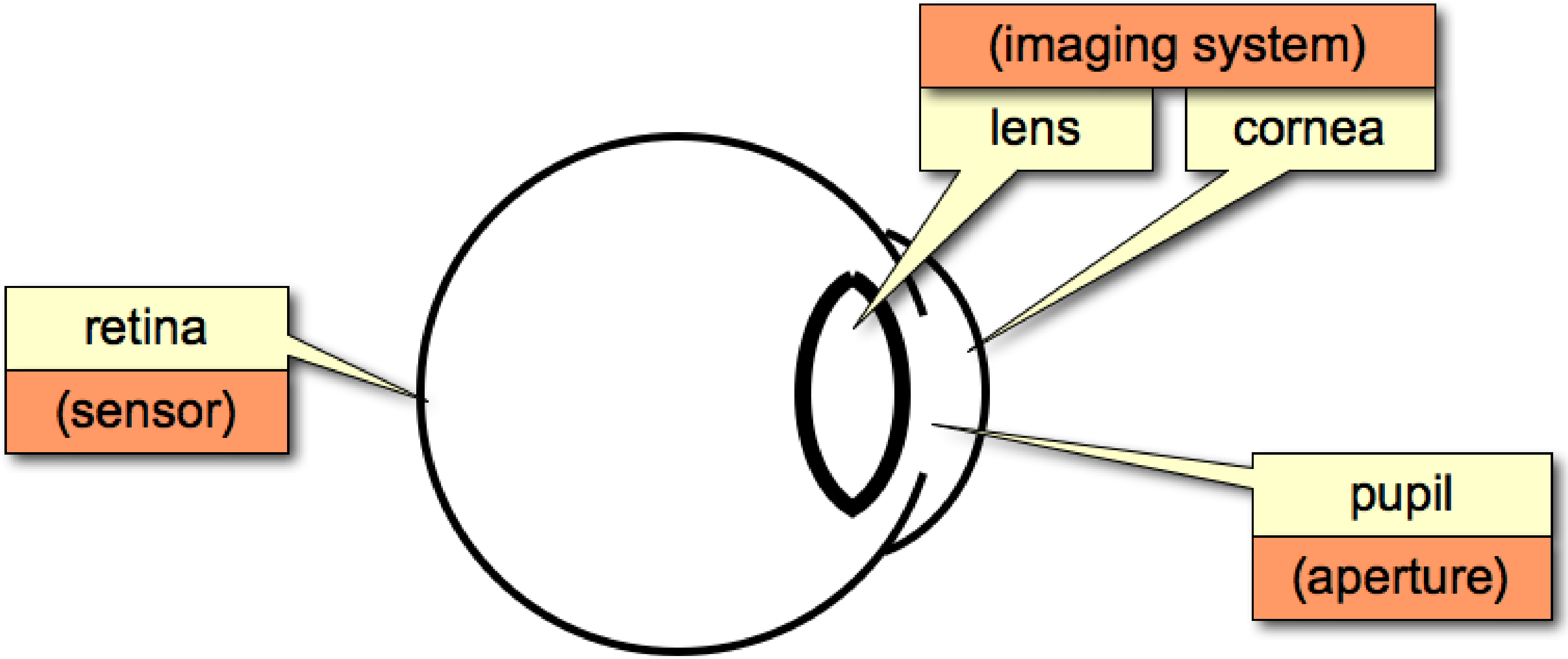
The anatomy of the eye

The level of detail shown here is beyond what we need to know in order to appreciate how a telescope works...



The simplified eye

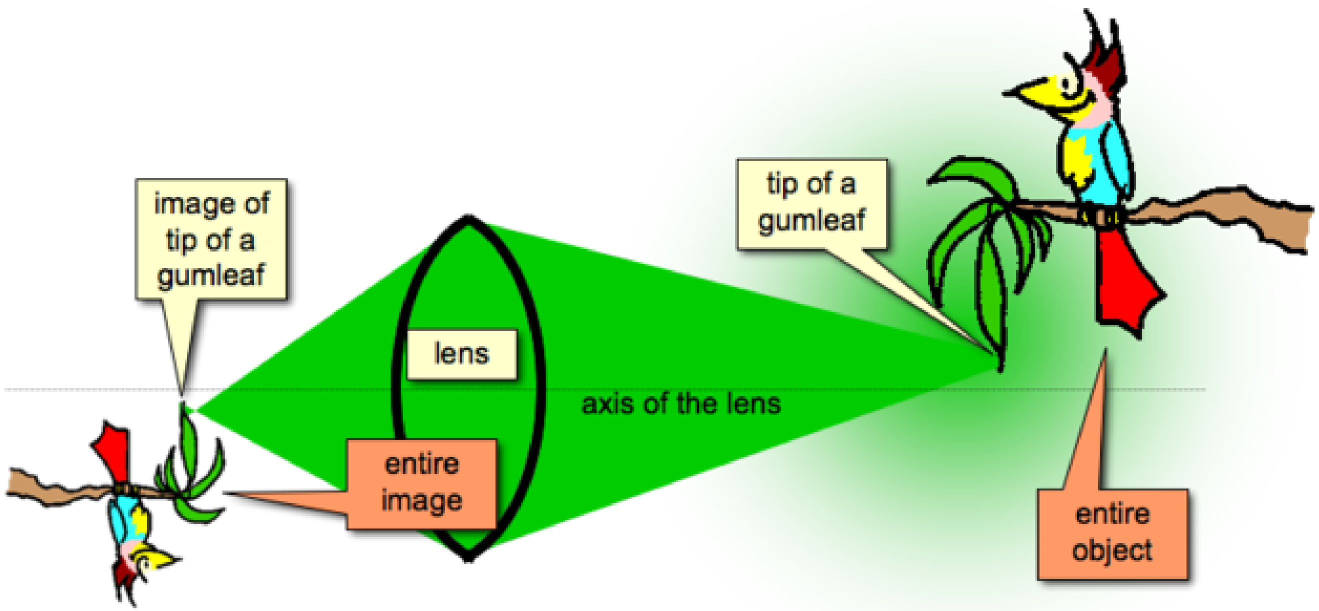
All we are going to show here is a very simple diagram which includes only those functions and structures of the eye which are also present in some form in telescopes.



First of all, we have to understand the imaging system, and that means understanding how convex **lenses** collect light and form images.

How a lens works

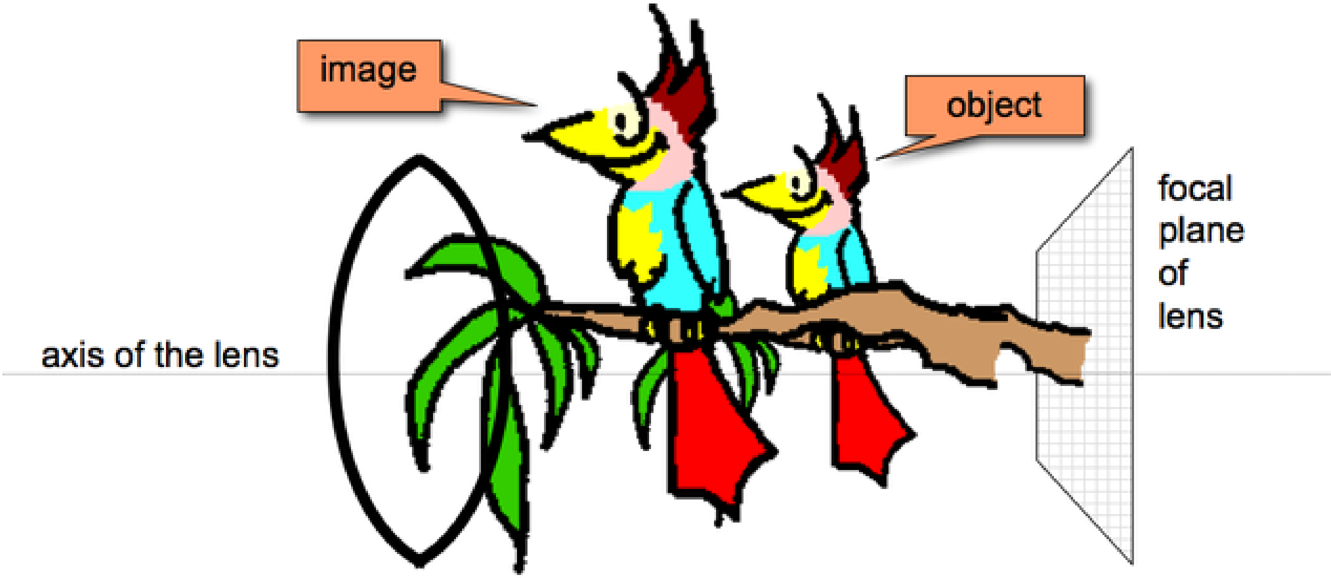
If it’s illuminated, like this bird on a branch in the sunlight, **every part** of the object radiates light in all directions. Let’s see what happens just to the light that the **tip of the gumleaf** sends through the lens (which may be an eye or a camera).



The lens bends the light, and focuses it in a small area. This happens for the whole object, and a complete image forms.

