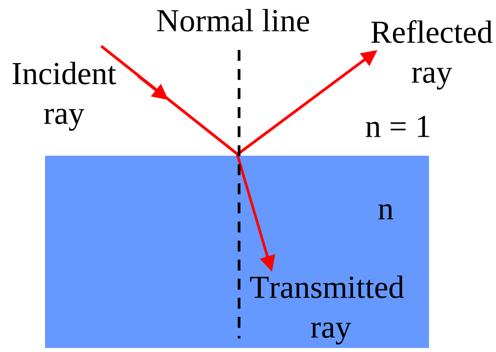
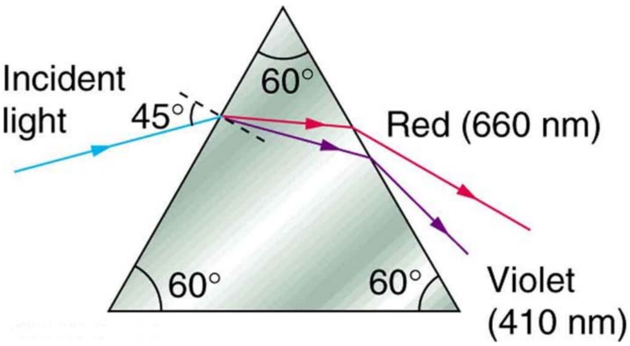
PHYS:1200 LECTURE 30 — LIGHT AND OPTICS (2)

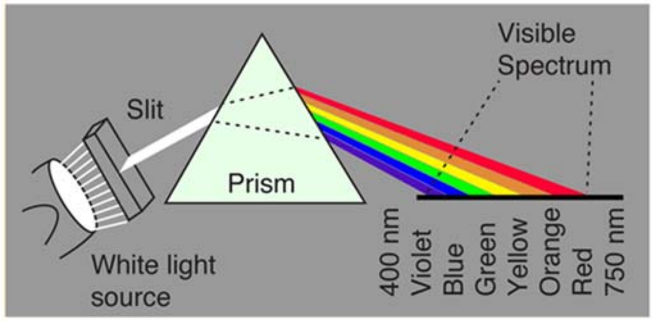
In Lecture 29 we described the phenomenon of **refraction**, or the bending of a light rays as it travels from a medium of one index of refraction into a medium of another index or refraction. e.g., air to water. This process is illustrated in the figure on the right. When the incident ray encounters the boundary part of the light energy is reflected (the reflected ray) and part of it is transmitted into the medium (transmitted or refracted ray). The refracted ray is bent away from the original direction of the incident ray and toward the normal line – this is refraction.



This lecture presents an important consequence of the refraction of light – **dispersion.** We will describe how dispersion is responsible for the formation of rainbows. We will then discuss the important topic of atmospheric scattering, which is also associated with the appearance of color in the atmosphere. Atmospheric scattering is the phenomena that causes the sky to appear blue and why sunsets appear reddish. Finally, the law of reflection is presented, and applied to explain image formation by plane and curved mirrors.

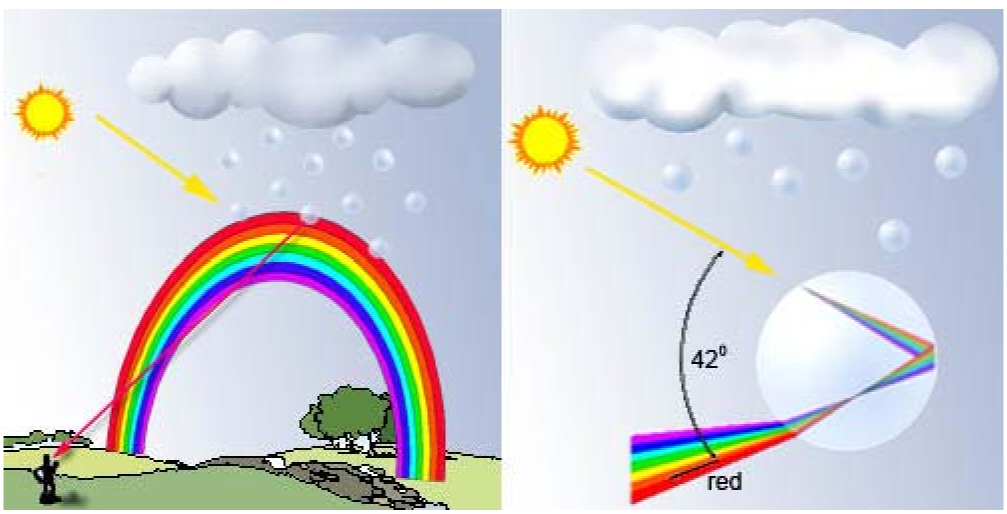
30-1. Dispersion of Light.—The various colors of visible light correspond to different wavelengths—with **longer wavelengths in the red and shorter wavelengths in the blue** (slide 3). The index of refraction of a medium determines the speed of light in that medium, through the relation $v = c/n$. **The index of refraction depends on the wavelength of the light** --- this is the phenomenon called **dispersion**. Slide 4 shows a table of the index of refraction for glass at various wavelengths. The index of refraction is slightly larger for violet light than red light. Therefore, it a beam of red light and blue light both fall on a glass surface at the same angle of incidence, the beam of violet light will be refracted more (more bending) than the beam of red light. This is most easily seen using a triangular glass prism as shown below on the left.





