Optics: reflection, refraction and lenses

Chapter 8

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electromagnetic waves and light

Electromagnetic waves are transverse waves with electric and magnetic field components, which oscillate in phase perpendicular to each other and to the direction of wave propagation.
Unlike a wave on a string or a sound wave, electromagnetic waves do not require a medium in which to propagate.
Electromagnetic waves can travel through a vacuum or through substances (depending on the absorption properties of the substance).

All electromagnetic waves move through a vacuum at the same speed: the symbol c is used to denote its value.

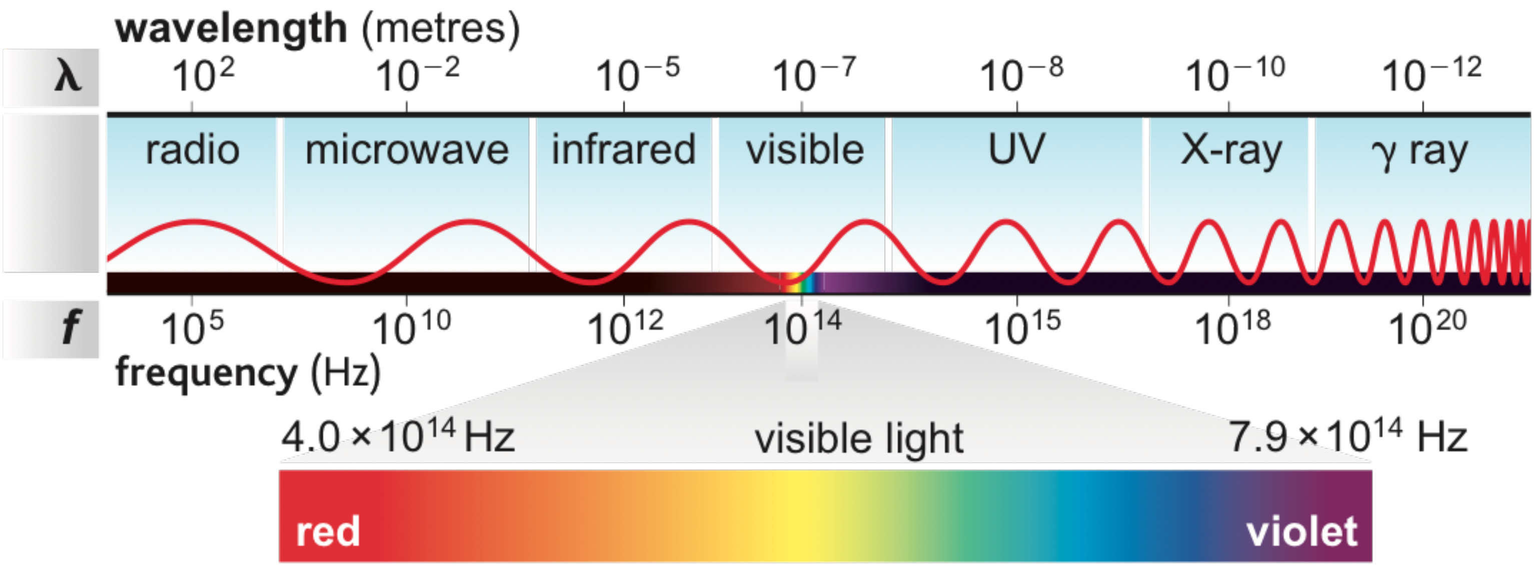
c = 299,792,458 m/s

J.C.Maxwell developed a theory for electromagnetic waves that also accurately described the propagation of light and inferred that light is an elecrtromagnetic wave.