Different distances

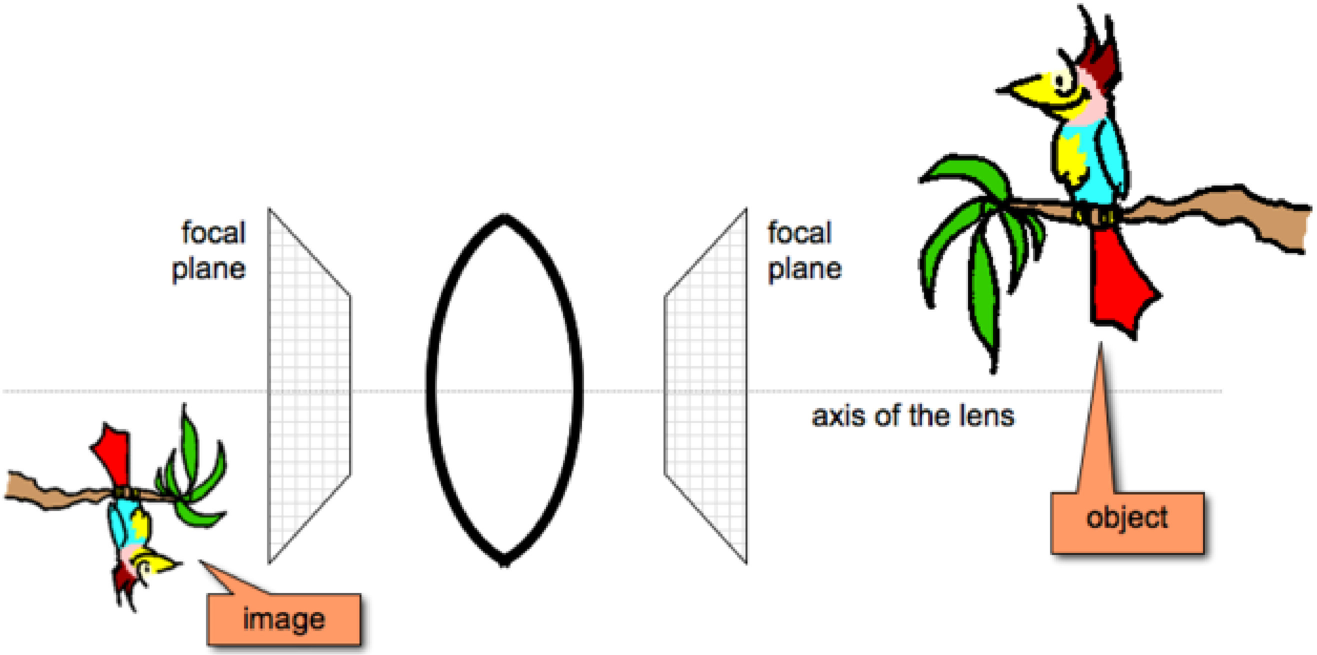
The position and size of the **image** depend largely on the position of the **object** relative to the **focal plane** of the lens (we'll explain that soon).



If the object is between the **focal plane** and the lens, then the image is large and near the object . This is how a **magnifying glass** works.

At medium distance

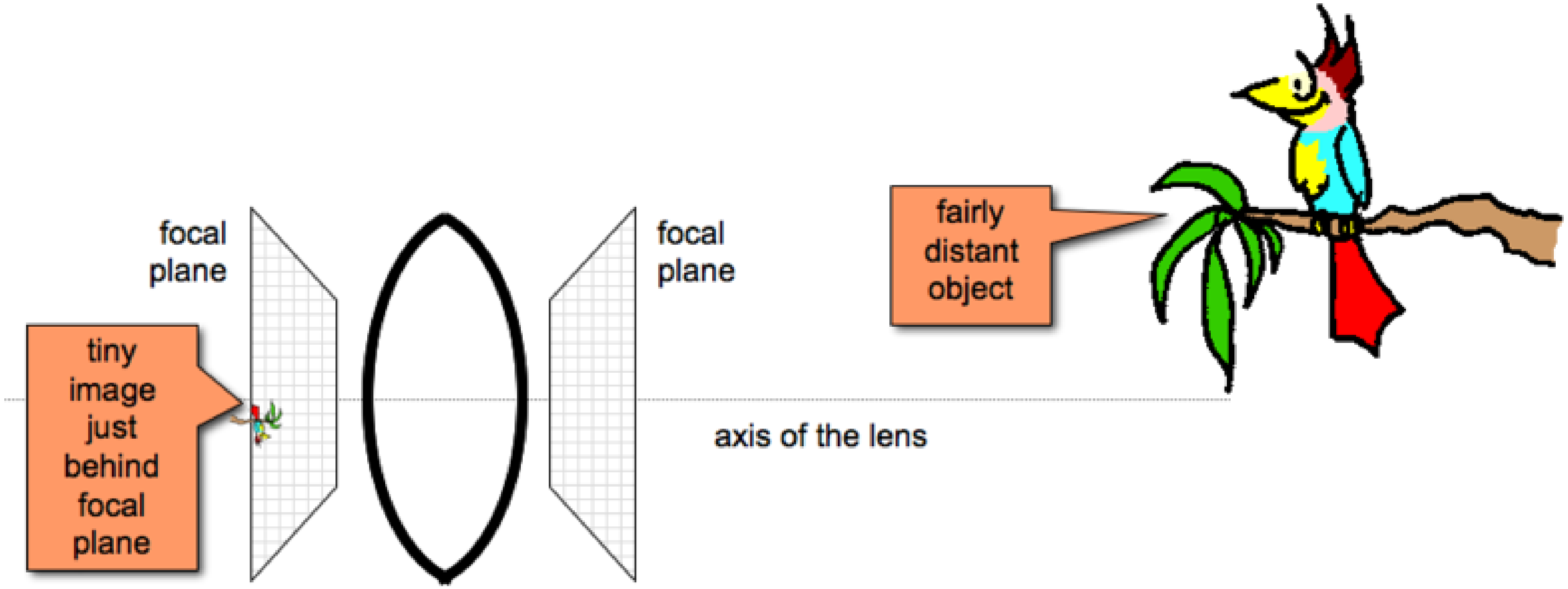
If the object is outside the focal plane, but not too far away, the image is still of a reasonable size and also not too far from the lens, but is inverted (upside down).



Lenses actually have ***two*** focal planes, symmetrically placed, one on each side.

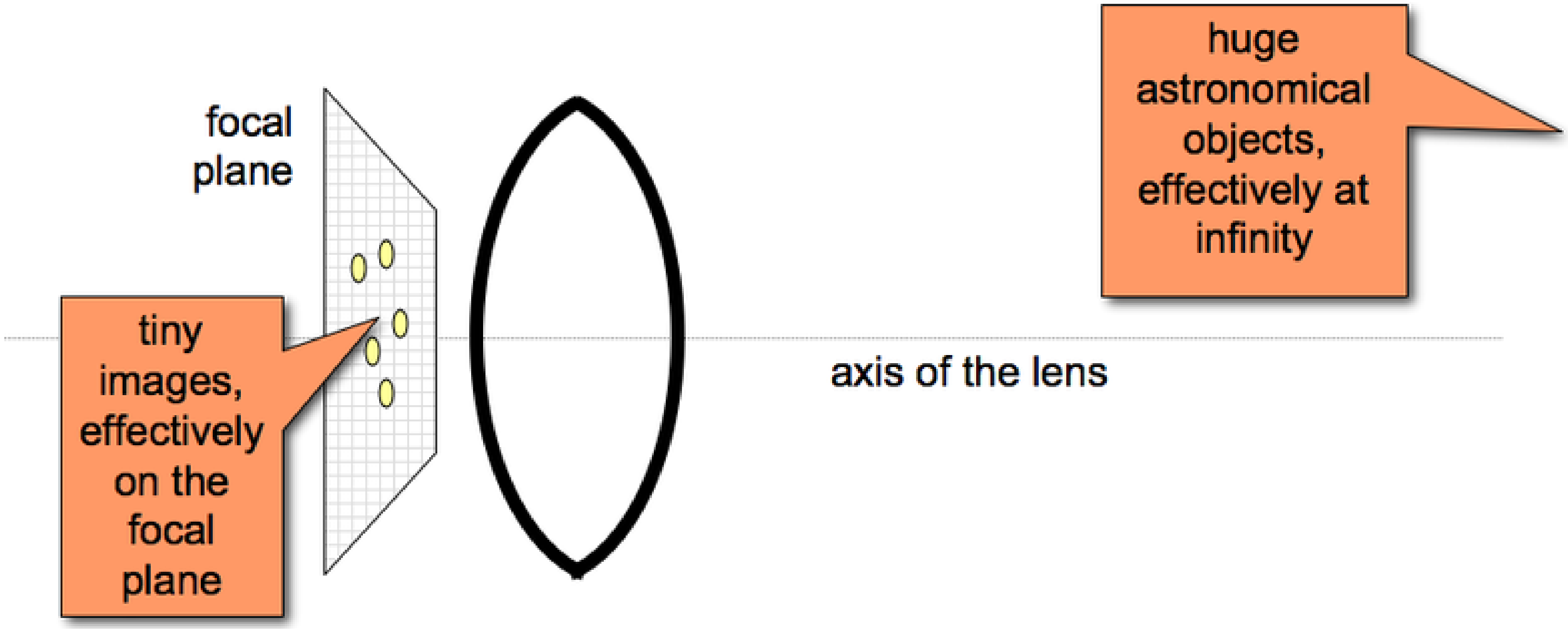
At great distance

If the object is much further away from the lens than the focal planes are, then the image is very small and almost on one focal plane. It is inverted.



