



THE NORWEGIAN ASTRONOMY AND ASTROPHYSICS
OLYMPIAD COMMITTEE

IOAA NOTES

Part 3: Optics and Telescopes

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12th October 2024

1 Optics

This section will be a very short introduction to geometric optics. The key components to gain an understanding of are lenses and mirrors and how they work. These two are the building blocks of telescopes, and understanding the principles behind how they work will make it much easier to understand how telescopes work. This section will technically not come as a question on the Olympiad, but it is essential to understand if you want to gain a complete understanding of telescopes and how they work, so ensure you have at least read through it.

1.1 Lenses

Lenses are classified based on their geometry into convex (bulging outwards) and concave (going inwards, think "cave goes in"). No matter the type of lens, if a light ray passes straight through its centre, it will continue on the same exact path.

1.1.1 Convex Lenses

Figure 1 shows light rays entering a convex lens and being refracted. If you look closely at the colours of the light rays (no relation to actual colour, this is just us marking the rays so you can follow them easier), the rays entering at the top end up being on the bottom after crossing a point aptly named "focus". This means that if we were to look behind the focus (behind being towards the right here), the image we would see would be upside-down as compared to the actual object! Because the lens makes the light rays get closer to each other and cross each other, you will also see convex lenses being called converging lenses.

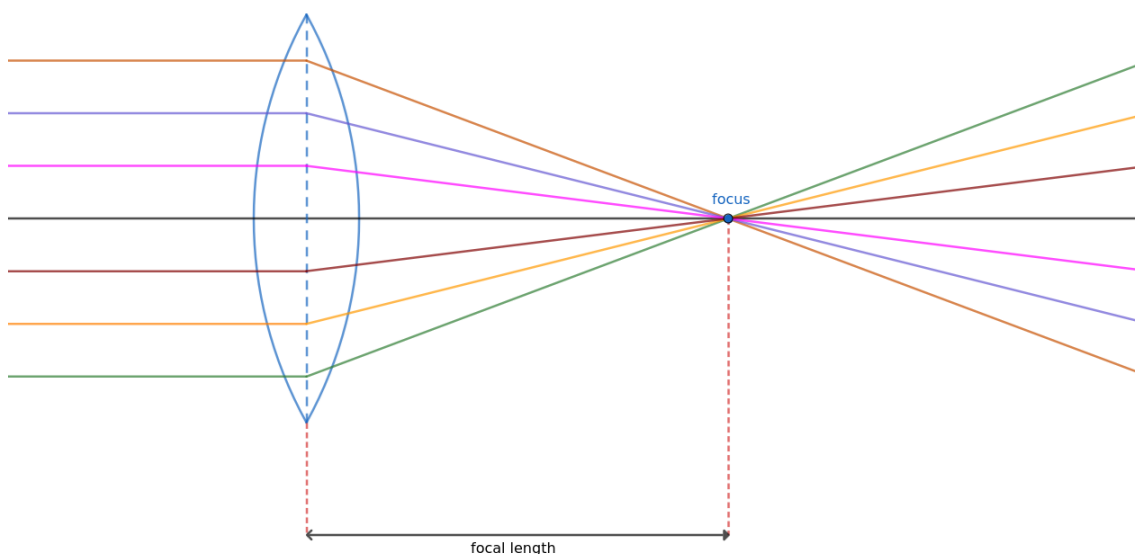


Figure 1: Refraction of light rays by a convex lens.

Images can be formed in different ways based on where the object is located in relation to the lens. In Figure 1, we marked one focus point behind the lens, but since the lens is symmetric about the vertical axis, there must also be a focus in front of the lens, at the same distance as the first focus.

If an object is placed somewhere in front of the focus point, we will get what we call a "real image" formed on the other end of the lens. The reason we say real is because the light rays actually intersect in the point where the image is formed. We can see a schematic representation of this in Figure 2. Notice how the real image formed is a magnified and inverted version of the object.