An electromagnetic wave, like any periodic wave, has a frequency f and a wavelength λ that are related to the speed v of the wave by $v = f\lambda$:
therefore if $v = c \rightarrow c = f\lambda$

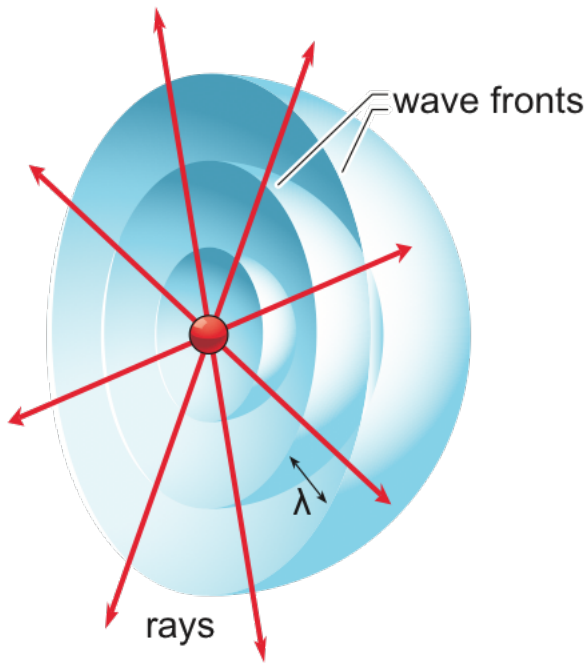
the electromagnetic spectrum

The electromagnetic spectrum is the range of all possible frequencies or wavelengths of electromagnetic radiation. One direction along the spectrum represents increasing energy and frequency and decreasing wavelength and the other direction decreasing energy and frequency and increasing wavelength.



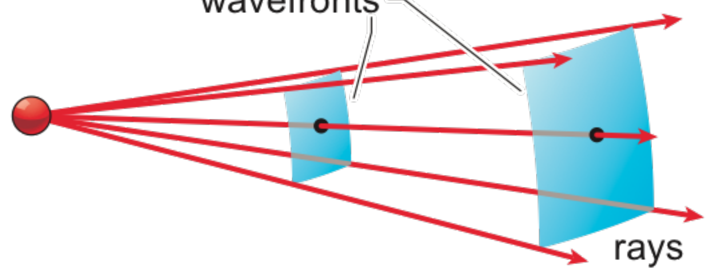
The visible spectrum: only waves with frequencies between about 4.0×10^{14} Hz and 7.9×10^{14} Hz (390 to 750 nm) are perceived by the human eye as visible light.

wavefronts and rays



Consider a point source that emits light in all directions. To graphically represent a wave from the source, a spherical surface is drawn through all points on the wave that are in phase (in step with one another).
This surface of constant phase is called a **wavefront**.

The radial lines pointing outward from the source and perpendicular to the wavefronts are called **rays**. Rays correspond to the direction of flow of radiant energy.

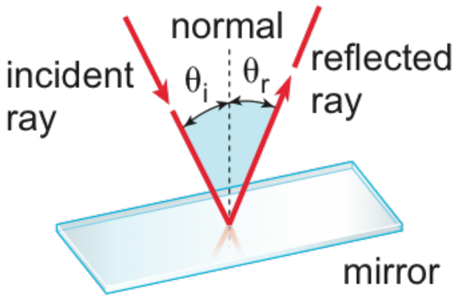


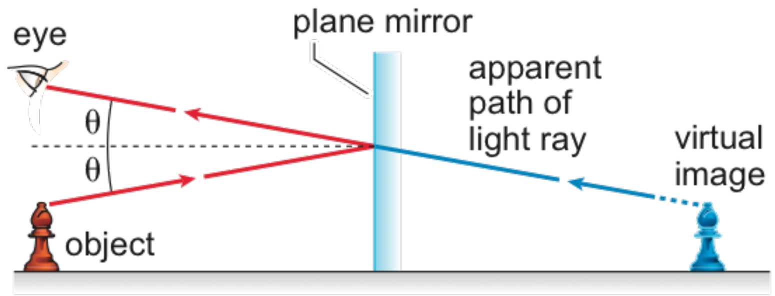
reflection of light

Law of Reflection

The angle of incidence θ_i equals the angle of reflection θ_r, and the incident ray, reflected ray, and normal to the surface all lie in the same plane.

$$\theta_i = \theta_r$$





θ_i is the angle between
the incident ray
and the normal.
θ_r is the angle between
the reflected ray
and the normal.