The focal planes

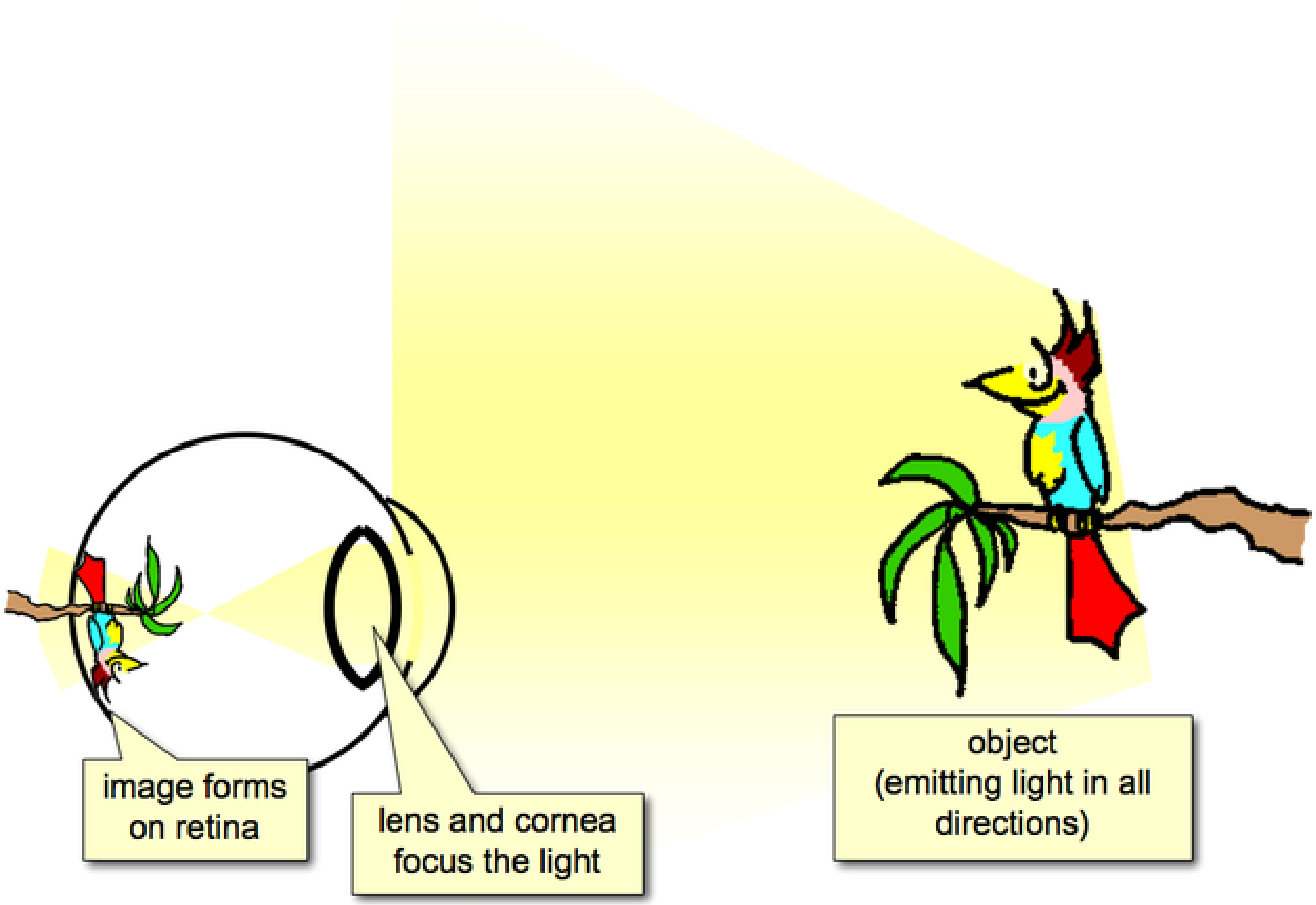
The **focal planes** of the lens are, in fact, defined as the planes on which images form when objects are infinitely far away (there is one such plane on each side of the lens, as objects can be placed, and hence images formed, on either side).



How the eye works

Having covered the basic facts about lenses, we can return to the function of the eye (and later, the telescope).

If some of the light emitted by an object enters the eye through the pupil, it is focused by the lens to form an image on the retina.



Adjustments

Animals want to see objects close and far, and in bright or dim light.

So there are a number of ways in which animal eyes are adjusted and varied so that they can obtain the most useful images:

- the **direction** in which the eye looks can be changed;
- images should be clear for different **object distances**;
- many animals need **depth perception** (that is, they need to judge the distance to the object);
- they often want adjustment to **differing light conditions**; and
- they may benefit from perception of **colour**.

During this and the next Activity we shall look at each of these in turn, most particularly to compare the way animal eyes work with the way telescopes and other imaging devices are designed in astronomy.

There are many similarities, and many important differences.

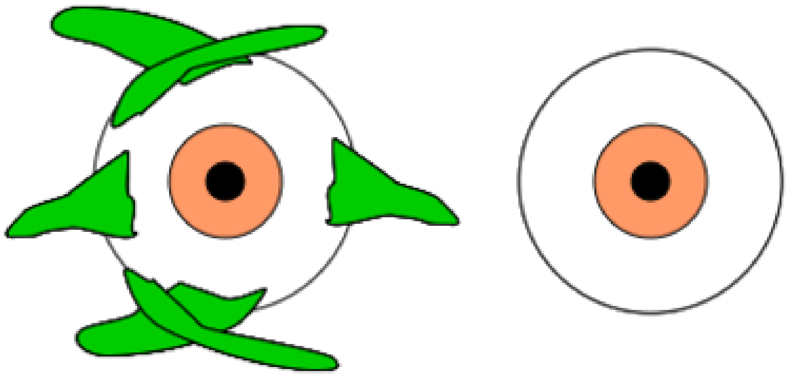
Change of direction

The human eye is equipped with three sets of muscles to allow the eyes, usually as a pair, to be swivelled to point in different directions.

During its first few days of life, baby animals (including humans!) learn to contract and relax these muscles to point their eyes in the direction of choice.

Frequently a direction is chosen because of an earlier input or stimulus from one of the other senses; a noise, a prod, a feeling of heat or cold.

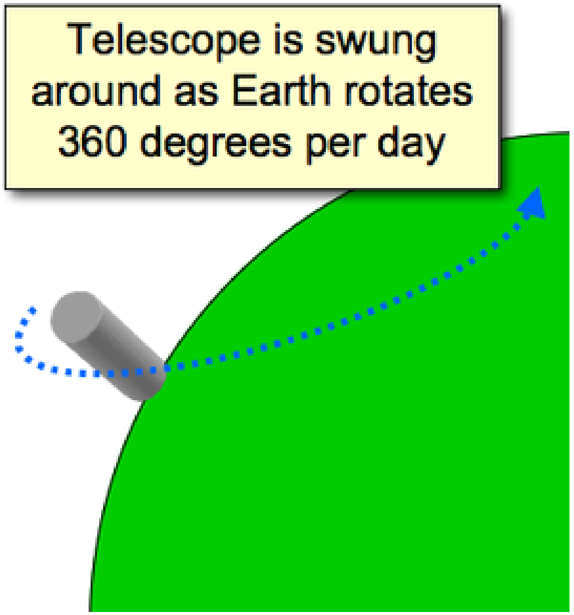
Often it is also just curiosity.



Adjustment in the telescope

Curiosity also usually selects the direction in which a telescope is pointed. This direction needs to be changed, not just to look at different objects but most particularly because the Earth is rotating once every 24 hours. Objects will rapidly swing out of view unless the telescope rotates to follow them.

Although the human eye has three sets of muscles for similar adjustments, in a telescope we make use of rotation about just two axes. There are two main choices for these pairs of axes, and a great deal more is learned about them in the later Activity *Principles of telescope mount and housing design*. Here is a quick introduction.



The equatorial mount

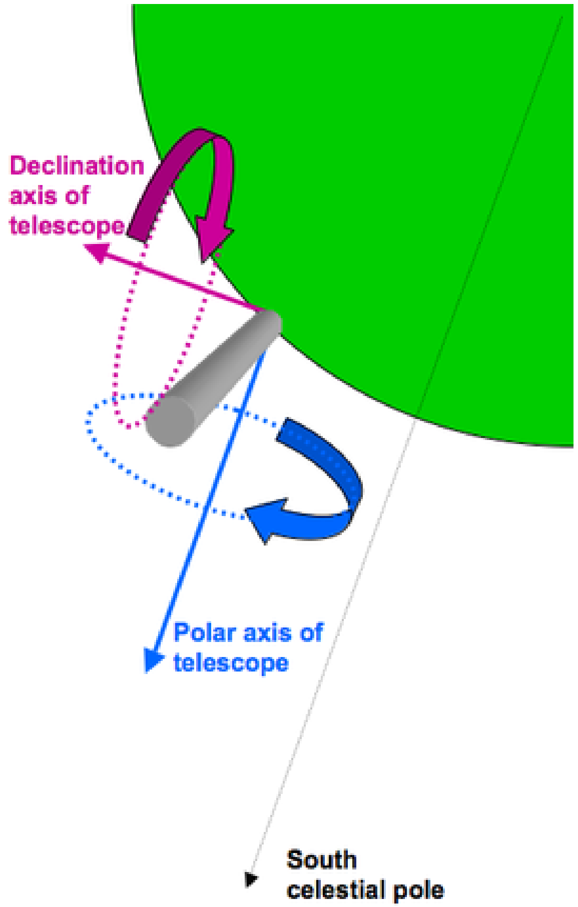
The **equatorial** mount is named by the fact that one of its axes is always perpendicular to the plane of the **equator** and the other is always parallel to it.

This axis (the **polar** axis) is always set up **parallel to the Earth's rotation axis**, so it points to the north (or south) celestial pole.

Motion about the polar axis changes the right ascension (RA).

The other axis (the **declination** axis) is **perpendicular to the Earth's spin axis**, and outward from it.

Motion about this axis changes the declination (dec).