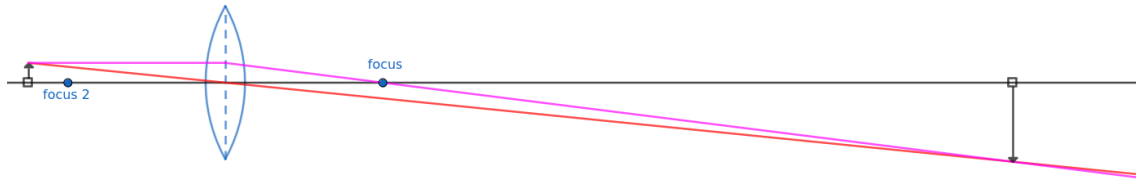


Figure 2: Formation of a real image behind a convex lens.

Now, if an object is placed between the focus point and the lens, we will get what we call a virtual image of the object. This virtual image is formed in front of the lens, and in Figure 4, the virtual image is signified by the dashed lines. This image is also magnified, but the right way up. We call it virtual since the light rays past the lens diverge, so we have to draw their extensions (signified by dotted lines) to see where they cross.

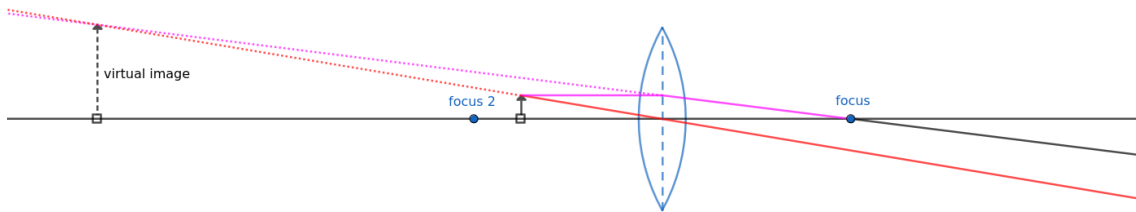


Figure 3: Formation of a virtual image in front of a convex lens.

In the case of the object being placed exactly in focus, a real image will be formed infinitely far away, since the light rays will be parallel, and thereby won't intersect either in front or behind the lens. We don't say that an image isn't formed, but rather that it is formed infinitely far away from the lens.

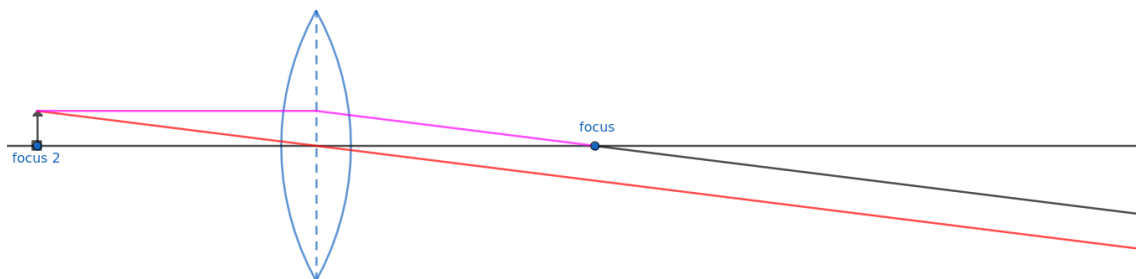


Figure 4: Formation of a real image in infinity using a convex lens.

Convex lenses are used in glasses for farsighted individuals, i.e. individuals whose vision is blurry to close objects. This is because farsightedness is caused by the distance between the eye lens and the retina shortening, requiring us to have to converge light rays so that they hit the correct part and that the vision is no longer blurry.

1.1.2 Concave Lenses

Figure 5 shows how light rays are refracted using a concave lens. We see that the light rays go further and further away from each other past the lens, and for this reason, concave lenses are also called diverging lenses. The focus point is therefore in front of the lens, and we find it by drawing extensions of the light rays, indicated in the sketch by the dashed red and green lines.

