

Section 13.3

Telescopes and Microscopes

Not everything that we wish to see is visible to the naked eye. We have trouble making out details in distant objects and can't resolve the tiny structures in nearby ones, either. We need help. To enlarge and brighten distant objects, we use telescopes, and to do the same with nearby objects, we use microscopes. Because these devices are almost identical in structure, though specialized to apparently different tasks, it's natural to describe them together in this section.

Questions to Think About: *Where is the image that you see when you look into a telescope or microscope? Why does that image often appear upside-down and backward? How do the eyepieces in telescopes and microscopes contribute to their magnifications? Why does the image become dimmer as the magnification increases? Is there a limit to a telescope or microscope's usable magnification? Why do major telescopes have such large diameters? What is the advantage to a telescope in space?*

Experiments to Do: *Building a simple telescope is easy if you have two different magnifying glasses. You need one with a long focal length (low magnification) and one with a short focal length (high magnification). Use the long focal length lens to form a real image on a sheet of paper. Once you know how far from the lens the real image forms, you can begin looking at that image with the more powerful magnifying glass. But instead of looking at the real image on the sheet of paper, hold the two lenses up in line with one another and look right through both. If you look into the high-powered lens and adjust the separation between the two, you should find a special distance at which you see a clear image of the scene in front of you. This image will be enlarged, but upside-down and backward. Can you explain this inversion?*

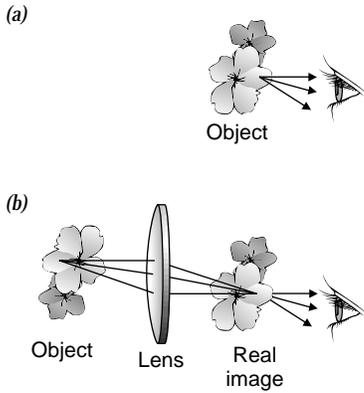


Fig. 13.3.1 - (a) The lens of your eye takes light diverging from an object and focuses it onto your retina. (b) When you look at a real image, you again see light diverging from a region of space and the lens of your eye focuses it onto your retina.

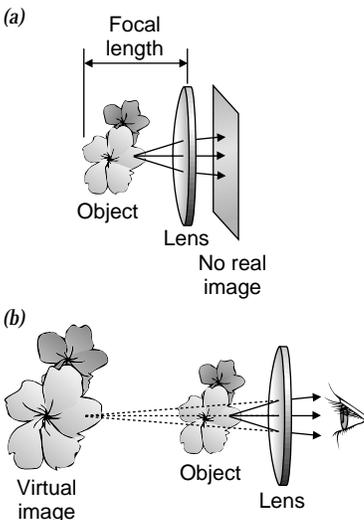


Fig. 13.3.2 - (a) Light from an object very near a converging lens diverges after passing through the lens. (b) Your eye sees a virtual image that is large and far away.



Fig. 13.3.3 - This magnifying glass creates an enlarged virtual image located far behind the printed text.

Photographic and Visual Telescopes

Let's begin by looking at light telescopes, which form images of distant objects either on film or in front of your eyes. Most telescopes used by professional astronomers are photographic—essentially gigantic telephoto lenses that form real images of stars on pieces of film or electronic light sensors. However visual telescopes are still popular among amateur astronomers and for terrestrial work. Binoculars are essentially a pair of visual telescopes, carefully matched to one another and equipped with devices that produce upright images.

A photographic telescope produces a real image in which light from one part of the sky is brought together on one part of the film or light sensor. But a visual telescope doesn't create a real image behind its final lens. Instead, it creates a **virtual image** in front of its final lens.

To understand a visual telescope, imagine removing the film or light sensor from a photographic telescope. With nothing to stop it, light continues past the real image and forms a stream of diverging light. If you look into this stream of light, you'll see the real image floating there in space (Fig. 13.3.1). Because light from the real image diverges in the same way it would from a solid object, the real image looks like a solid object. In fact, it can be hard to tell whether you're looking at an object or at a real image of that object.

But in a visual telescope, you don't look directly at the real image; you look at it through a magnifying glass. A magnifying glass is just a converging lens that's so close to the object you're looking at that a real image doesn't form *after* the lens (Fig. 13.3.2a). The object distance is less than the lens's focal length, so the image distance is negative and a virtual image forms *before* the lens (Fig. 13.3.2b). This means that light rays from the object continue to diverge after passing through the lens and appear to come from an enlarged virtual image, located farther away than the object itself. While you can't touch this virtual image or put a piece of paper into it, it's quite visible to your eye (Fig. 13.3.3).