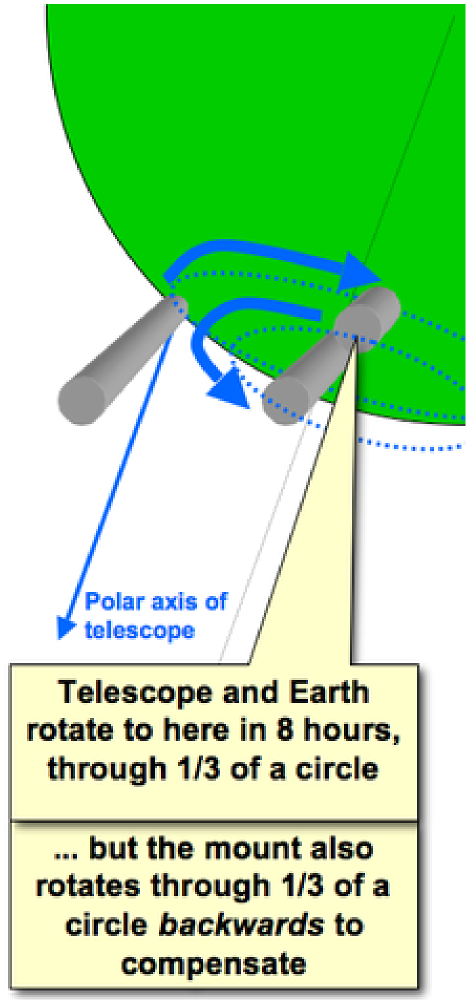
Pros and cons of an equatorial mount

Once the polar axis has been properly aligned there needs only to be **smooth rotation about this one axis** (360 degrees per day, to compensate for the Earth's rotation) to keep a particular celestial object in view.

Because this is relatively easy, particularly if the telescope has a small motor, ***an equatorial mount is considered preferable for deep space work and for astrophotography***.

Various designs include German, English, yoke, horseshoe and fork; each has its benefits in terms of **support** and **freedom of movement**, and above all, for the latitude at which it will be used.

However all are expensive.



Alt-az mount

If fitted with an alt-azimuthal mount, an optical instrument is rotated around **vertical** and **horizontal** axes.

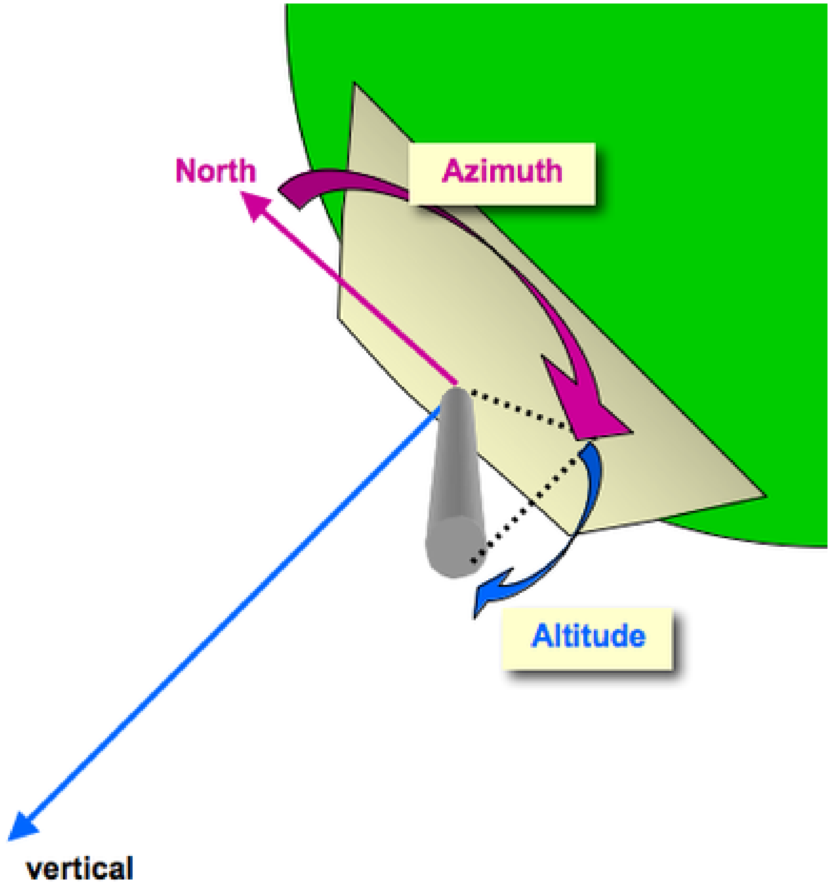
A good mount will have fine-adjustment knobs for both motions.

Altitude is the angle between a celestial object and the horizon, measured vertically.

Azimuth is the bearing of an object measured as an angle round the horizon eastwards from north.

If the telescope points in the direction shown, alt might be about 60 degrees and az might be about 120 degrees.

Alt and az depend on the observer's latitude and longitude.



Pros and cons of an alt-az mount

An alt-az mount is good for terrestrial observing and low-power sky scanning, but not for deep space work.

It is definitely ***the simplest type of mounting***, particularly the **Dobsonian**[1] variation.

Unfortunately, since stars appear to move across the sky in arcs which are not parallel to the horizon, they change from moment to moment in ***both*** altitude and azimuth.

Therefore it is necessary to rotate the telescope about **both axes simultaneously** in order to follow any particular object.

That makes the alt-az mount unsuitable for small motor-driven telescopes, which are far better fitted with an equatorial mount where constant adjustment need only be made about one axis.

However new advances in computer control of larger telescopes have caused a revival in the popularity of the alt-az mounting, since computers can easily cope with simultaneous motion about two axes.

[1] Click here for more information about Dobsonian telescope designs.

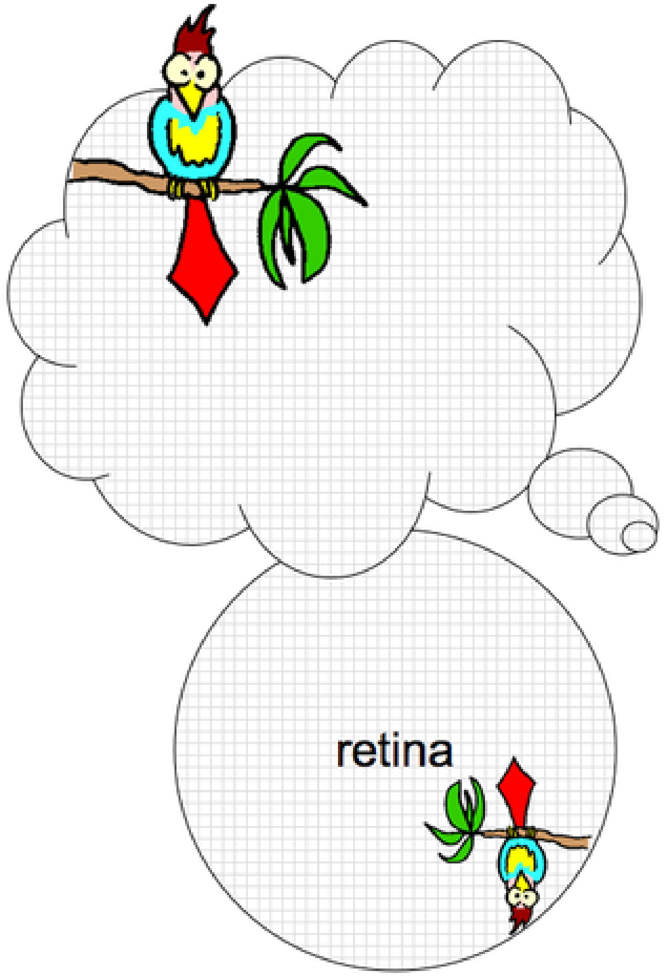
Upside down

The images of distant objects, when formed by convex (bulbous) lenses, are always **upside down**.

In human vision, if an object is **above** us the image is formed on the **lower** part of the retina. If the object is to our **left**, the image forms on the **right** side of the retina.

All images formed in the eye are diametrically opposite to their position relative to us in the real world!

Baby animals spend time training their brains to **invert** images, so that an image received on the lower right of the retina will be ascribed to an object that the rest of the senses say is above and to the left of the eye.



No real up or down

The same happens when using lenses and mirrors in astronomy. Astronomers may therefore choose to rotate images before publishing them.

However there is no real “up” or “down” in astronomy, or “left” or “right”.

Here’s the (fictitious) C constellation as it would be photographed near the horizon as it rises, and as it sets.

Astronomers use a “constant” coordinate system by specifying the **declination** (that is, the angle above or below the celestial equator) and the **right ascension** (in hours and minutes anticlockwise from Aries).

Different distances

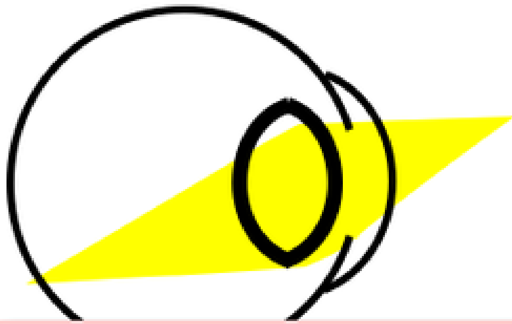
The eye must also adjust to objects at different distances.

If the image is to form neatly on the surface of the retina, then the focal length of the lens must be adjusted for each object.

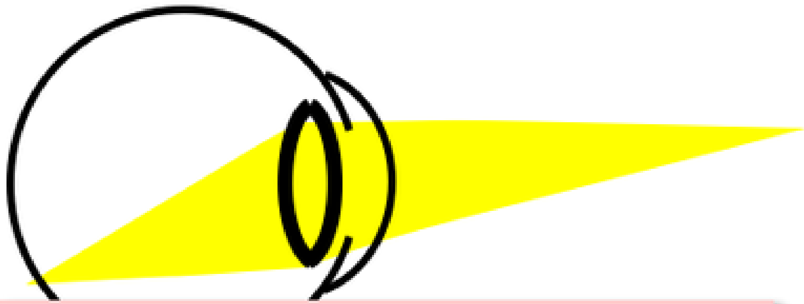
This is why you can see either **distant** objects clearly, or **close** objects clearly, but not both at the same time.