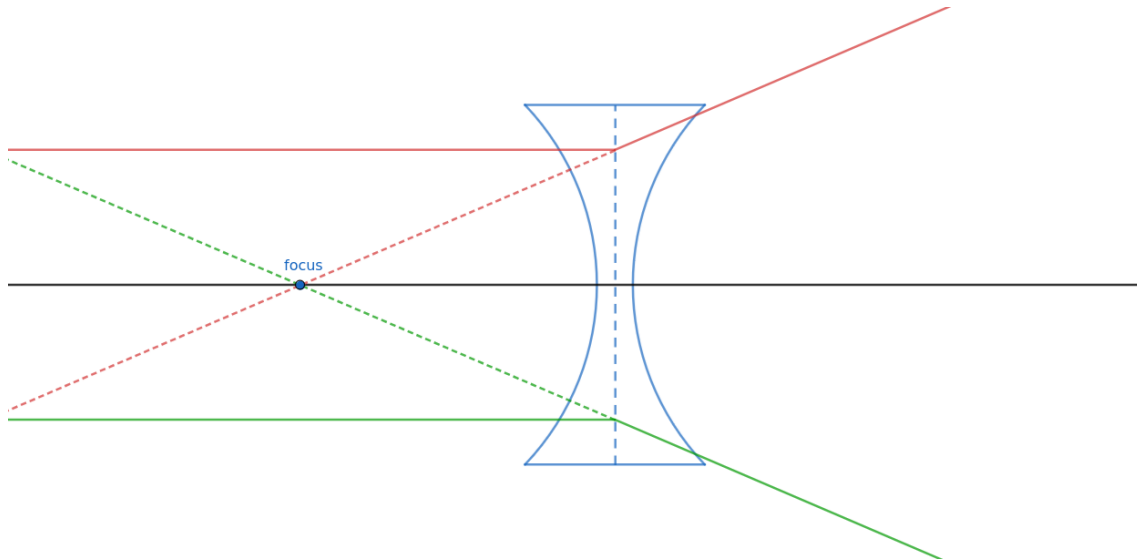


Figure 5: Refraction of light rays by a concave lens.

No matter where the object is located in relation to the lens, the image formed will be an upright minimised virtual image of the object, just like shown in Figure 6.

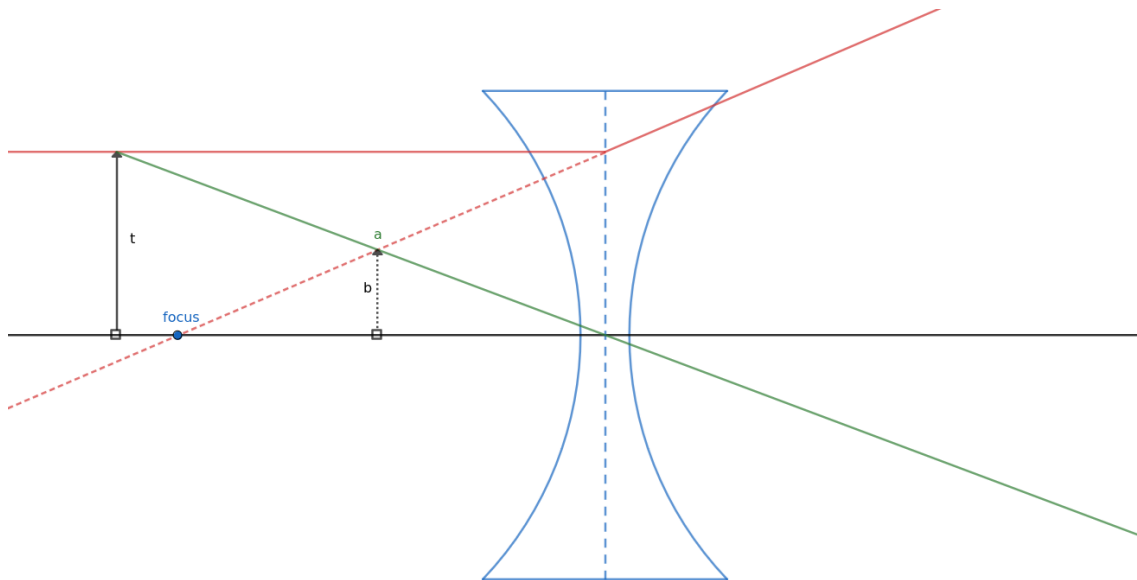


Figure 6: Virtual image formation by a concave lens.

1.2 Mirrors

Mirrors can be either planar (a flat mirror, just like the ones you probably have home), convex and concave. Mirrors have the property that light rays hitting them will bounce right back with the same angle as they hit the mirror with. We call this reflection.