In a visual telescope, the object you look at through the magnifying glass is actually the real image from the first part of the telescope. You use the magnifying glass—actually called the **eyepiece** or *ocular lens*—to enlarge the real image so that you can see its detail more clearly. You can focus the eyepiece, like any magnifying glass, by moving it back and forth. The farther the eyepiece is from the real image you're looking at, the less the light rays diverge after passing through the lens and the farther away the virtual image becomes. When the object distance is exactly equal to the eyepiece's focal length, the virtual image appears infinitely distant. You can then view the enlarged image with your eye relaxed, as though you were looking at something extremely far away.

The eyepiece provides magnification because when you look at an object through it, that object covers a wider portion of your field of vision. This magnification increases as the eyepiece's focal length decreases. That's because a short focal length eyepiece must be quite close to the object, where it can bend light rays coming from a small region so that they fill your field of vision. A long focal length eyepiece must be farther away from the object, where it can bend light rays coming from a large area to give you a broad but relatively low-magnification view of the object.

CHECK YOUR UNDERSTANDING #1: Real and Virtual Images

As you move a magnifying glass slowly toward the photograph in front of you, you see an inverted image that grows larger and nearer to your eye. This image eventually becomes blurry and then a new upright and enlarged image appears on the photograph's side of the lens. What is happening?

Refracting Telescopes

A common type of visual telescope uses two converging lenses: one to form a real image of the distant object and the second to magnify that real image so that you can see its fine detail (Fig. 13.3.4). The first lens is called the **objective** and the second lens is the eyepiece. Because this telescope uses refraction in its objective to collect light from the distant object, it's called a *refracting telescope*. More specifically, it's called a *Keplerian telescope*, after the German astronomer Johannes Kepler (1571–1630). An alternative design that uses one converging lens and one **diverging lens**—a lens that bends light rays away from one another—is called a *Galilean telescope*, after the Italian scientist Galileo Galilei (1564–1642).

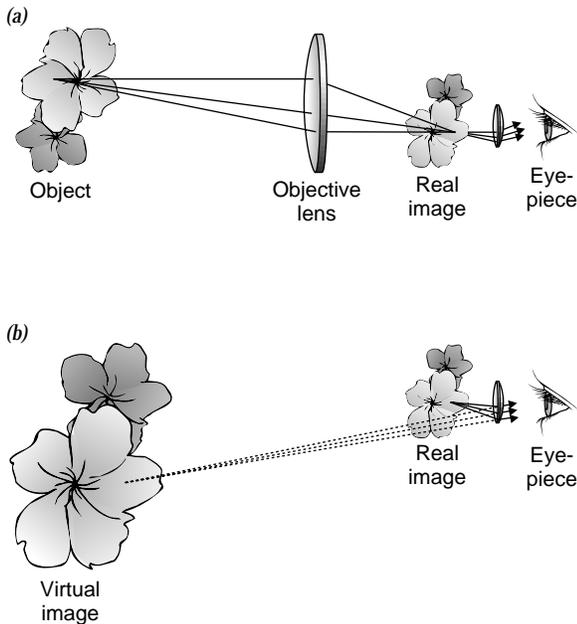


Fig. 13.3.4 - (a) A Keplerian telescope consists of two converging lenses. The objective lens forms a real image of the distant object. The eyepiece acts as a magnifying glass, allowing you to inspect that real image in great detail. (b) As you look through the eyepiece, you see a very large, far away, and inverted virtual image of the object.

Because a Keplerian telescope's objective forms an inverted real image, the virtual image you see through the eyepiece is also inverted. This inversion is tolerable for astronomical use but is a problem for terrestrial use. It's hard to watch birds when they appear upside down and backwards. That's why binoculars, which are basically Keplerian telescopes, include erecting systems that make the final virtual image upright. These erecting systems fold the optical paths of the binoculars and give them their peculiar shape.

When you look at an object through a visual telescope, you see a magnified virtual image. The magnification of a Keplerian telescope depends on the focal lengths of the two lenses. As the focal length of the objective increases, its real image becomes larger and the telescope's magnification increases. As the focal length of the eyepiece becomes shorter, you look more closely at the real image so the telescope's magnification again increases. Overall, a Keplerian telescope's magnification is its objective's focal length divided by its eyepiece's focal length.

