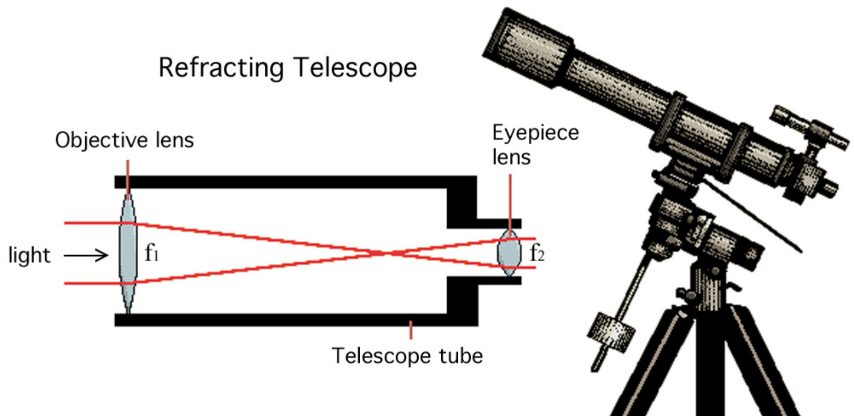
Telescopes

A simple telescope can be thought of as a double lens arrangement in which both the object and the final image are at infinity. (Thus, when you look at the infinitely distant image, you are also looking at the infinitely distant object, except magnified.)



These facts and a bit of algebra tell us that the magnification of a telescope is $M = -f_1 / f_2$, where f_1 is the focal length of the first lens (objective lens) and f_2 is the focal length of the second lens (eyepiece).

One of the misconceptions about telescopes is that you need a large objective lens to achieve a large magnification. No. The magnification of any system of lenses or mirrors is determined by the ratio of the final image size to the object size, and in principle that can run from zero to infinity with lenses or mirrors of any diameter. Microscopes have quite small lenses, yet can achieve magnifications of several thousand times.

The problem is, when you magnify an object (expand the area that its image covers) you are increasing the detail that can be seen, but you are not increasing the wattage of light coming off the object. The same light is spread over a larger area, and thus the larger the image the dimmer the image. This effect is not terribly noticeable for a hand magnifier, but when the magnification reaches into the hundreds or thousands it begins to be a real limitation. Microscope manufacturers deal with it by simply putting intense little lamps on their instruments, or at least little mirrors to reflect additional light onto the sample.

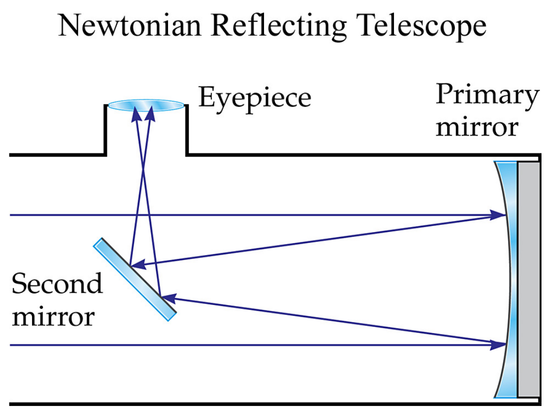
Astrophysicists aren't so lucky. They cannot turn on a lamp to light up Mars, so their only option is to use *huge* lenses, the bigger the better, to collect as much light as possible. The large objectives used in professional telescopes are for illumination, not magnification.

The largest (useful) glass objective ever made is the 40-inch-diameter lens of the Yerkes Observatory in Williams Bay, Wisconsin, manufactured in 1895 after nearly three years of grinding. Unfortunately, the weight of such massive pieces of glass is so formidable that if you tried to make a lens much larger than the Yerkes, it would just sag and distort the image into useless garbage. A 49-inch lens manufactured in Paris in 1900 was purposely distorted in the opposite direction from gravity – it was pre-sagged, so to speak – under the theory that when it was mounted it could then sag into the correctly curved shape. This meant that the lens could not actually be mounted in a telescope tube, but instead had to installed so that it always faced straight up. A huge flat mirror above the lens could be rotated to show different parts of the sky to the 49-inch behemoth. Alas, the pre-sagging didn't work very well, the whole contraption was hopelessly inconvenient to use, and the telescope was junked after a year. But the lens still exists – it is stored in a warehouse near the Paris Observatory.