In order to cope with this, little muscles alter the shape of the lens within the eye so that images still form perfectly on the retina.

Click here to use your little lens-adjusting muscles.



Focussing light from a nearby object requires a fat lens

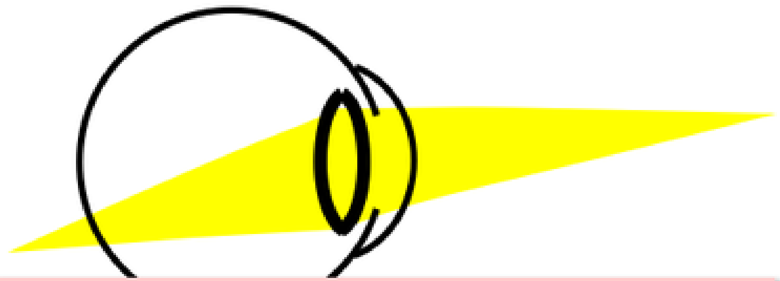


Focussing light from a distant object requires a thinner lens

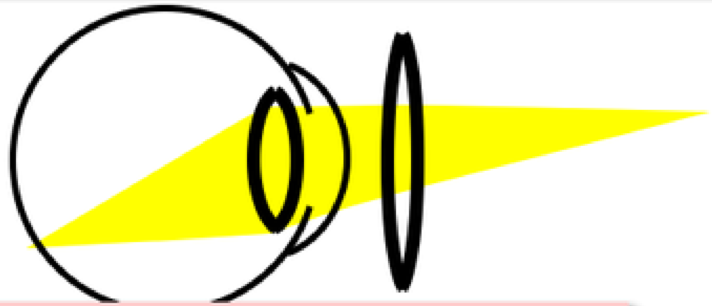
Helping the adjustment

If the muscles don't properly adjust the shape and therefore the focal length of the lens, additional corrective lenses are sometimes added to fix the problem, outside the eye, in the form of glasses or contact lenses.

Nowadays clinics also re-shape the cornea with laser surgery to compensate for faulty focal lengths and the consequently blurry images.



A far-sighted person sees a blur because the image forms *behind* the retina



The addition of another lens "strengthens" the imaging system and corrects the problem

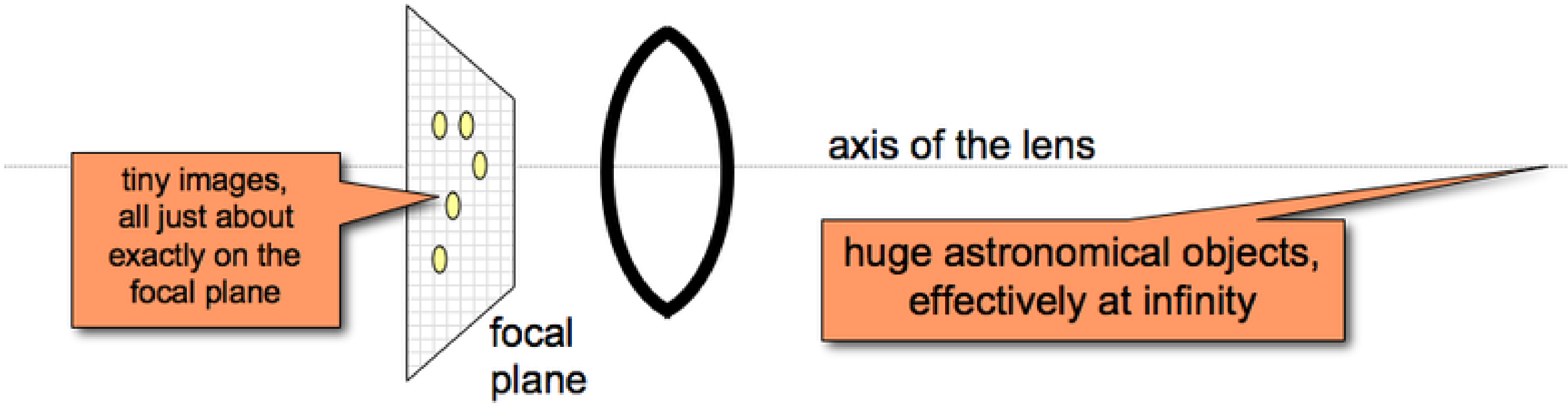
Adjusting lenses in astronomy

In astronomy we don't need to bother with such things.

The objects you are interested in are ***so far away*** that you can use the one lens for them all, with no adjustment.

Once you locate the focal plane, you can expect all images to form almost on it. Unfortunately, however, these images will be absolutely tiny!

So instead of adding corrective lenses to alter the **location** of the image, astronomers add corrective lenses to alter the **size** of the image.

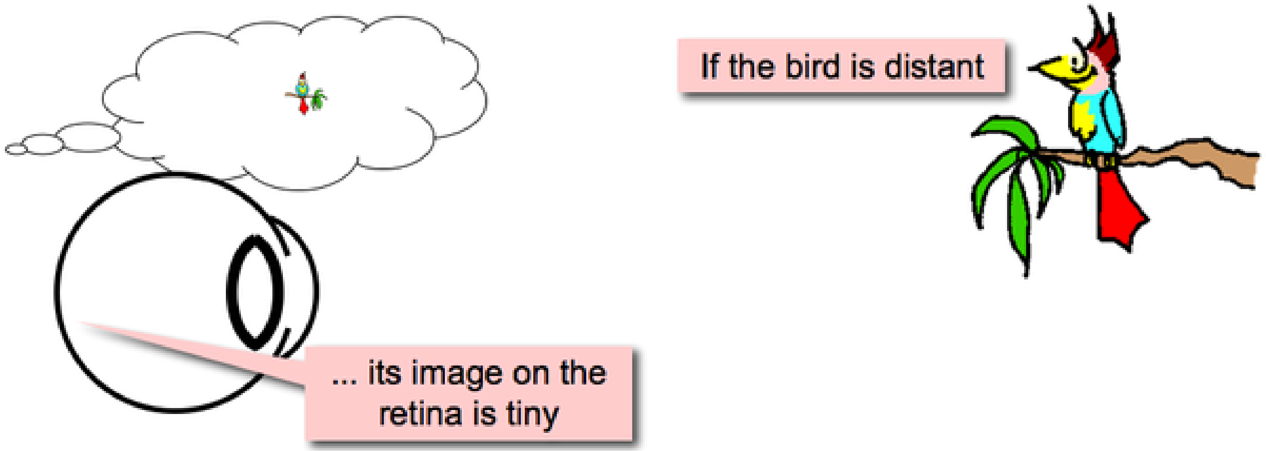


Telescopes 1, eyes 0

Astronomers are very lucky indeed; the telescopes wins this particular comparison.

No known creature on Earth can do what we can do with a telescope in terms of magnifying the image.

Distant objects will ***always*** look absolutely tiny to the unaided eye, because the eye contains only the lens-and-cornea system.

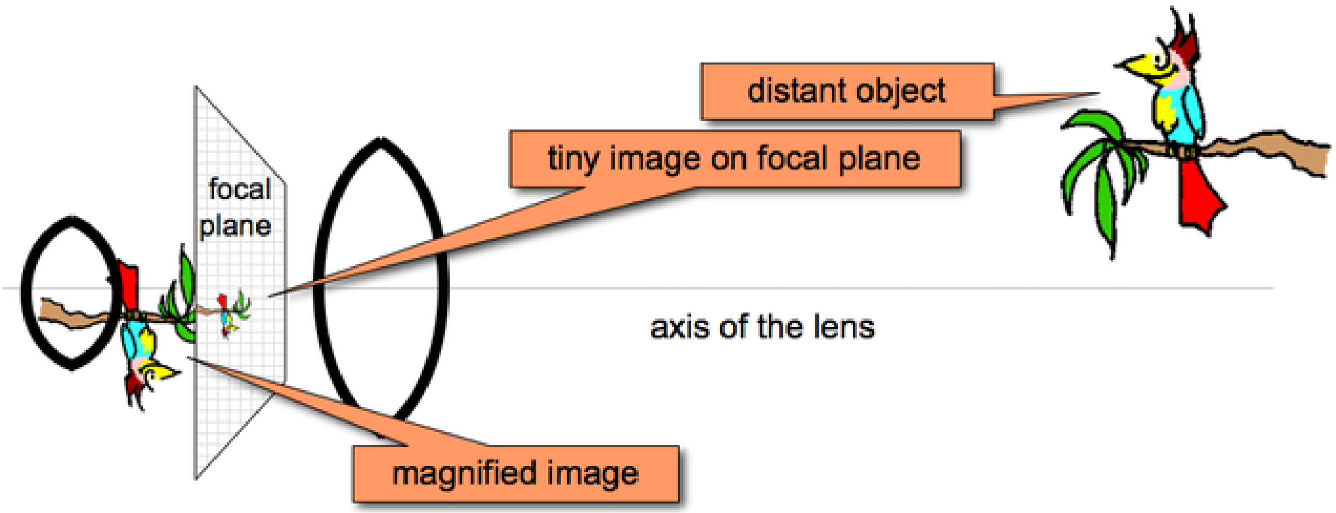


Adding another lens

In astronomy, though, we can install more lenses if we like.

Remember what was revealed earlier about convex lenses: if the object is between the focal plane and the lens, the image is upright, close to the lens and magnified.