1.2.1 Planar Mirrors

Planar mirrors are probably the simplest ones to look at. The working principle of such a mirror is sketched in Figure 7, from which we can clearly see that the image formed is virtual, upright

and of the exact same size as the object being mirrored. This means that the image we see in a mirror is actually virtual - our eyes can see both virtual and real images!

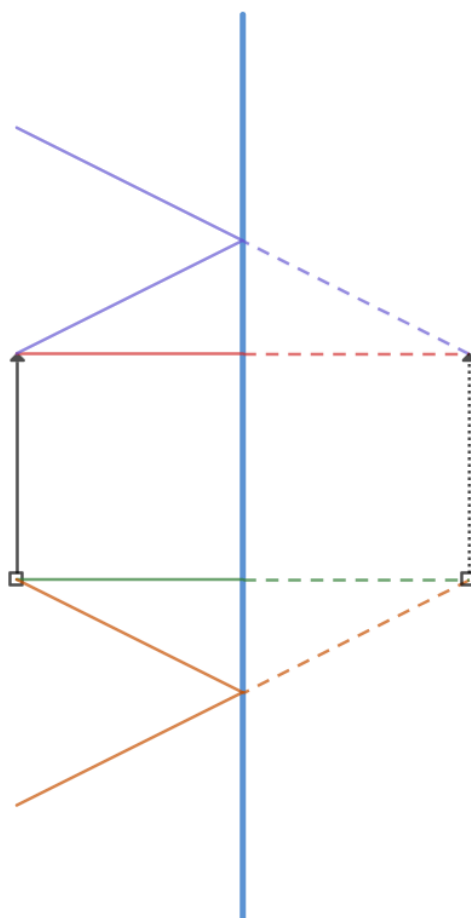


Figure 7: Virtual image formation by a planar mirror.

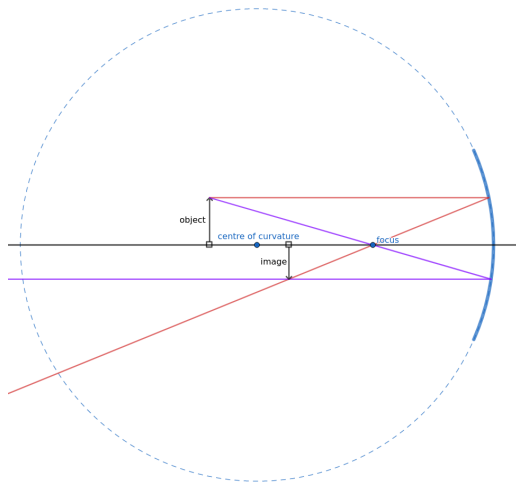
1.2.2 Convex and Concave Mirrors

Convex and concave mirrors are assumed to be arcs of a circle (or sphere), with the centre of the circle being called the centre of curvature. Spherical mirrors have a single focal point, either behind the mirror in the convex case, or in front of it with the concave case. No matter the case, the focus point will always be halfway between the centre of curvature and the mirror surface. With these types of mirrors, three important rules govern how light rays behave upon hitting them:

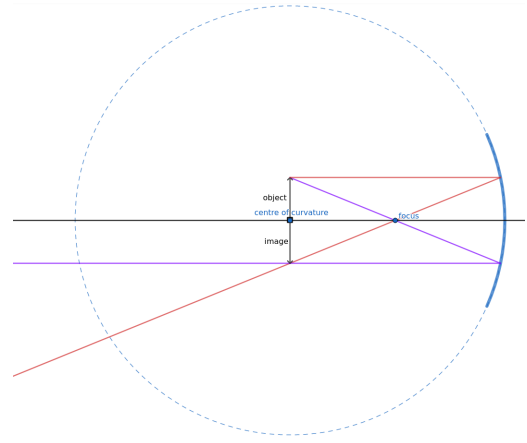
- if the light ray is parallel to the x -axis before hitting the mirror, the reflected ray will pass through the focus
- if the light ray passes through the focus before hitting the mirror, the reflected ray will become parallel with the x -axis
- if the light ray passes through the centre of curvature before hitting the mirror, the reflected ray will follow the same path back.