A consequence of dispersion is that a beam of white light (white light is a combination of many wavelengths) passing into a medium is ***dispersed***, i.e., separated into its constituent colors. This is illustrated in the figure above on the right. The appearance of the colors of the spectrum reveals clearly that white light contains many wavelengths.

Rainbows are the result of the **dispersion of sunlight from water droplets** in the atmosphere. Rainbows are typically seen after a storm when one is looking up at the sky with the Sun behind you as illustrated in the diagram below. Sunlight contains a combination of visible light



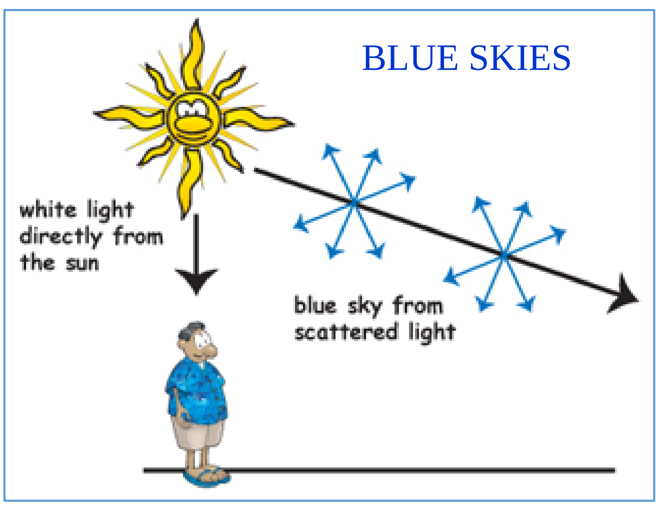
wavelengths. Spherical water droplets in the atmosphere act as tiny prisms to disperse the sunlight into colors as illustrated on the right side of the diagram above. The dispersion occurs when the sunlight enters the water droplet. The dispersed rays are reflected from the back side of the droplet, and refracted again as individual colored beams as they pass through the front of the droplet. The angle between the observer and incoming sunbeam is a critical factor in enabling the observation of a rainbow. The critical angle is satisfied along an arc of a circle giving the familiar bow shape of the rainbow.

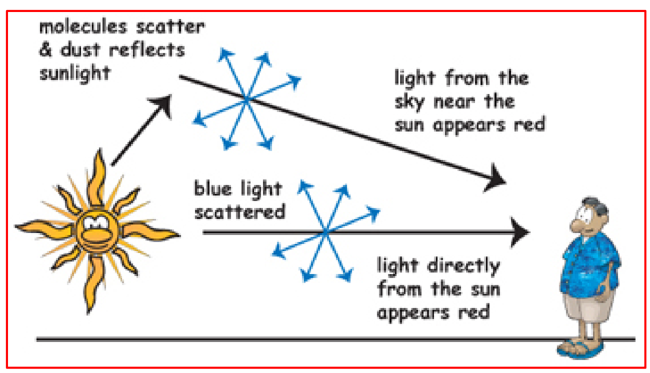
30-2. Atmospheric Scattering.—Sunlight first passes through the Earth's atmosphere before reaching our eyes. The oxygen and nitrogen molecules in the atmosphere produce an effect called **scattering** which is responsible for blue skies and red sunsets. Scattering is a physical