So once an image of a very distant object is formed by ***one*** lens, we can locate that tiny image close to ***another*** lens, and use that lens to magnify it!

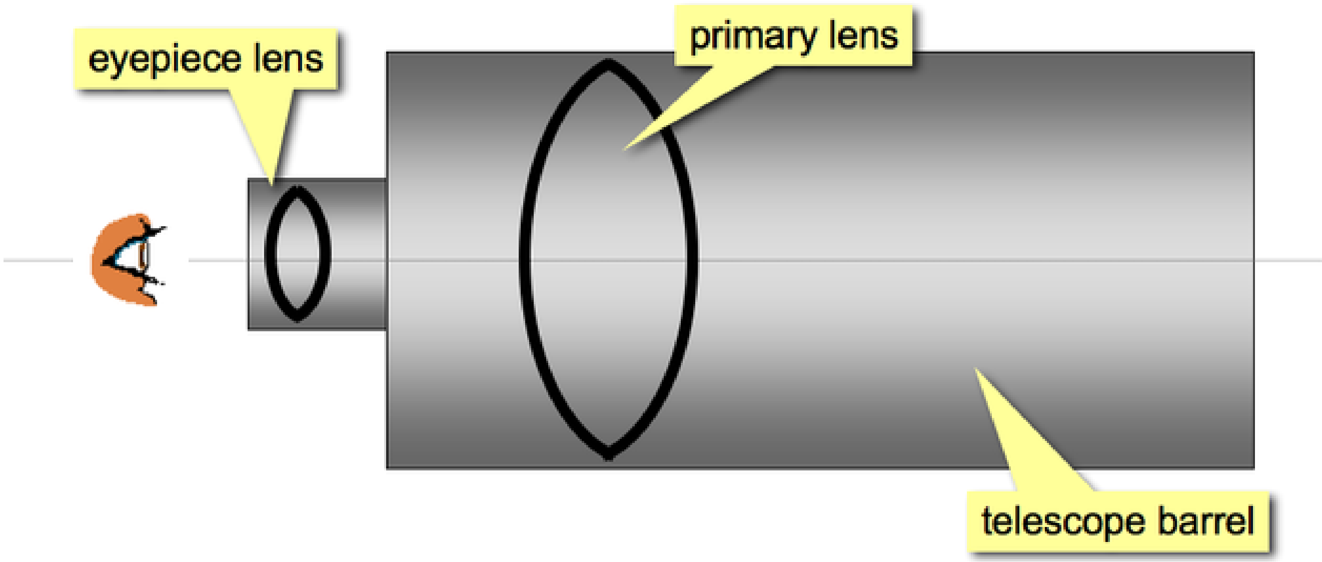


Introducing the eyepiece

The lens assembly that is used to do this, in microscopes, binoculars and telescopes, is called the **eyepiece lens** (because that's the lens we look through).

The lens that does the initial focussing is called the **primary lens**.

Both lenses are usually enclosed in tubes.



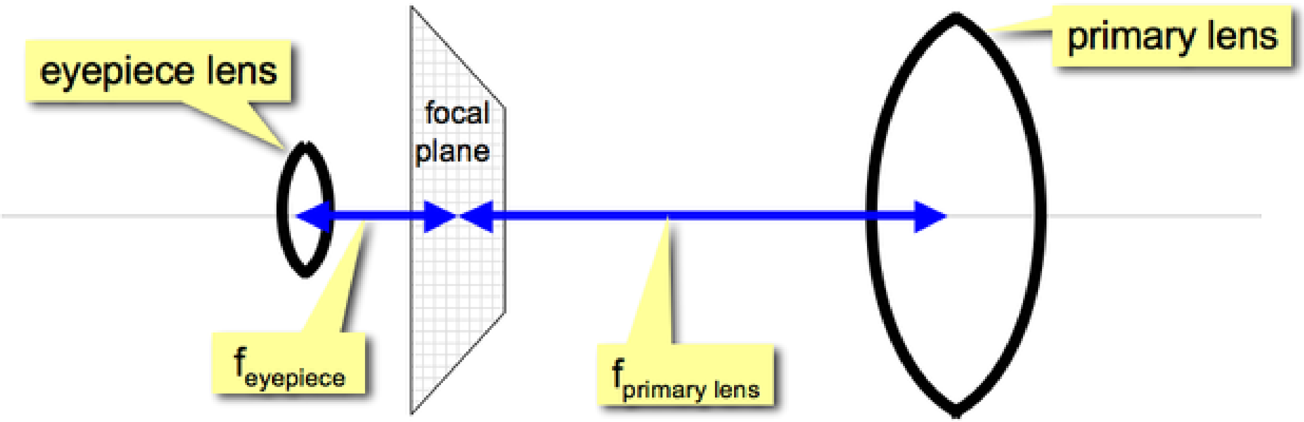
Maths of magnification

The **magnification** provided by a telescope is the number of times larger the image is ***with*** the telescope than it would be ***without*** the telescope.

Magnification can be worked out in terms of the **focal lengths f**, of the two lenses: that is, the distance of their focal planes from their centres.

With this two-lens system, the magnification is given by:

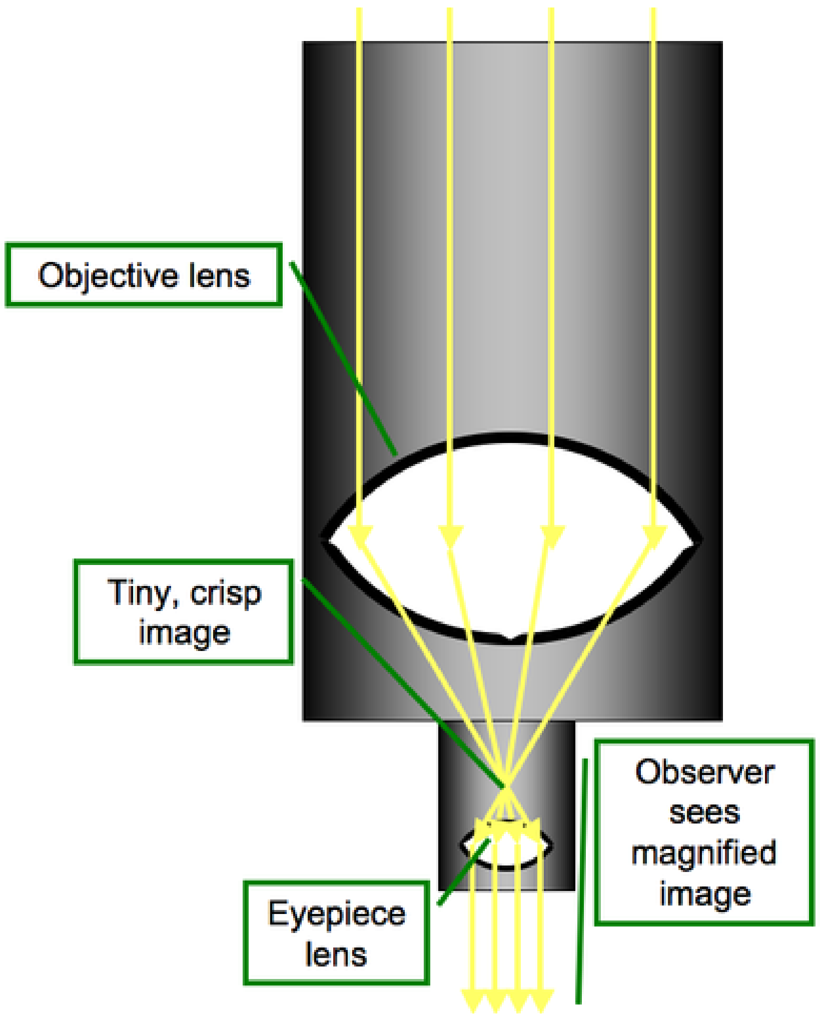
$$M = f_{\text{primary lens}}/f_{\text{eyepiece lens}}$$



Two types of telescope

The first type of telescope to be developed was inspired by opera glasses in the early 17th century.

This is called the **refracting** telescope, because the collected light is focussed by being refracted through a lens.