A ray of light from the top of the chess piece reflects from the mirror. To the eye, the ray seems to come from behind the mirror. The bundle of rays from the top of the object appears to originate from the image behind the mirror, which appears reversed, left to right.

refractive index

The refractive index n of an optical medium is the ratio of the speed c of light in a vacuum to the speed c_m of light in the medium:

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the material}} = \frac{c}{c_m}$$

medium	refractive index
glass, crown	1.523
diamond	2.419
ice (0 °C)	1.309
water (20 °C)	1.333
air (0 °C, 1 atm)	1.000293
oxygen, O_2 (0 °C, 1 atm)	1.000271
hydrogen, H_2 (0 °C, 1 atm)	1.000139

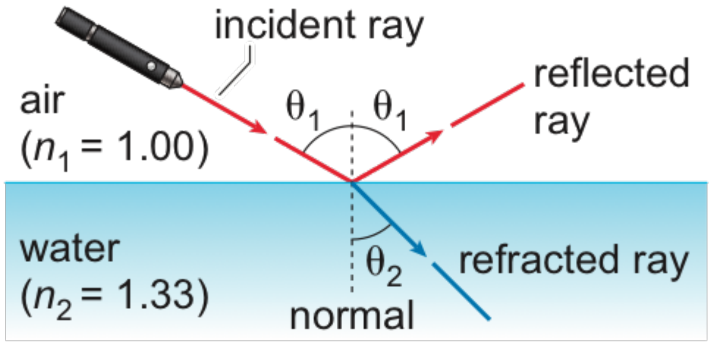
Light travels through an optical medium with a lower speed than c, as atoms in the medium absorb, reemit, and scatter the light. For example, the refractive index for diamond is n = 2.419, so the speed of ligth in diamond = c/n

$$c_{\text{diam}} = \frac{c}{n} = \frac{3.00\times10^{8}\ \text{m/s}}{2.419} =$$
$$= 1.24\times10^{8}\ \text{m/s}$$

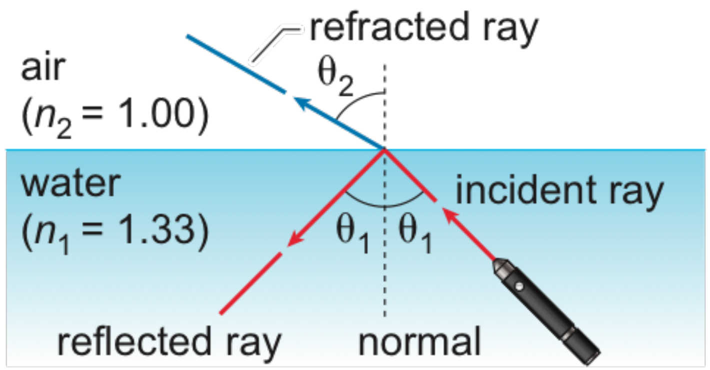
Snell's law and the refraction of light

For light that travels from a medium with refractive index n_1 into a medium with refractive index n_2 – the incident ray, refracted ray, and normal to the interface between the materials all lie in the same plane – the angle of incidence θ_1 is related to the angle of refraction θ_2 by:

$$n_1 \sin\theta_i = n_2 \sin\theta_2$$



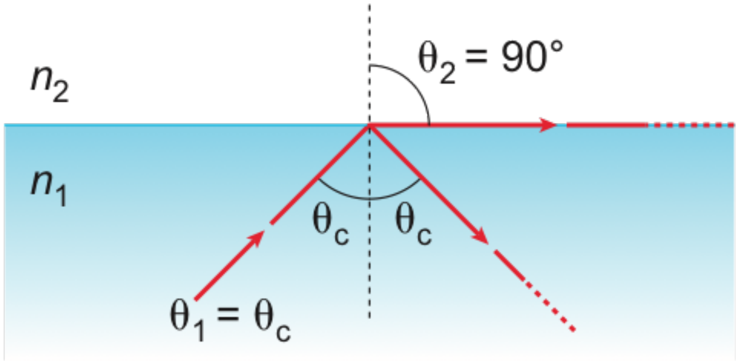
When a ray of light is directed from air into water, part of the light is reflected at the interface and the remainder is refracted into the water, towards the normal.