process in which the visible light from the sun is absorbed by the molecules of the atmosphere causing the molecules to become excited. When the excited molecules relax, they re-emit the visible light, but not at the

same wavelength as it was absorbed. Scattering is the term given for this absorption and re-emission of radiation. **The scattering process is highly dependent on the wavelength of the light**, with short wavelengths (blue light) scattered much more than long wavelengths (red light). The scattering process that leads to blue skies is illustrated in the diagram below and to the left. When we look at the sky in the direction away from the sun, we see scattered light. Since blue wavelengths are scattered more effectively than red ones, the scattered sunlight appears blue – the sky is blue.

The scattering process leading to the observation of red sunsets is illustrated on the diagram shown below on the right. At sunset, the sun is low on the horizon and is viewed directly along a



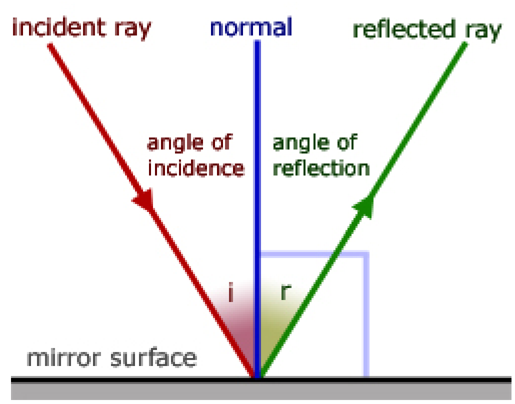


RED SUNSETS

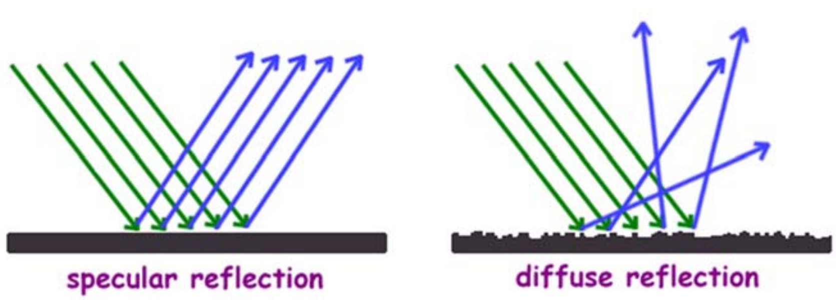
relatively long path through the atmosphere. Because of the long path, a large fraction of the blue light is scattered away from the observer who then sees mostly the un-scattered red light—sunsets appear reddish.

Of course, we do not see blue skies on very cloudy days—**clouds appear white**. The physics behind white clouds is due to a different scattering process. Clouds contain water droplets and ice crystals that consist of a huge number of water molecules. A water droplet is considerably larger than an individual oxygen or nitrogen molecule. The scattering process from water droplets and ice crystals is essentially independent of the wavelength. Since all wavelengths are scattered with more or less the same efficiency, clouds appear white.

30-3. The Law of Reflection.—When light is incident upon a surface, part of the light is reflected. If the surface is a metal, almost 100% of the incident light is reflected. When light is incident on a transparent material such as glass, a small amount is reflected. The law of reflection is illustrated in the diagram to the right. **The law states that the angle of reflection is equal to the angle of incidence**. The angles are measured with respect to the normal line. The incident ray, normal line, and the reflected ray all lie in the same plane.

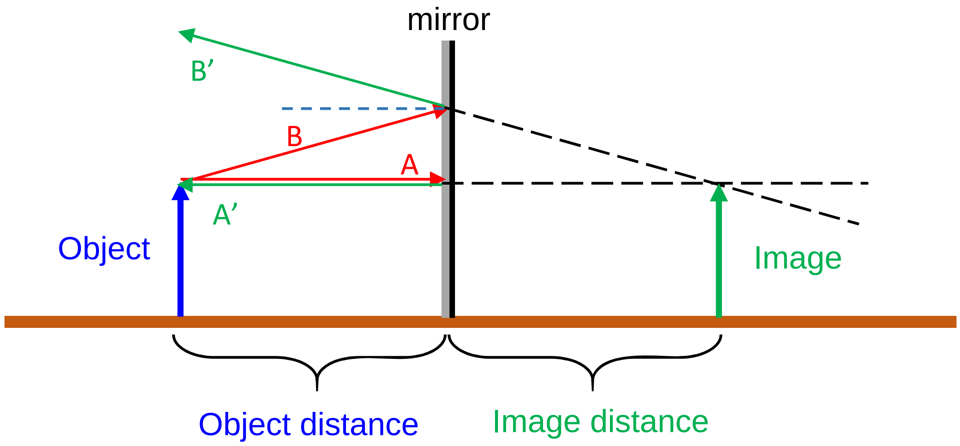


There are two types of reflection that occur depending on the surface conditions. If the surface is rough (not polished) parallel light rays