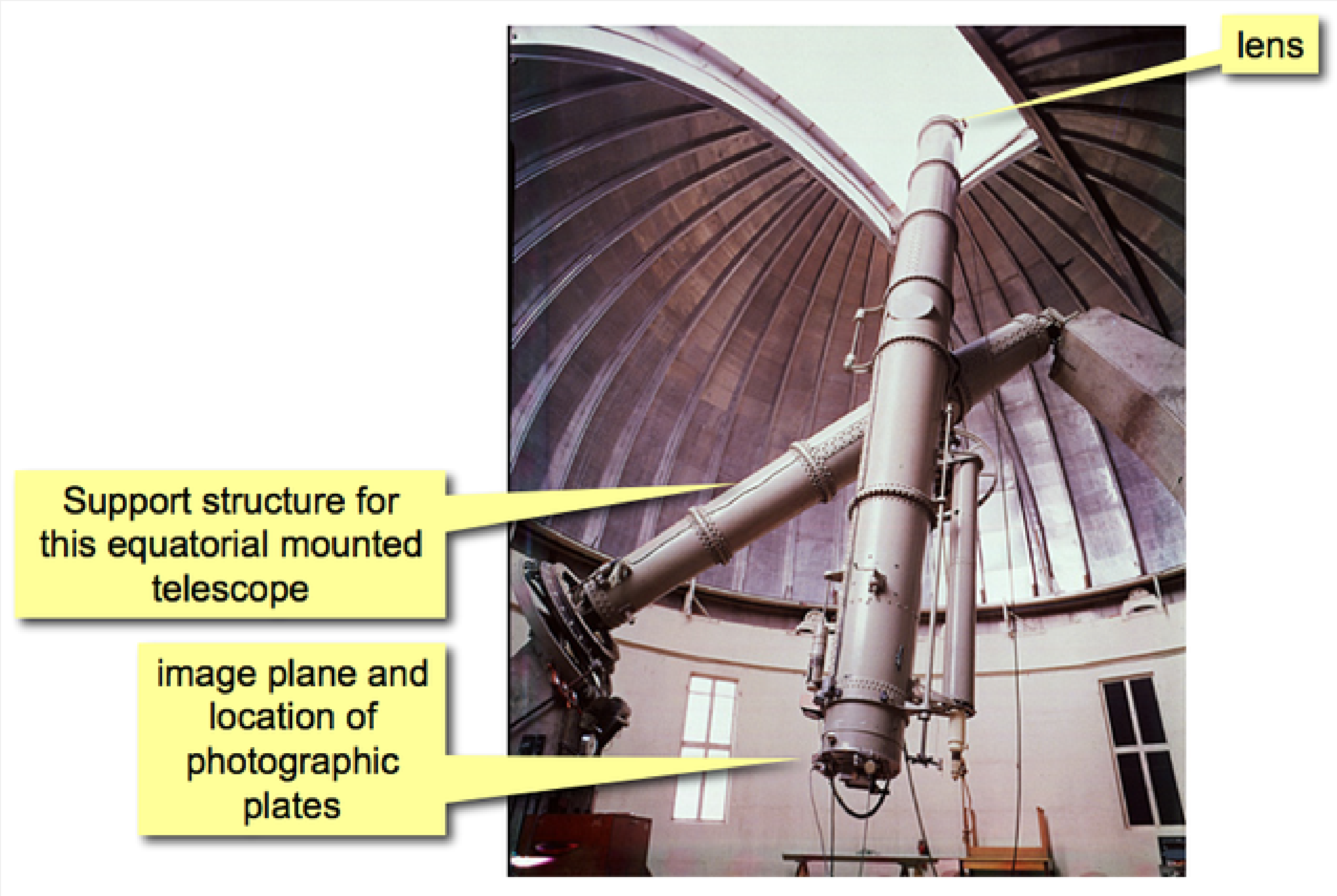
Problems with refractors

There are many difficulties when using a lens, particularly with a very large one that will collect a great deal of light in a short time.

- The material of the lens has to be of uniformly **high quality**.
- A large lens will have enormous **weight**.
- The lens has to be all in **one piece**.
- The lens can only be **supported** at its thinnest, most brittle points on the rim, which can be awkward.
- Because of the different thickness, different parts of a lens will expand and contract differently as temperature changes, possibly causing **fractures**.
- Images formed by lenses suffer **chromatic aberration**: the focal length varies with wavelength.
- Because light passes *through* the lens, the **barrel** of the telescope must be long.

The Yale-Columbia telescope

The Yale-Columbia telescope, which resided at Mount Stromlo Observatory in Canberra, Australia until destroyed by the 2003 bushfires, was a classic example of the old refractor style of telescope.

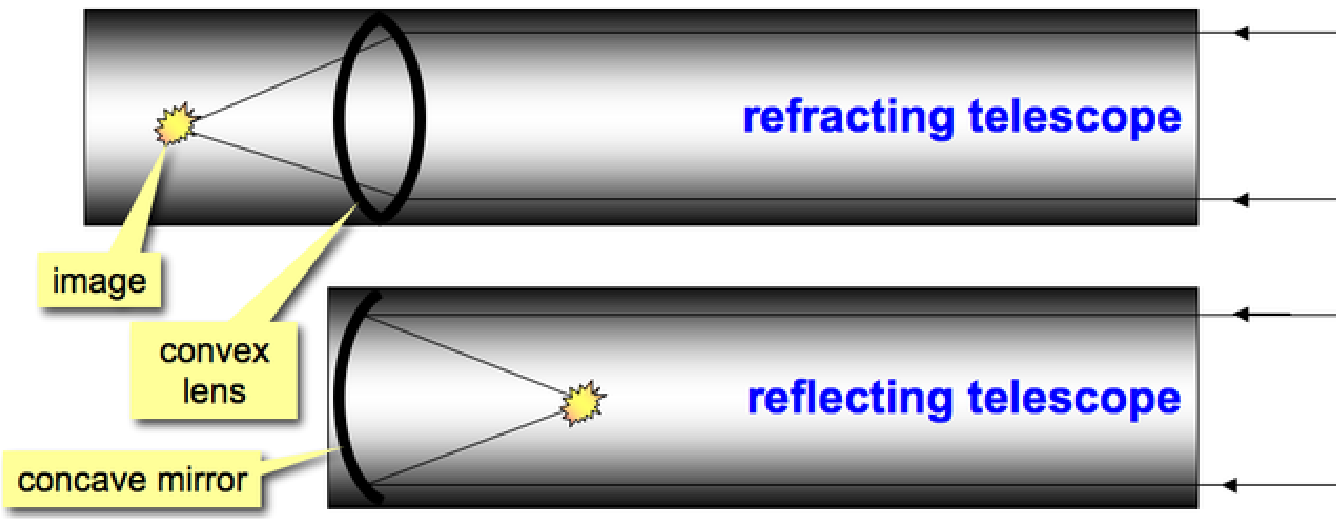


Credit: Mount Stromlo Observatory, ANU

Reflectors

The study of optics proceeded to the point where people realised that concave mirrors could be used to function much as convex lenses did.

The primary lens could be replaced by a concave mirror: a **reflector**. An image would form the same way, but on the other side...



Advantages of reflectors

There are many advantages to using a mirror in a reflecting telescope.

- Only the surface of the mirror has to be of uniformly **high quality**.
- A mirror will have far less **weight** than a lens of the same size.
- A mirror does not have to be all in **one piece**. Some mirrors are made of segments (e.g. the Keck telescopes)
- A mirror can be **supported** at many points, not just on its rim.
- The mirror can be of uniform thickness, making it far less likely to suffer **fractures** because of uneven cooling or heating.
- Images formed by mirrors suffer far less from **chromatic aberration** (and other types of aberration).
- Because light is reflected from the mirror, the mirror is the last item in the **barrel** of the telescope and it need not be extraordinarily long. Moreover, one can replace the barrel with an alternate framing.

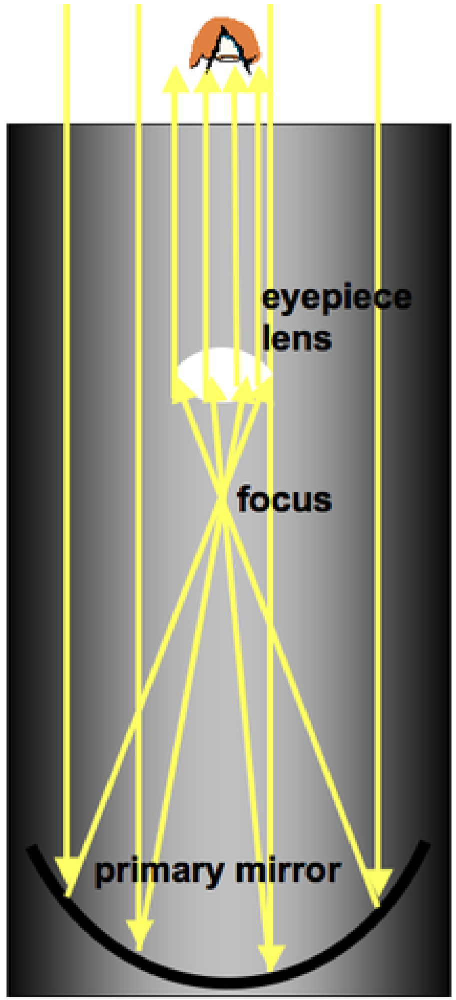
Where's the eyepiece?

Once reflecting telescopes were first developed, the next major step was to decide exactly *where* to put the **eyepiece**.

The obvious first choice is to place the eyepiece and the observer in the barrel of the telescope itself.

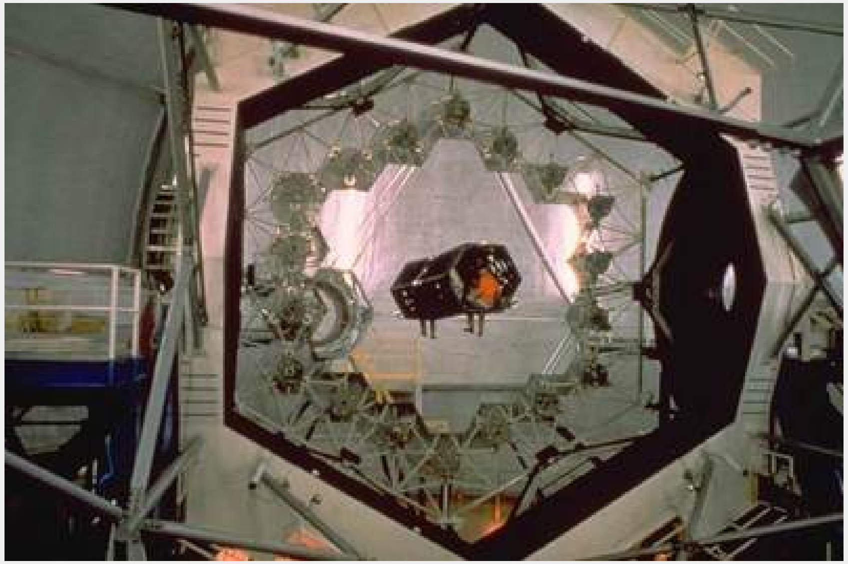
This design is called **prime focus**.