However, as we discussed in the section on cameras, simple lenses create poor quality images. Most telescope objectives and eyepieces are actually constructed from several optical elements. To avoid chromatic aberration (color focusing problems), these lenses are built from *achromatic doublets*, pairs of matched optical elements that are joined by clear cement. The two elements in a doublet are made from different types of glass so that their dispersions cancel and they act as a single lens that's almost free of chromatic aberration.

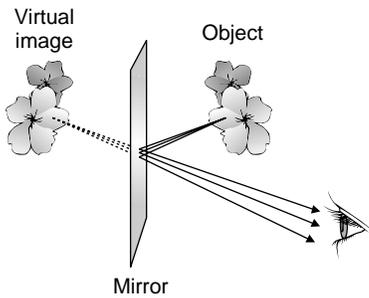


Fig. 13.3.5 - A flat mirror forms a virtual image of any object in front of it. The virtual image is located exactly opposite the original object and is flipped side-for-side.

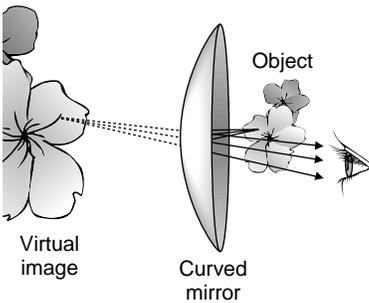


Fig. 13.3.6 - A concave mirror forms a virtual image of any object in front of it and close to its surface. The virtual image appears larger than the original object and is more distant from the mirror than the object itself. Like the flat mirror, the virtual image is flipped side-for-side.

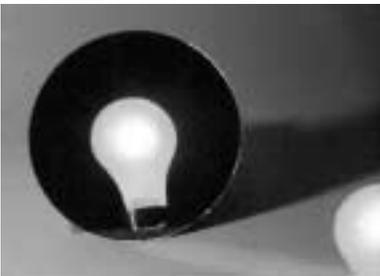


Fig. 13.3.7 - A curved mirror produces an upright virtual image of a light bulb located just in front of it.

Fig. 13.3.8 - When an object is far from a concave mirror, the mirror forms a real image of the object. In such a reflecting telescope, a photographic film or other light-sensitive surface is usually placed where the real image forms.

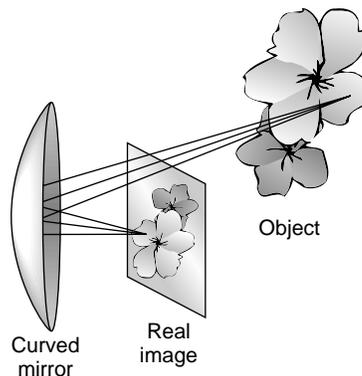
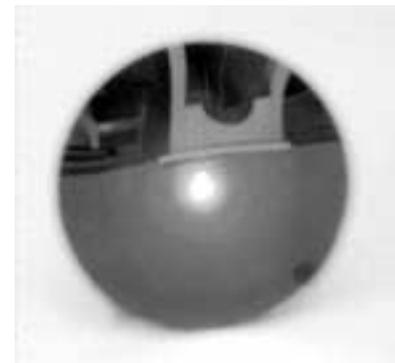


Fig. 13.3.9 - A curved mirror produces an inverted real image of a light bulb located on a table far in front of it.



But even achromatic doublets don't create perfect images. That's why telescope eyepieces frequently contain four, five, or even six individual optical elements. These precision eyepieces produce images that are sharp from edge to edge. As in camera lenses, these individual elements are anti-reflection coated so that you don't see any reflections when you look into the telescope.

CHECK YOUR UNDERSTANDING #2: A Long Look at the Stars

Why are refracting telescopes and binoculars with high magnifications so long?

Reflecting Telescopes

But not all telescopes use lenses as their objectives. A *reflecting telescope* uses an objective mirror to create the initial real image. For reasons we'll discuss shortly, reflecting telescopes have almost completely replaced refracting telescopes for astronomical observation.

A flat mirror is already an interesting optical device. It forms a virtual image of any object (Fig. 13.3.5). Light diverging from the object bounces off the mirror and continues to diverge until it reaches your eye. This light appears to come from a virtual image located on the other side of the mirror, at just the same distance from the mirror as the object itself. This virtual image is reversed side-for-side from the object, so you see a "mirror image." When you view this mirror image, it looks the same size as the object itself.