incident on the surface are reflected in random directions, depending on where they fall on the surface. This case is called **diffuse reflection**. On the other hand, if the surface is polished, parallel rays will all be reflected at the same angle of reflection. This case is called **specular reflection**. These two cases are illustrated in the diagram above. The formation of images by mirrors requires that specular refection occurs. Mirrors are typically formed by evaporating a very thin layer of aluminum or silver on a flat piece of glass.

30-4. Image Formation by a Plane Mirror.—The formation of an image by a plane mirror is illustrated in the diagram below. The object is the blue arrow and we locate the image by finding the position where at least two rays intersect after leaving the same point on the object (arrow

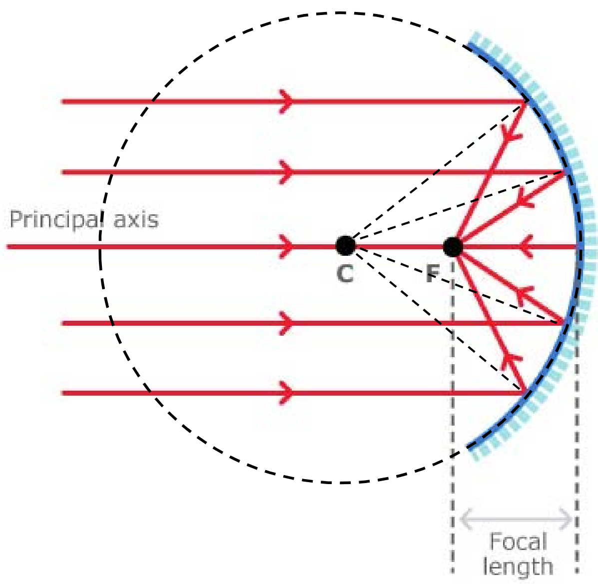


head) and reflect off of the mirror. The rays that originate from the arrow head are shown in red, (labeled A and B) and the reflected rays are shown in green (labeled (A’ and B’). The ray (A in red) that leaves the arrow head and hits the mirror at an angle of incidence of zero reflects directly back (ray A’ in green). Ray B (red) hits the mirror at an angle and is reflected at an angle of reflection that is equal to the angle of incidence (law of reflection); the reflected ray is labeled B’ (green). Notice that the reflected rays A’ and B’ do not converge, but diverge (spread apart after reflection). In this case, the image is found by extending the reflected rays back to find the point where they *appear* to come from. The point where they intersect is then the location of the image of the arrow head (shown in green). This type of image is called a **virtual image**, since no light rays actually exist at that location. Thus the image of an object in a plane mirror appears to be **behind** the mirror. Using simple geometric arguments we find that the (virtual) image is located at the same distance behind the mirror as the object distance (object to mirror distance). Also the height of the image is identical to the height of the object, and is upright. This is of course what we expect from a mirror – the image size is the same as the object size and is upright. The fact that the image appears to be behind the mirror (virtual image), is the reason for the common perception that mirrors tend to make rooms appear larger – you seem to be looking at something beyond the wall holding the mirror.

Although mirrors do not produce an inverted image, left and right are inverted. In the photo on the right, the word "Bold" is backwards in the mirror. The image of a right hand is a left hand. (see slide 16). Finally, slide 15 illustrates that you are able to see your entire body in a plane mirror that is only half your height.