. . . But the observer is in the way!



The Keck Observatory

This image shows a person (orange clothing) at the forward cassegrain position of the Keck telescope, in front of the primary mirror.



Credit: W. M. Keck Observatory

One can see how the primary mirror is comprised of a tessellation of smaller hexagonal mirrors (note: the outer ring of 18 mirror segments has yet to be installed in this image).

The forward cassegrain position is where some Keck instruments can be stationed, or where a tertiary mirror can be positioned to direct the light off to the nasmyth instruments (see the platform left of image).

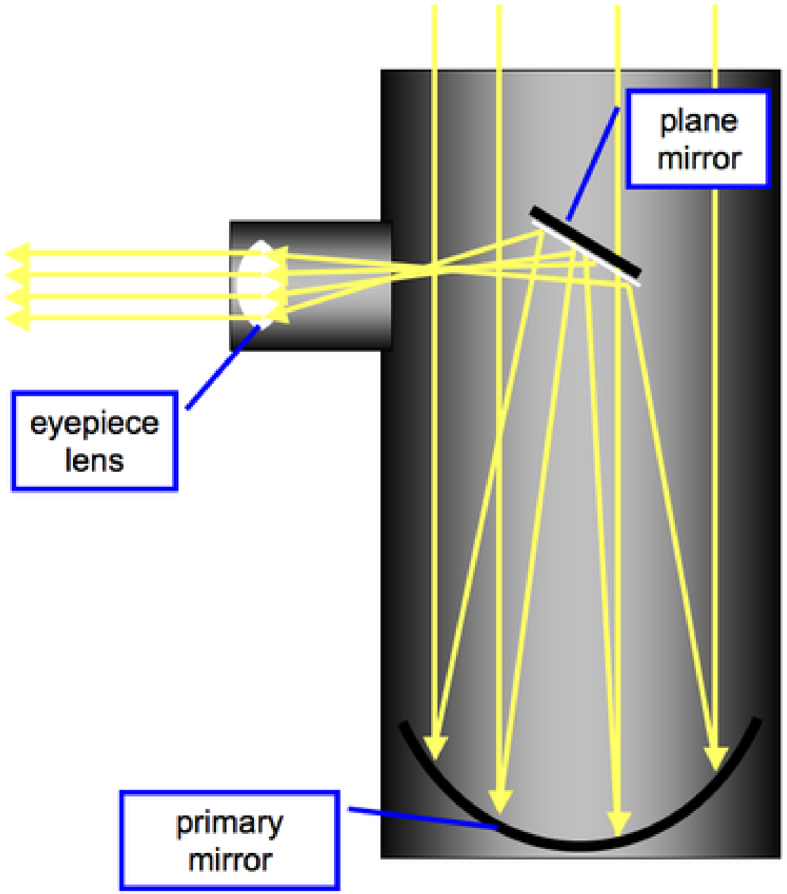
Keck previously had a long wavelength spectrometer (LWS) that sat in the ”fwd cass” position and required a person to sit on top of it with a wrench for around an hour to help establish calibration. Wearing an orange bunny suit for warmth, they would tie their wrench to their suit so that it could not fall and hit the primary mirror.

Some telescopes had a ”prime focus” cabin where an observer could spend the night. Palomar, for example, used a fine meshed cage while the Anglo-Australian Telescope had a solid frame.

Newtonian focus

Other designs block less of the incoming light, but are harder to set up.

The **newtonian focus** design uses a plane mirror to deflect the light before it reaches the focus, so that the eyepiece assembly can be more conveniently installed outside the barrel.

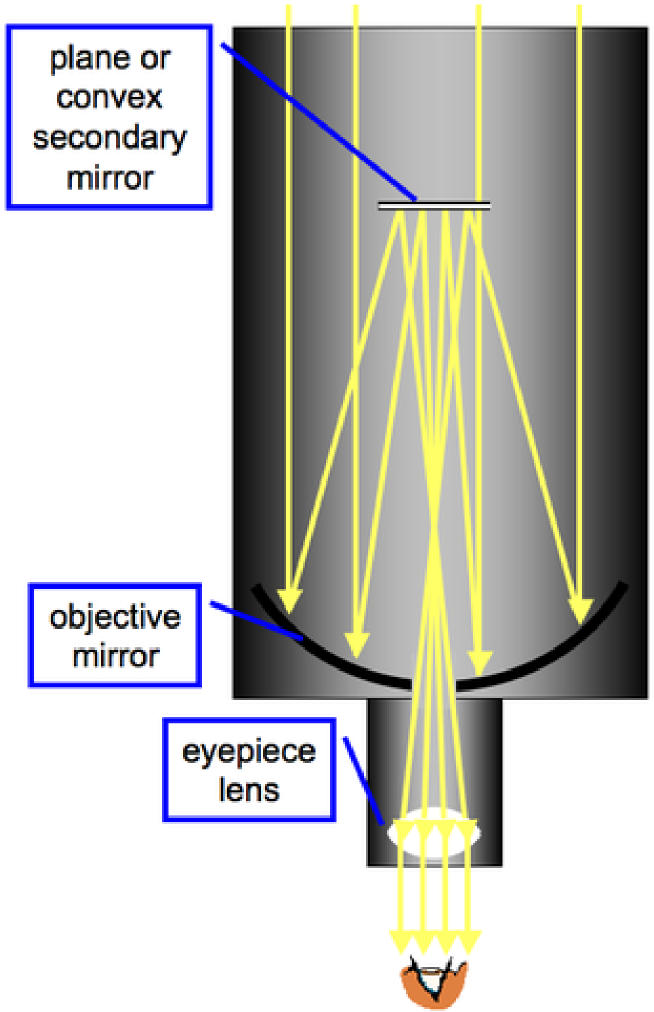


Cassegrain focus

The **cassegrain focus** design uses a plane or curved mirror to deflect the light through an aperture in the primary mirror itself.

Apart from its regular geometry, this design is suitable for primary mirrors with very long focal lengths (up to about twice the barrel length).

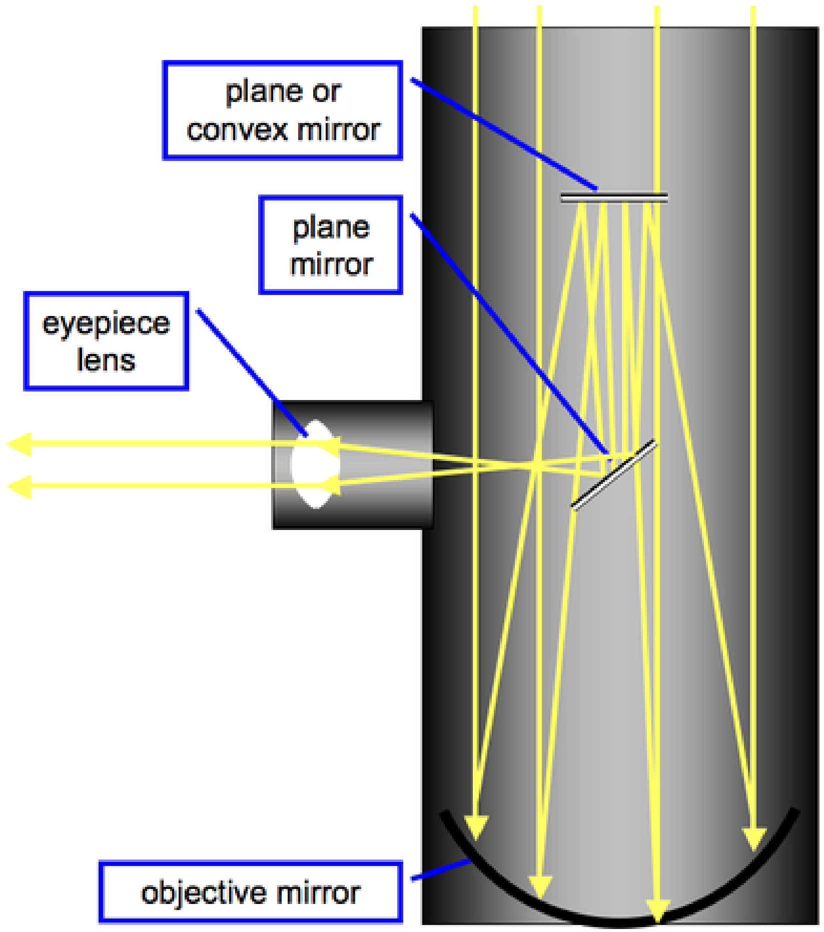
The **primary** mirror in telescopes is also often called the **objective** mirror; the mirror used to deflect the light after that is called the **secondary** mirror.



Coudé focus

The **Coudé focus** design combines the geometry of the Cassegrain focus design with the deflection achieved in the Newtonian focus design.

Because it has **three** mirrors and a lens, with this design precision alignment is much harder to achieve and maintain.



Different scopes for different folks

The choices of whether to use a reflecting or refracting telescope and what sort of focus design to install, depend on many factors.

The Cerro Paranal site of the European Southern Observatory, a suite of four 8-m telescopes (and several smaller ones), 2635 metres above sea-level in Chile.

If you are interested in doing further research on this issue, you may visit the Large Telescopes site by following this link.

Credit: ESO

Summary

In this Activity, we have begun to investigate how vision works in the visible light region in creatures on Earth, and have started to seek out the similarities and differences between that kind of vision and the vision that astronomers hope to achieve.

We learned about how lenses can be used to gather light to form an image, and then magnify it for better viewing.

Reflecting and refracting telescopes were discussed, plus the most commonly-used arrangements of the primary mirror and eyepiece lens.

In the next Activity, animal vision and vision in astronomy are extended in discussions of distance, light conditions and colour.