If the mirror is curved rather than flat, it still creates virtual images. But the virtual images are no longer located exactly opposite the original objects and they don't appear the same size. A mirror that is bowed inward like the inside of a bowl is **concave**. When an object is located near a concave mirror, light diverging from the object bounces off the mirror and continues to diverge, but not as quickly (Fig. 13.3.6). It appears to come from a large virtual image that's located far behind the mirror (Fig. 13.3.7). This effect explains why makeup mirrors give you an enlarged view of your face. As long as your face is close to the bowl-shaped mirror, you see an enlarged virtual image of your face located far behind the mirror. (In contrast, a mirror that is bowed outward in the middle, a **convex** mirror, creates a reduced virtual image located just behind the mirror.)

However, when an object is located far from a concave mirror, light diverging from the object bounces off the mirror and converges to form a real image (Figs. 13.3.8 and 13.3.9). This real image is just like one formed by a lens except that it occurs *in front* of the mirror. You can project this real image onto a sheet of paper or onto a piece of film, which is how a photographic reflecting telescope works. As usual, the real image is inverted and flipped side-for-side.

A visual reflecting telescope simply adds an eyepiece, through which you

can inspect the real image in great detail (Fig. 13.3.10). Through that eyepiece, you see an enlarged virtual image of the original object.

Like the objective lens of a refracting telescope, the mirror of a reflecting telescope must be carefully shaped to create a sharp real image. Since it uses reflection rather than refraction, it has no chromatic aberration and handles colors well. But a single mirror suffers from a variety of image imperfections, which, though usually negligible near the center of the real image, become progressively worse toward its periphery. The mirrors used for observing astronomical objects generally have parabolic shapes and create real images that are nearly perfect at their centers but relatively poor at their edges. Such telescopes normally only let you see the central portions of their real images, where those images are sharp and clear.

The visual reflecting telescope of Fig. 13.3.10 places your head in front of the curved mirror as you look into the eyepiece. While some giant telescopes allow you to sit in front of their mirrors to inspect their real images, most smaller telescopes try to get you out of the mirror's way. They redirect light from the objective mirror so that you aren't in front of it. The two most common ways of doing this are the *Newtonian reflecting telescope* (Fig. 13.3.11a) and the *Cassegrainian reflecting telescope* (Fig. 13.3.11b).

In a Newtonian telescope, a flat secondary mirror deflects light from the concave objective mirror by 90°, so that the real image forms at the side of the telescope. You can then look at this real image through an eyepiece without blocking light on its way to the primary mirror (Fig. 13.3.12).

In a Cassegrainian telescope, a convex secondary mirror reflects light from the concave objective mirror back through a hole in the center of the primary mirror. Since the secondary mirror bends the light outward slightly, it delays the light's convergence so that a real image forms behind the telescope. You look at this real image through an eyepiece at the end of the telescope (Fig. 13.3.12).

In both the Newtonian and Cassegrainian telescope designs, something

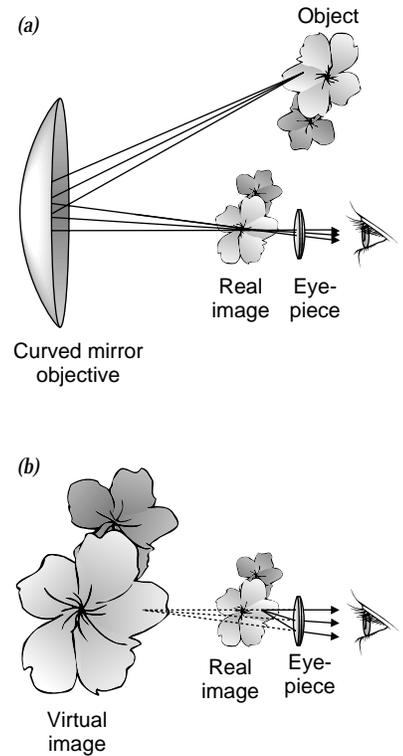


Fig. 13.3.10 - (a) A visual reflecting telescope consists of a curved mirror objective and a converging lens eyepiece. The concave mirror forms a real image of a distant object while the eyepiece allows you to inspect that real image in great detail. (b) As you look through the eyepiece, you see an enlarged and inverted virtual image of the object out in the distance.