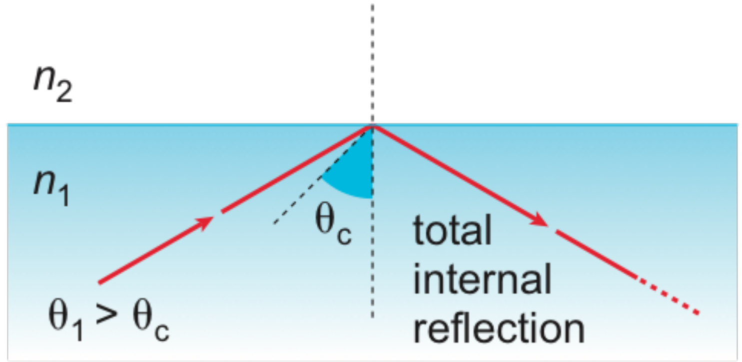


When a ray of light is directed from water into air, the ray that passes into the air is refracted away from the normal.

total internal reflection

When the angle of incidence reaches a certain value, called the critical angle q_c, the angle of refraction is 90° and the refracted ray points along the interface between the media. Total internal reflection occurs when the angle of incidence is greater than the critical angle.





An expression for the critical angle θ_c can be obtained from Snell's law by setting $\theta_1 = \theta_c$ and $\theta_2 = 90°$:

$$\sin\theta_c = \frac{n_2 \sin 90°}{n_1} = \frac{n_2}{n_1}$$

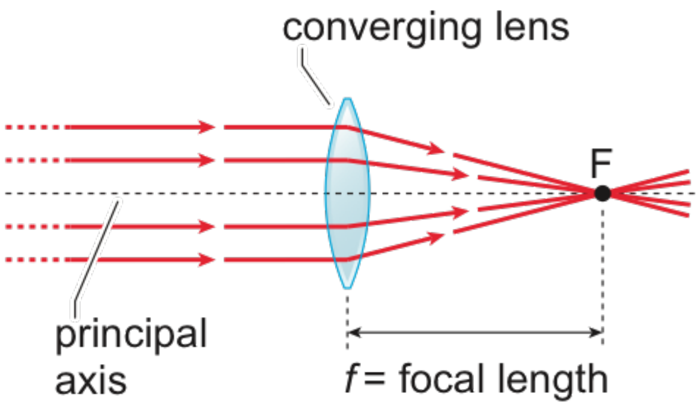
$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad n_1 > n_2$$

For instance, the critical angle for light travelling from water (n_1 = 1.33) to air (n_2= 1.00) is

$$\theta_c = \sin^{-1}\left(\frac{1.00}{1.33}\right) = 48.75°$$

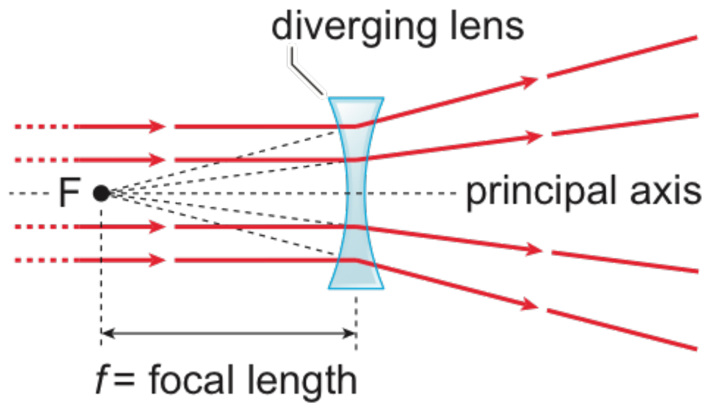
lenses

Lenses are objects made of transparent materials that refract light in such a way that an image of the light source or illuminated object is formed.



Converging lens

Rays that are parallel to the principal axis (paraxial rays) converge to a single point called the **focal point *F***.