Based on this, you can conclude that if a ray is parallel to the x -axis and passes through the focus on its way to the mirror, it will simply bounce back the same way! You now have the knowledge necessary to confirm the following statements (use Geogebra if you wish to play around a bit):

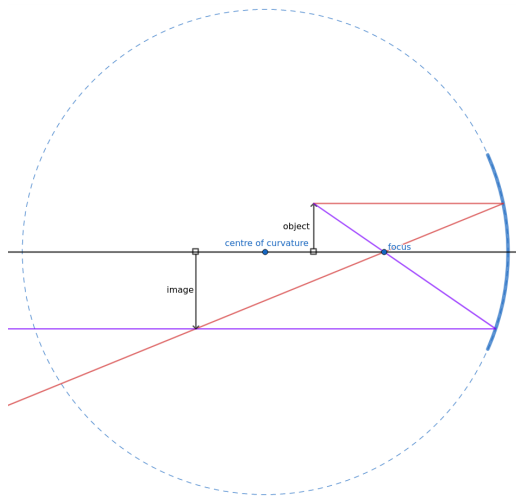
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- for a convex mirror, virtual upright images reduced in size are created no matter where the object is placed (we leave it to you to draw out and prove this).
 - for a concave mirror, images created vary based on where the object is in relation to the mirror and some of its defining points:
 - if the object is in front of the centre of curvature, a real, inverted, reduced image is formed between the centre of curvature and the focal point, depicted in Figure 8a
 - if the object is at the centre of curvature, the image will also be real and at the centre of curvature having the same size as the object, but be inverted, depicted in Figure 8b
 - if the object is between the centre of curvature and the focal point, an inverted, enlarged, real image will form behind the centre of curvature, depicted in Figure 8c
 - if the object is at the focal point, the real image will form in infinity, depicted in Figure 8d
 - if the object is behind the focal point, an upright, enlarged, virtual image will form behind the mirror, depicted in Figure 8e!



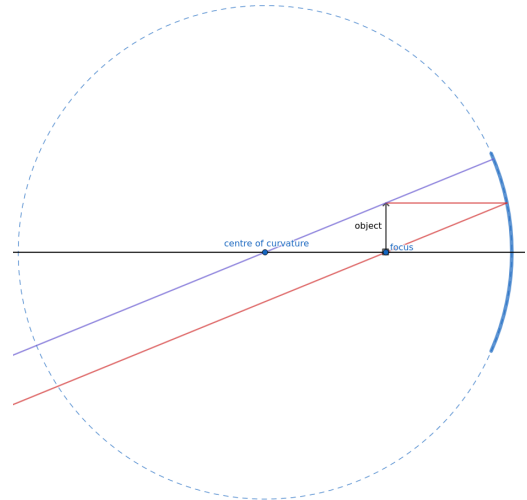
(a) Formation of image when object is in front of centre of curvature.



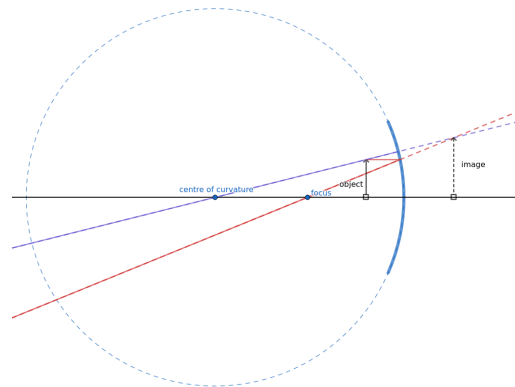
(b) Formation of image when object is exactly on centre of curvature.



(c) Formation of image when object is between centre of curvature and focus point.



(d) Formation of image when object is exactly in the focus point.



(e) Formation of image when object is behind the focus point.

Figure 8: Image formation for different scenarios for a concave mirror.

2 Telescopes

Naked eye observations are fun (and necessary for the competition), but the real fun begins when we help our eye out by using telescopes - powerful instruments that reveal a whole new side to the starry sky! Telescopes can mainly be classified based on whether they use refraction or reflection for magnification, as well as their mounts and what coordinate system they are set up to follow. In this section, we will give a short introduction to all of these classifications that are necessary for you as a competitor in the IOAA to know.

2.1 Refractive Telescopes

We divide telescopes into two main types, based on what is being done to the light rays from the object before reaching our eye: refractors (or refracting telescopes) and reflectors (or reflective telescopes).