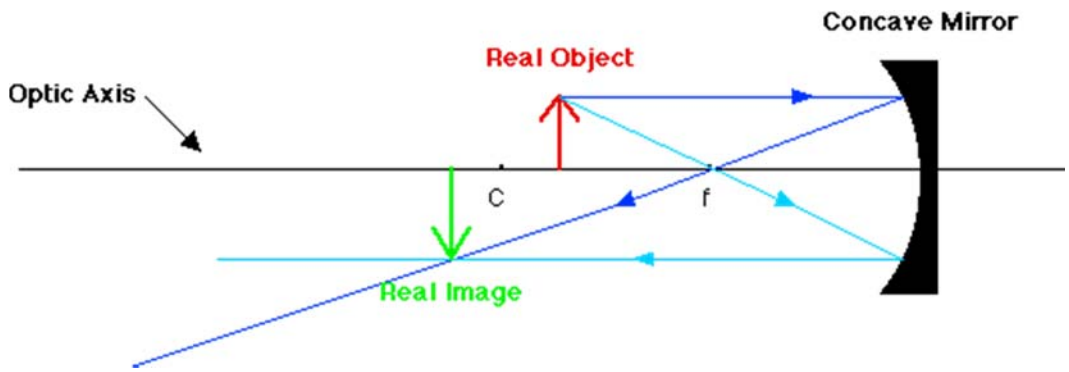
30-5. Image Formation by Curved Mirrors

a. Concave mirror.—A concave mirror is one that has the reflecting surface curved inward. The reflection of light rays from a concave mirror is simply the law of reflection, however there



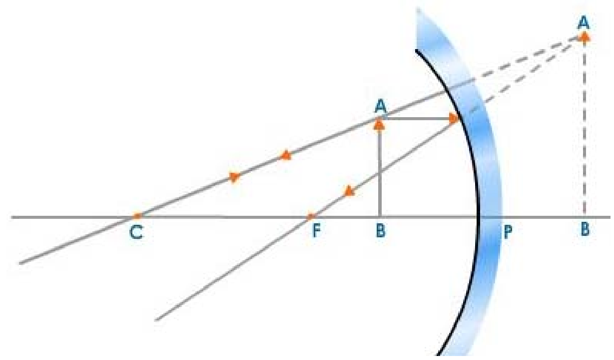
is a unique normal line for each point on the mirror. A concave mirror reflects all rays that are parallel to the axis of the mirror through a single point called the focus (F) as shown in the diagram below. A concave mirror is a portion of a full circle, as shown dashed. The normal line at any point on the mirror is just the radius of the circle to that particular point. The uppermost light ray is reflected so that the angle of reflection and incidence are equal at that point on the mirror. All rays reflect at an angle equal to the angle of incidence at that particular point on the mirror. A concave mirror is characterized by its focal length, which is the distance from the center of the mirror to the focus. The focal length is ½ of the radius of curvature of the mirror.

The diagram below illustrates the formation of a real image by a concave mirror. The object



(red arrow) is place beyond the focal point (f) of the mirror. The blue ray originating from the top of the object travels parallel to the optic axis and reflects through the focus. The light blue arrow also originates at the top of the object, passes through the focus and emerges parallel to the optic axis. The image of the top of the object is located where the blue and light blue arrows intersect. A ray originating at the bottom of the object and travelling along the optic axis is reflected directly back along the optic axis. Thus the image of the bottom of the object is located along the optic axis. The image is then located at the intersection of the two rays originating from the top of the object and the optic axis. Since light rays actually do converge at the image location, this is called a real image. Note that the image is inverted (upside-down) and slightly larger than the object. The image can be seen if an opaque screen placed at the image location. The height of the image depends on where the object is placed. If the object is located at a distance of twice the focal distance, the image will also be at that location but inverted. (see slide 19).

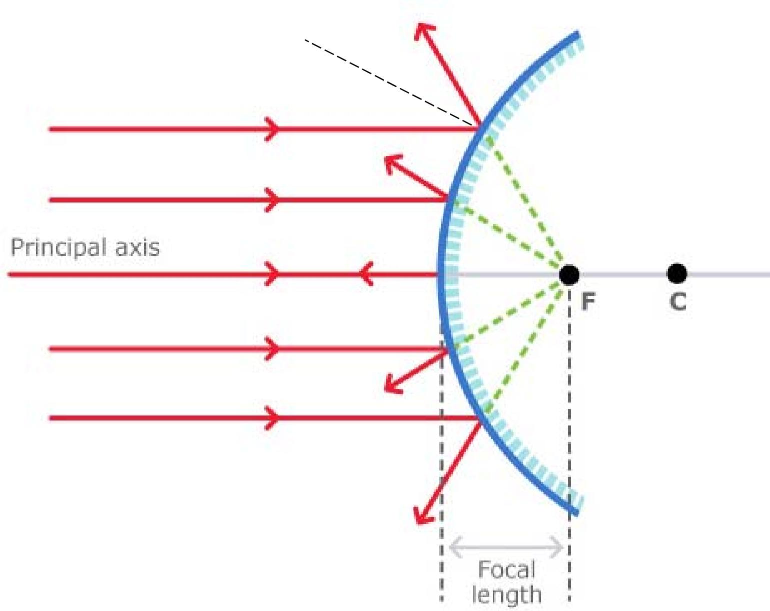
A concave mirror is also capable of producing virtual images, depending on where the object is located. A magnifying mirror operates on this principle as shown in the diagram below The