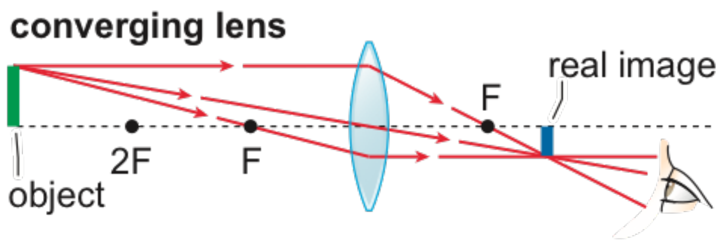


Diverging lens

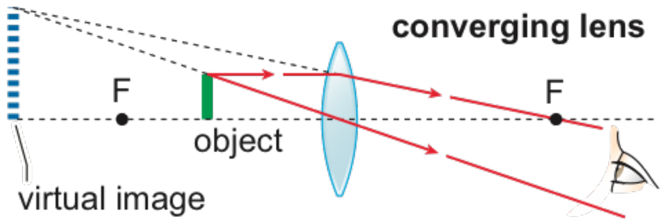
Rays that are parallel to the principal axis (paraxial rays) appear to originate from the virtual **focal point *F*** after passing through the lens.

The distance between the focal point and the centre of the lens is the **focal length *f***.

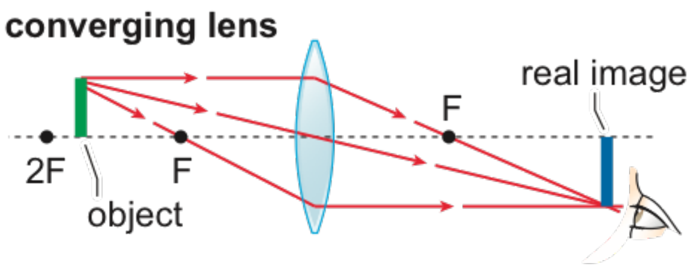
image formation from lenses



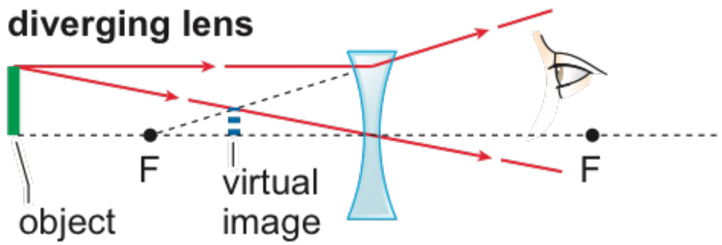
An object placed to the left of the point labelled 2*F* (2 times the focal length), results in a real image that is inverted, and diminished with respect to the object.



An object placed within the focal length *F* of a converging lens results in a virtual image that is upright and magnified with respect to the object.



An object placed between 2*F* and *F*, results in a real image that is inverted, and magnified with respect to the object.



A diverging lens always forms a virtual image of a real object. The image is upright and diminished with respect to the object.

learning the basics

1. Light can travel through a vacuum or any medium. T F

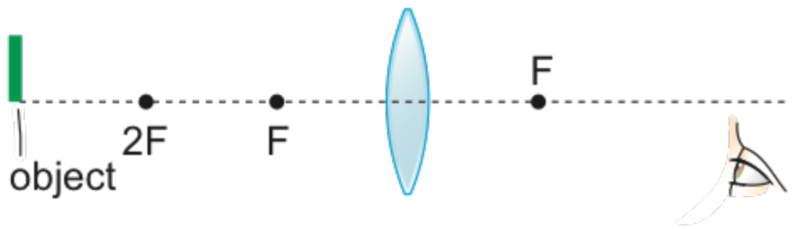
2. The speed of light is always *c* when it travels within an optical medium. T F

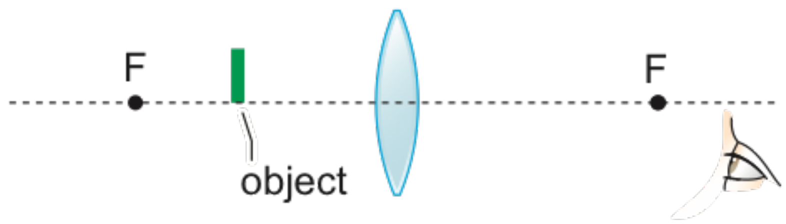
3. When a ray travels into an optical medium with a different refractive index, its trajectory does not change. T F