After 1900 astronomers shifted almost exclusively to reflecting telescopes, which replace the objective lens with a concave mirror. The great advantage of using a mirror is that it can be supported from the back and therefore can be built to much larger sizes than 40 inches. The largest diameter telescope in the world (at the moment – larger ones are planned) is the Great Canary Telescope in the Canary Islands, at 10.4 meters = 409 inches. In terms of using the thin lens equation, $^1/_O + {}^1/_I = {}^1/_f$, there is no difference at all between a refracting or a reflecting telescope. All you need to remember is that mirrors have a different sign convention from lenses. It is still the case that $M = -f_1 / f_2$, and you still need the focal point of the primary mirror to touch the focal point of the eyepiece for maximum magnification.

In the real world, of course, one has to deal with the problem of how exactly do you project the image from a telescope's mirror to a place outside the telescope where you can see it? One way is to simply tilt the mirror so that the reflected light is sent back up the tube but at an angle, so that one can sort-of peek over the edge and see the image directly. This is basically what I did in class when I used a concave hand mirror to reflect the (real) image of a lamp onto a screen: if the lamp and the mirror had been perfectly aligned, then the reflected light would have hit the lamp and the screen would have only shown a shadow. However, a major problem with the tilt method is that it distorts the image so that round objects are warped into an approximately pear-shaped figure.

A more elegant solution is the *Newtonian reflector* shown at right, so called because the first known working example was built by Isaac Newton in 1672. In this design, a small flat mirror fixed in the center of the telescope tube at a 45° angle to the incoming light reflects the image to an eyepiece located on the side of the tube. You might have to draw a few diagrams to convince yourself of it, but reflecting the path of a real image at 90° like this changes nothing: the focal length is the same, the image size and shape is identical, all you do is rotate the image to the side. You can still use the same old formula $^1/_O + {}^1/_I = {}^1/_f$ as if the flat mirror isn't even there!



But, you say, aren't there problems with a Newtonian reflector? Won't that flat mirror in the middle of the tube block your view of the middle of the astrophysical object? Also, the flat mirror has to be held in place by wires or something. Won't an image of that superstructure (or at least a shadow of it) be superimposed on your astrophysical photography?

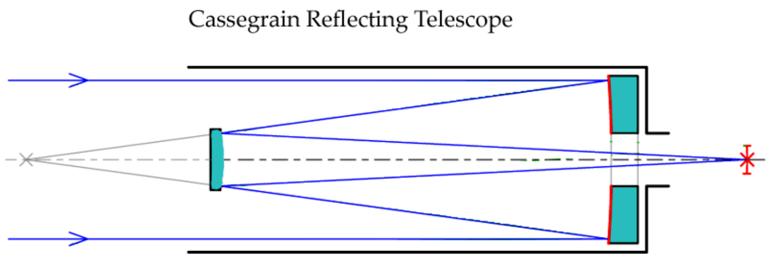
Well, the answers are no and no. The answers would be yes and yes if your eyeball was located where the primary mirror is, but your eyeball isn't a 10-inch concave mirror. Light from the distant star Sirius which misses the superstructure and hits the mirror will still be focussed to the proper place. The only effect of blocking part of the light from Sirius is that the overall light intensity is reduced. Given a primary mirror of 10 inches radius, and a secondary mirror of 1 inch radius, the ratio of the light blocked is only $(^1/_{10})^2 = 1\%$, quite acceptable in view of the advantages of using a reflecting telescope.

To put it another way, if I put two objects in front of a lens or mirror at different distances, then I will get two images, also at different distances. However, the telescope's eyepiece is set to focus at infinity but the supports for the second mirror are *inside* the focal length of the primary, which means that their image is a virtual image well *behind* the primary mirror. Since this virtual image is also an "object" for the eyepiece, we know that its distance from the eyepiece must be at least $f_1 + f_2$. But f_2 is much smaller than f_1 for a telescope, so the virtual object distance must be much greater than f_2, or $^1/_O \approx$ zero as compared to $1/f_2$. This yields an image distance for the support structure of $I \approx f_2$, which is a lot less than infinity. The superstructure is blurred to near-nothingness.