Refractors work, just like the name suggests, on the principle of refracting light. Refracting light means bending the rays by making use of the fact that the path changes when light goes from one medium to another. Two lenses are used for this purpose, one being the objective, and one the eyepiece. The objective lens is always convex, but the eyepiece can be either convex or concave. A convex eyepiece gives us a Keplerian telescope, while a concave one is characteristic for Gallilean telescopes.

For space observations, we use Keplerian telescopes, so we won't cover the Gallilean ones here. The working principle of Keplerian telescopes is illustrated in Figure 9. The objective is responsible for collecting the light and focusing it, while the eyepiece magnifies the image. The magnification of a refractor telescope is given by:

$$M = \frac{f_{\text{total}}}{f_{\text{eyepiece}}} \quad (1)$$

The eyepieces can be swapped out to provide different magnifications. Another change that can be made to increase magnification is adding a Barlow lens right in front of the eyepiece. A Barlow lens is a concave lens that effectively shortens the focal length of the eyepiece and thereby provides further magnification.

When you go out and buy a telescope, it will often be marked with something along the lines of *f/some number*. This is what we call the focal ratio (or f-number / F#) of a telescope, and it is a defining characteristic that can be found by using the following equation:

$$N = \frac{f_{\text{total}}}{D}, \quad (2)$$

where f is the total focal length of the telescope, and D is the diameter of its aperture (the part pointing to the sky). Telescopes below $f/7$ are referred to as "fast", while those above $f/8$ are referred to as "slow". This division has roots in photography, where if you have two telescopes with the same focal length, the one with the lower focal ratio will have a bigger aperture diameter and therefore be able to capture more photons. If we capture more photons, we don't need as much time to take an exposure picture, and this reduction in time is why these telescopes are called "fast".

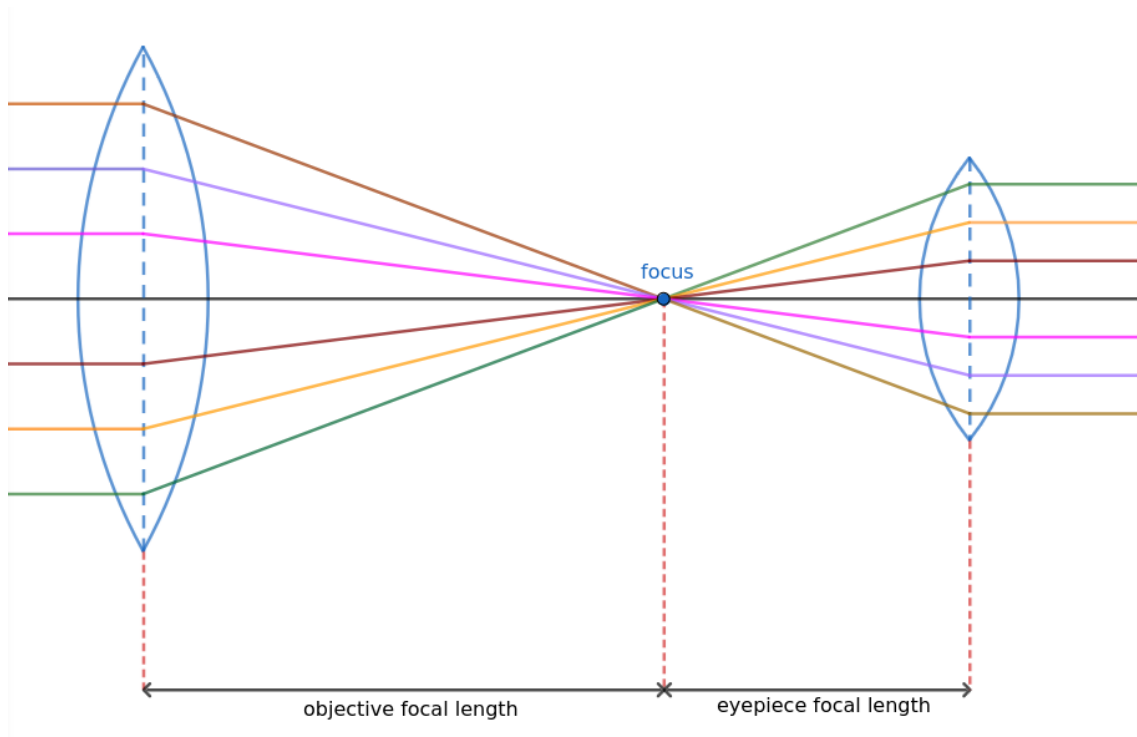


Figure 9: Working principle of Keplerian telescope, consisting of two convex lenses.