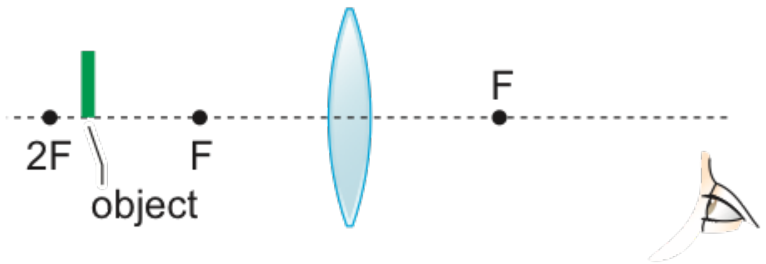
4. A converging lens can be used to produce a magnified image. T F

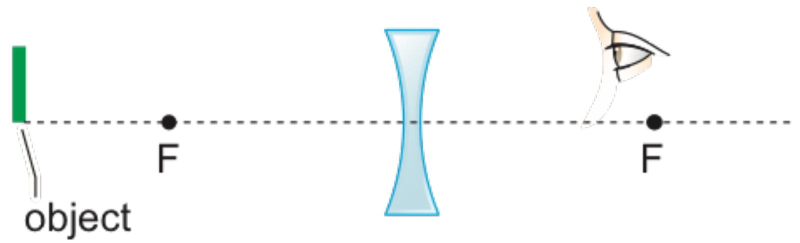
applying the concepts

1. Draw the rays from the object to show the images formed by the lenses.



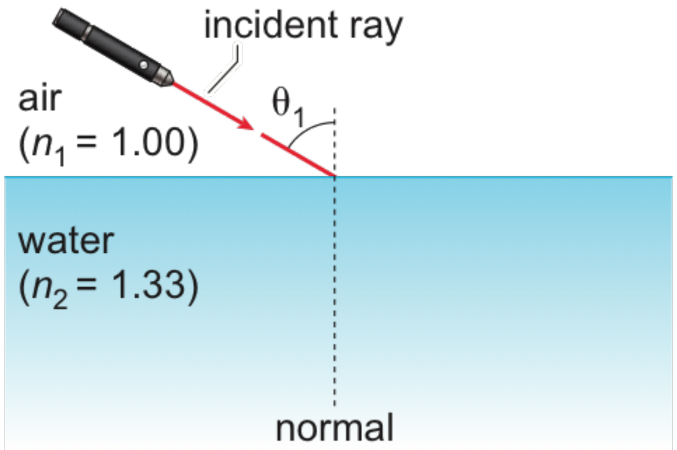


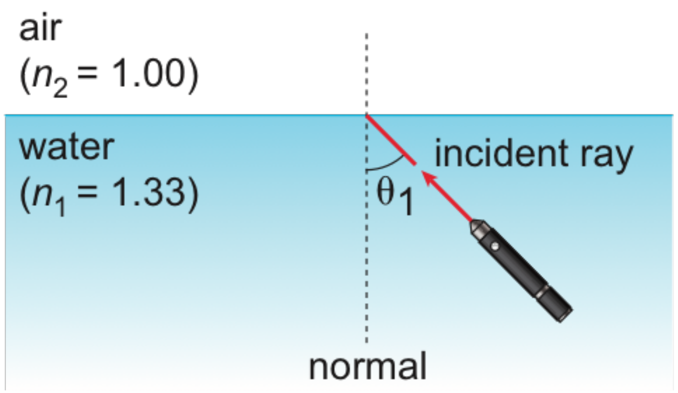




applying the concepts

2. Draw the reflected (θ_{reflet}) and refracted ($\theta_{refract}$) rays with their corresponding angles. For each diagram, mark the correct relationships between the angles with a cross.





$\theta_1 = \theta_{reflect}$	$\theta_1 = \theta_{refract}$	$\theta_1 = \theta_{reflect}$	$\theta_1 = \theta_{refract}$
$\theta_{reflect} > \theta_{refract}$	$\theta_{reflect} < \theta_{refract}$	$\theta_{reflect} > \theta_{refract}$	$\theta_{reflect} < \theta_{refract}$