A reasonable analogy is the specks of dust on your glasses or sunglasses. Your eyes are focused at infinity, more or less, on the blackboard where your physics teacher is scribbling down crystal-clear equations (at least in an optical sense). The blackboard is a real image about a centimeter behind your eye lens. But the dust specks on your glasses are far closer than infinity, and I don't know enough about the human eye to say exactly where their image is, but it isn't anywhere near the back of your eye. They are super-magnified and blurred almost out of existence and again, the main effect is that they somewhat lessen the amount of light entering your eye.

Newtonian reflectors have a more subtle problem from the viewpoint of professional astronomers. The side-saddle nature of the viewing arrangement means that massive cameras, spectrometers, and the like have to mounted on the side of the telescope. For really large instruments, this leads to considerable difficulty in making the telescope sturdy enough to hold the off-center weight yet light enough to be delicately pointed with 12-digit precision.

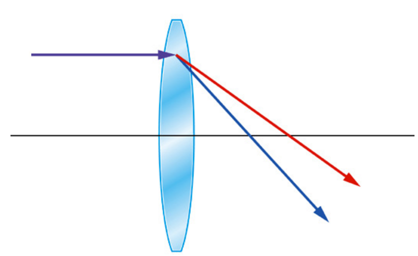
A common solution to this problem is the Cassegrain reflecting telescope, shown schematically at right. In this design, light from the primary mirror is sent to a secondary mirror and then reflected straight back through a hole drilled in the center of the primary mirror! Exactly like the Newtonian reflector, however, none of this has any significant effect on the image quality except to lower the light-collecting efficiency somewhat. The advantage of Cassegrain-type reflectors (there are a half-dozen variations on the basic design) is that heavy instruments can be mounted in back, along the axis of the telescope, which makes them much easier to balance and therefore to construct.



On a mundane level, this means that a physics problem involving a reflecting telescope (Newtonian or Cassegrain) can be solved by just plodding along and using a mirror as the *first* element in a pair, and a lens as the second element. No modifications are needed to the lens equation, and the usual sign conventions apply. The flat mirrors can be ignored. The fact that you have a concave mirror blocking the lens does complicate the actual construction, but the theory is fine. As we have seen, there are ways of getting the light to the lens.

I could talk forever about complications, of course. For example, some Cassegrains substitute a concave mirror for the second mirror to increase the magnification – essentially, these are three-element systems. Some small Cassegrain telescopes made for the home market are really quite remarkable if you take a close look at them. They are in fact combination reflector/refractors in which the first element is a convex lens that focuses light onto a concave mirror at the back, which then reflects the light back to a second concave mirror that is actually mounted in the center of the primary lens(!), and then this light is reflected through the back. This gives you the equivalent of a long focal-length, four-element telescope packed into only one-third the length, a support structure for the second mirror that is made out of glass and therefore truly is invisible, and it allows you to completely seal off the interior of the telescope so that the customer never needs to take it apart to dust it. Pretty impressive, for only $1995.

Newton's original reflector was quite tiny, only about six inches in diameter, so obviously he did not build it out of any concern for engineering costs or weight support. The problem Newton was tackling was *dispersion*, i.e., the propensity of the index of refraction to vary slightly with wavelength. In simple terms, this means that a single lens always refracts white light into a rainbow, as illustrated at right – the blue and red rays have different *n*'s, and thus refract at different θ. Early telescopes were plagued by spurious bands of red, blue, and green glowing alongside every star and planet. Newton turned to mirrors because the law of reflection, $\theta_I = \theta_R$, is true for any wavelength. Mirrors do not make rainbows.



What Newton did not know is that different types of glass can have different degrees of dispersion. As illustrated at right, this means that one can combine lenses made of different types of glass in devilishly clever ways so that there is an overall magnification, but the different colors can still be brought to a single focus at some point. The art of making achromatic lens has now advanced to the point where the flimsiest pair of $79 binoculars that K-Mart sells would astound Newton or Galileo. Even cheap optics today can combine five or six lenses back-to-back to suppress chromatic aberration.