Refractive telescopes are highly susceptible to image artefacts, especially one we call chromatic aberration. This is because different wavelengths of light will be refracted in different ways when passing through a lens. For that reason, the different wavelengths of light will have different focus points, and the resulting image we see would be something akin Figure 10. You can notice a blue-and-orange halo around the Moon in Figure 10, and the image is very blurry. A small layer of glass can be placed behind the objective to get rid of this, but this is another extra component, which is not desirable for telescopes of bigger scales. One can also use so-called achromatic and apochromatic lenses, that respectively correct two or three different wavelengths, but this is just for the interested and is not something you need to know.



Figure 10: Chromatic aberration as seen when observing the Moon through a refracting telescope.

We don't want upside down images of whatever we're looking at, so often times, refractors are equipped with so-called "star diagonals". Just like the name suggests, it is a diagonally-angled mirror that bends light so that the rays are flipped the right side up again. Even with this extra piece of equipment, the image in the eyepiece will still be mirrored left-to-right. An example of a star diagonal is shown in Figure 11a



(a) An example of a star diagonal - a component added to a refractive telescope to flip the image the right way up (but not left-right!).



(b) An example of a Barlow lens - a concave lens made to increase magnification of the telescope.

Figure 11: Two common additions to refractive telescopes.

In addition to susceptibility to artefacts, the lenses of refractive telescopes are very difficult to produce as their diameter goes up, making it very impractical for observations for which we need to collect a lot of light.

2.2 Reflective Telescopes

Reflective telescopes use mirrors for observing. The mirrors used are often parabolic rather than spherical, but we have only introduced spherical mirrors for simplicity's sake. They're very well suited for larger-scale applications, and some telescopes are even based on so-called liquid mirrors, where a reflective fluid serves as the primary mirror to the telescope!

Here, we will focus on the two most popular types of reflectors: Newtonian reflectors, and Schmidt-Cassegrain reflectors (often just shortened to Cassegrain telescopes). You will hear Newtonian telescopes also referred to as Dobsonians, but there is a subtle difference, not in the optics, but in how they are mounted. All Dobsonians are Newtonian, but not all Newtonians are Dobsonian!

For Newtonian reflectors, the light rays coming from space hit a concave mirror in the back of the telescope. This concave mirror reflects the light back to a planar mirror that directs it into the eyepiece, where we can see the image.

Cassegrain telescopes also use a concave mirror as their primary, but the secondary mirror is a convex one that reflects the light back through a gap in the concave mirror.