object (AB) is placed close to the mirror (between the mirror and the focus). Two rays originating from the top of the object are shown reflecting from the mirror. Note that these rays are diverging after reflection, but if they are extrapolated back, they appear to come from point A behind the mirror. Point B on the object reflects straight back and appears to come from point B behind the mirror. A virtual image AB (dashed) appears behind the mirror. Note that the image is upright (not inverted) and larger than the object, as one expects from a magnifying mirror.

Because of their ability to take parallel rays and focus them to a point, concave mirrors are used as satellite dishes. These dish antennas reflect electromagnetic signals from a distant satellite and focus them onto a detector located at the focal point of the concave mirror. Since the electromagnetic waves involved in this process have much longer wavelengths than visible light, it is not necessary to have a polished surface, in fact the antenna can even be made from a mesh.

b. Convex mirror.—A concave mirror has its reflecting surface curved outward. The diagram below shows the reflection of several light rays that travel parallel to the axis of the mirror. Due to the outward curvature of the mirror, the rays are reflected away from the optic axis at an angle consistent with the law of reflection at that particular point on the mirror. For the convex mirror, the reflected rays appear to originate from a focal point (F) behind the mirror.



The formation of a virtual image by a convex mirror is shown below. Since the rays that reflect off of a convex mirror are diverging, a convex mirror produces only virtual images. Note that the

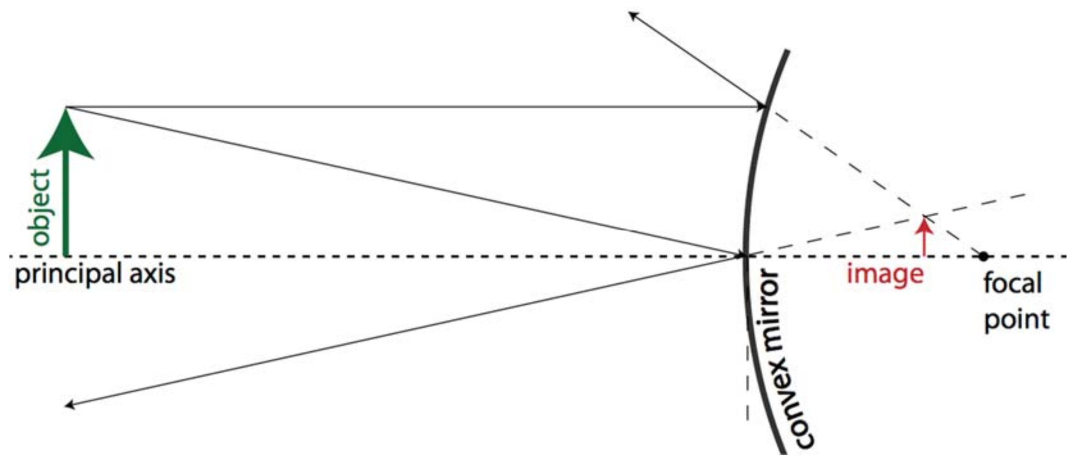


image is smaller than the object and upright. Convex mirrors are used to provide wide angle views of a large area. This type of mirror is used in a store like Walmart or Target so that the employees can monitor a large area of the store. The large angle view comes at the expense of the size of the images which it produces --- more area is observed, but everything is a bit smaller in the image. Convex mirrors are also used as the passenger side car mirror to provide a wide angle view. Since the images seen are smaller than the objects, our brain tells us that they are far away; hence a warning to this effect is posted on the right side mirrors of autos.