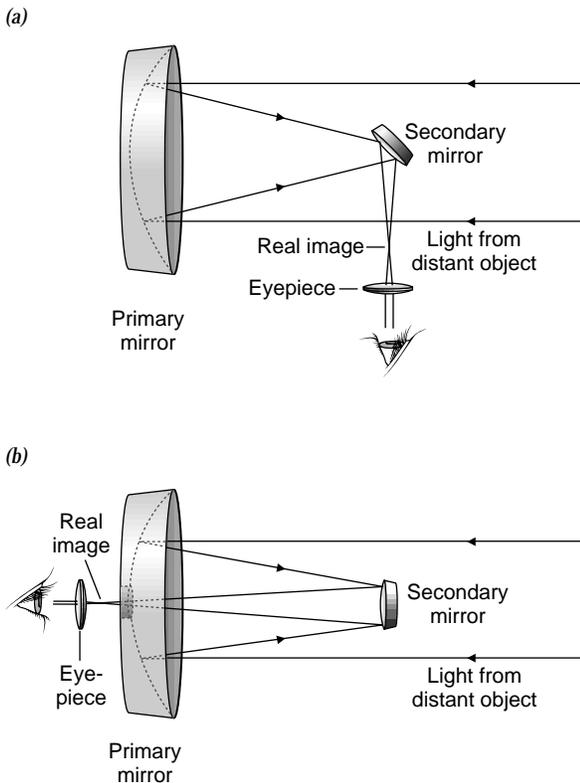


Fig. 13.3.11 - (a) A Newtonian telescope bends light from the primary mirror by 90° so that you can view it from the side of the telescope. (b) A Cassegrainian telescope sends light from the primary mirror back through a hole in the center of the primary mirror so that you can view it from the end of the telescope.

Fig. 13.3.12 - Light entering the right end of a Newtonian telescope (left) reflects from a large curved primary mirror at the far end. A small secondary mirror then turns the reflected light toward an eyepiece located on the side of the tube. In a Cassegrainian telescope (right), a small secondary mirror sends light reflected by the large primary mirror toward an eyepiece located beyond a hole in the primary mirror. An added prism just before the eyepiece bends the light 90° to make viewing easier.



must support a small mirror in the center of the telescope's field of view. These rigid supporting structures or "spiders" often appear in the photographs of stars because of interference effects and give each star an artificial cross shape.

CHECK YOUR UNDERSTANDING #3: Your Smile, Upside Down

If you hold a shiny spoon at arm's length in front of you and look into its bowl, you will see an inverted image of yourself hovering a few centimeters in front of the spoon. Explain.

The Telescope's Aperture

The size of the telescope's lens or primary mirror determines two important features of the telescope: its ability to gather light and its ability to resolve two nearby objects from one another. The issue of light gathering is straightforward—the more light that the telescope can collect and focus into a real or virtual image, the brighter that image will be. Since objects in the night sky are dim and the telescope is spreading the light it collects over large images, the telescope should gather as much light as possible. High magnification is useless if all you see is enlarged darkness.

The other reason for building large mirrors is resolving power. Light travels as a wave. When a wave passes through a narrow opening, it tends to spread out as it travels into the region beyond the opening, an effect called **diffraction**. When the light waves coming from a distant star pass through the lens or mirror of a telescope, they diffract and begin to spread out somewhat. The larger the lens or mirror, the less diffraction occurs and the smaller the spread. This spreading may seem like a trivial detail. After all, the photographs that you take of a meadow or a schoolhouse appear extremely sharp and clear even if you use a small lens. But what if you were trying to count a person's eyelashes from a kilometer away? That's equivalent to what some telescopes try to do.

When the light from two nearby stars passes through a telescope, that light diffracts. The spreading waves of light from one star may overlap with the spreading waves of light from the other star. In this case, the two stars will be unresolved. They will appear as a single bright spot on the film or in the virtual image that you are viewing. To resolve the two stars, you need a lens or mirror that is large enough that light waves from the stars don't spread into one another. To reach the level of resolution needed by modern astronomers, telescopes have to be several meters in diameter.

Unfortunately, lenses more than about 0.5 m in diameter are extremely hard to fabricate because the glass becomes so thick and heavy that it deforms under its own weight. The glass also acquires stresses and strains as it cools from its molten state and these degrade its optical quality. To make matters worse, two separate elements are needed to make an achromatic doublet. While there are a few refracting telescopes with lenses more than 0.5 m in diameter, each of these lenses represents the lifetime's work of a master lens maker.