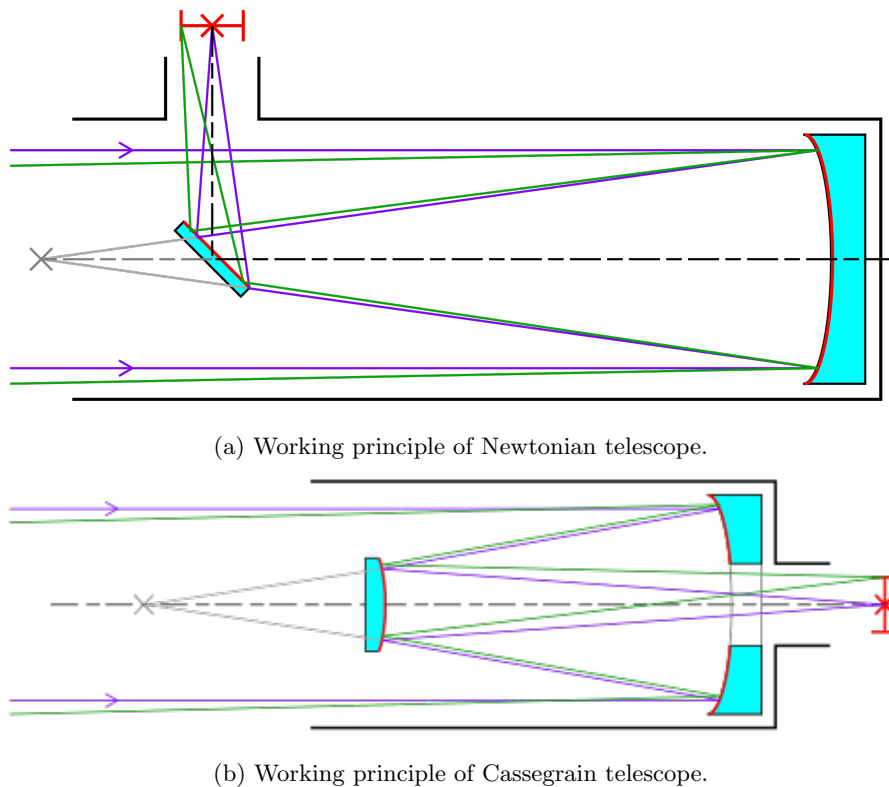


Figure 12: Working principles of two common types of reflectors.

Notice in both cases in Figure 12 that there is a mirror in front of the main one that obstructs the light coming in from where we're pointing at. This is a disadvantage that leads to the shadowing effect, thereby providing less light and less contrast compared to a refractor with the same parameters. Reflectors are still used, though, since large refractors are extremely difficult to construct.

Notice that even though the secondary mirror is blocking light from directly coming to the primary mirror, we don't see a dark spot in the image, but rather just the effects of fewer photons coming to the eyepiece! This also holds for refractors!

2.2.1 Mounts

The main two mounts you need to be aware of are the equatorial and alt-az mounts. They correspond to the coordinate systems they're named after.

Alt-az mounts are much simpler to use and set up - they have two rotational axes that follow the altitude and azimuth. Remember that the alt-az system is observer-centric, so this mount is essentially equivalent to you turning your head towards an object in the sky. The alt-az mount is probably the most recognisable to you, since it's essentially just a tripod, and is how telescopes are often drawn in cartoons, for example.

Dobsonian mounts, mentioned previously when talking about reflectors, are simply alt-az mounts that lock based on friction and are therefore easier to use, especially when we have to work with big and heavy reflectors.

Using any alt-az mount to track stars in the sky is incredibly difficult, since the night sky "moves" throughout the night and the stars drift both in altitude and azimuth. For this reason, we use equatorial mounts, recognisable by the characteristic counterweights they use.

Setting up an equatorial mount is a bit more involved, since one needs to align it with one of the celestial poles (depending on whether you're observing in the northern or the southern hemisphere).

In the northern hemisphere, we're very lucky to have Polaris as an indicator of the celestial north pole, so we can point the polarscope on the mount towards Polaris and lock it in place to align the RA (right ascension) axis with Earth's rotation.

Equatorial mounts are used much more for astrophotography, since the only thing one needs to do is simply polar align it, and then control the telescope so that it moves at the same rate as Earth rotates - with motorised control, this has almost become a trivial issue!



(a) An example of an alt-az mount.



(b) An example of a Dobsonian mount - with this mount, the base rotates.



(c) An example of an equatorial mount. Notice the essential counterweight that helps keep things in place. A polar-aligning scope is also built into the mount.

Figure 13: Three most common types of telescope mounts.

2.3 Limitations

No matter what optical instrument you end up using, it will have its limitations. The one you should be most aware of is what we call the Rayleigh criterion. If we have two point light sources in the sky, if they're too close together, we might not be able to see them as two distinct objects. How close they can be for us to see them is given by this Rayleigh criterion that determines the maximum angular separation of the two objects in the sky that they can have so that we can still see them. It is given by the following formula:

$$\sin \theta \approx 1.22 \frac{\lambda}{D}, \quad (3)$$

where θ is the angular separation of these point sources in the sky, λ the average wavelength of light coming from them, and D the aperture size of the telescope. For very small angles, we can often use the approximation $\sin \theta \approx \theta$, when θ is given in radians. Another consequence of the Rayleigh criterion are the so-called Airy disks (capital A, since they're not disks made out of air, but disks named after the English mathematician Sir George Biddell Airy), which look like what you can see in Figure 14.



Figure 14: Airy disks around a star, representing the limitations because of the diffraction pattern of light passing through a circular aperture.