Because enormous lenses can't be made, astronomers have turned to mirrors to photograph or observe the dim, distant objects of our universe. Mirrors are easier to fabricate than lenses, although producing a mirror larger than about 3 m in diameter is still a heroic effort. Because mirrors don't have to be transparent, their internal structures can be optimized for strength and stability. Mirrors are often made of translucent glass-ceramics that tolerate temperature changes much better than clear glasses. In recent years, it's become possible to build composite mirrors, in which several mirror segments are designed and crafted by computer-controlled machines and positioned by computers and laser beams. These giant segmented mirrors can gather light from enormous areas.

Unfortunately, the earth's atmosphere limits the resolution of large mirror telescopes. As light from a star passes through the atmosphere, density variations in the air distort the wave just enough that it can't be brought to a single point in a real or virtual image. The most straightforward way to reach the full resolving potential of a giant mirror is to remove it from the atmosphere by putting it in space. The Hubble Space Telescope achieves this potential spectacularly.

However, in recent years, adaptive optical techniques have made it possible for ground-based telescopes to achieve astounding resolution. These telescopes use computerized controls to alter the shapes of their flexible mirrors in order to compensate almost perfectly for atmospheric distortion. An adaptive telescope studies how the atmosphere distorts light from a real or laser-simulated star many times each second and uses that information to reshape its mirror so as to minimize atmospheric distortion. Although air still absorbs certain wavelengths of light and creates a background glow due to Rayleigh scattering, ground-based telescopes with adaptive optics are now quite competitive with space-based telescopes in their resolving powers.

CHECK YOUR UNDERSTANDING #4: A Good View of the Sky

Why are major observatories usually located on mountaintops?

Microscopes

Microscopes are almost identical to Keplerian telescopes, except for the focal lengths of their objective lenses and the locations of their objects. A Keplerian telescope uses a long focal length objective lens to project a large real image of a distant object while a microscope uses a short focal length objective lens to project a large real image of a nearby object (Fig. 13.3.13). The eyepieces in telescopes

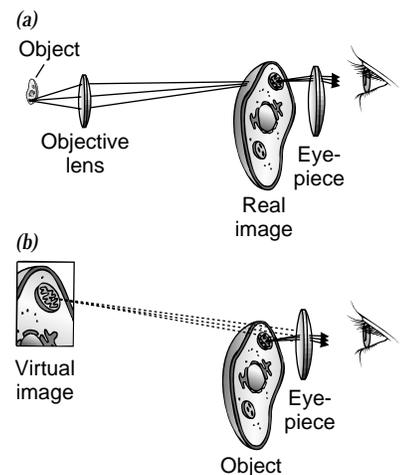


Fig. 13.3.13 - (a) A visual microscope consists of two converging lenses. The objective lens forms a real image of a tiny, nearby object. The eyepiece acts as a magnifying glass, allowing you to inspect that real image in great detail. (b) As you look through the eyepiece, you see a very large, far away, and inverted virtual image of the object.

and microscopes are virtually identical and serve as high quality magnifying glasses through which to inspect the real images.

Although microscopes are technically similar to telescopes, they have different constraints on their construction. While a telescope objective must be very large, a microscope objective must be very small. The microscope objective must move in close to the object, catch its rapidly diverging light rays, and make those rays converge together as a real image far from the lens. Because the objective's focal length must be even shorter than the object distance, the objective must be built from small, highly curved optical elements. Several elements are needed to form a high quality real image, one that will still appear sharp and crisp when you look at it through the magnifying eyepiece.

A microscope's magnification is difficult to calculate exactly, mostly because it depends on what you choose as the unmagnified view—an object held close to your eye looks bigger than one held farther away. Nonetheless, shortening the focal length of the objective lens always increases a microscope's magnification because the objective must then move closer to the object and will form a real image of a smaller region of the object's surface. Shortening the focal length of the eyepiece also increases the microscope's magnification because it then allows you to inspect the real image more closely.

Illumination is important for a microscope. In a telescope you must use the light that's available naturally, but in a microscope you can add whatever light you like. Most microscopes use a bright lamp to send light upward through the object or downward onto the object. What you observe in these two cases is different. If you send light through the object, you see how much light it absorbs in different places. If you bounce light off its surface, you see how much light it reflects in different places.

Many modern microscopes have two separate eyepieces so that you can use both eyes to look at the object. These microscopes have only one objective lens but light from this lens is separated into two parts with a partially reflecting mirror. Two identical real images form and each eyepiece magnifies its own real image. In fact, there are also microscopes that separate additional portions of the light for other viewers or for photography. In the latter case, some of the light from the objective lens is diverted and forms a real image right on a piece of film or on the optical sensor of a video camera.

CHECK YOUR UNDERSTANDING #5: When the Objective is Downsizing...

A typical microscope has a rotating turret housing 3 or 4 different objective lenses. If you turn this turret to replace the 10 mm focal length objective lens that you have been using with a 5 mm focal length lens, what will happen to the magnification of the microscope?

Non-Light Telescopes and Microscopes

We observe objects in the universe almost exclusively through the electromagnetic radiation they send toward us. Electromagnetic waves travel easily through empty space and can cross the vast distances from one side of the universe to the other. But light isn't the only kind of electromagnetic wave. The earth is also exposed to radio waves, microwaves, X-rays, and gamma rays from sources elsewhere in the universe.

To study these electromagnetic waves, astronomers generally use reflecting telescopes. But the characteristics of those telescopes are somewhat different from light telescopes. A *radio telescope* uses a huge concave metal dish to form a real image of the electromagnetic waves from a distant object. In most cases,

these waves are actually microwaves. Instead of using film or a magnifying glass to look at that real image, a radio telescope uses a small microwave receiver. The telescope studies the real image one spot at a time either by moving the microwave receiver around the image or by turning the dish and the receiver to point toward different regions of space.

A home satellite dish antenna is just a small radio telescope. It forms a real image of the microwaves coming toward it from the sky and examines the center of that real image with a microwave receiver. When the antenna is pointed at a satellite, that satellite's waves come to a focus exactly on the receiver's antenna.

Radio telescopes can be made of metal mesh rather than solid metal because electromagnetic waves are insensitive to holes that are substantially smaller than their wavelengths. This same insensitivity to details smaller than a wavelength works against optical microscopes. Because a light microscope can't observe details much finer than the wavelength of visible light, you'll need another kind of microscope to see structures smaller than about 1 micron on a side.

Two important types of non-optical microscopes are electron microscopes and scanning probe microscopes. *Electron microscopes* use electrons to form images of small objects. *Scanning probe microscopes* use extremely sharp needles to study the structures of surfaces, one point at a time.

The electrons in an electron microscope travel as waves and, like light, are unable to resolve structures substantially smaller than their wavelengths. However an electron's wavelength decreases as its kinetic energy increases so that the energetic electrons used in electron microscopes have wavelengths much less than atomic diameters. Some electron microscopes can resolve individual atoms.

Like optical microscopes, electron microscopes use lenses to form images with beams of electrons. However electron lenses aren't simply pieces of glass. Instead, they are electromagnetic devices that use electric and magnetic fields to bend and focus the moving electrons. In a *transmission electron microscope*, electrons pass through an object, through various electromagnetic lenses, and finally form a real image on a phosphor screen or a piece of film. The focal lengths of the lenses are chosen so that this real image is thousands or even millions of times larger than the object. A *scanning electron microscope* uses an electromagnetic lens to focus a beam of electrons to a tiny spot on the object and then detects reflected electrons. The microscope sweeps this spot back and forth across the object's surface and gradually creates an image of that surface.

Scanning probe microscopes originated in the early 1980's with the *scanning tunneling microscope*. The idea behind a scanning probe microscope is simple: move a sharp probe back and forth across a surface and use its interactions with that surface to study the surface. But few people imagined that a point could be made sharp enough to touch or interact with individual surface atoms.

Naturally, people were surprised when German physicist Gerd Binnig (1947-) and Swiss physicist Heinrich Rohrer (1933-) found that their metal probes could exchange electric currents with individual atoms. By scanning a probe across a surface, they could map out the locations of atoms and obtain images of the surface at the atomic scale. For their invention of the scanning tunneling microscope, this pair received the 1986 Nobel Prize in Physics.

Since then, a wide variety of scanning probe microscopes have been developed. In each case, an ultra-sharp probe scans back and forth across a surface, interacting with a few atoms on the surface as it moves along. A computer measures these interactions and builds a map of the surface. These interactions include the exchange of electrons, electric and magnetic forces, and even friction.

CHECK YOUR UNDERSTANDING #6: Aiming High

Why are many home satellite dishes so large?
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