Applied Physics for Engineers

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Electromagnetic waves, Geometrical optics, Reflection and Refraction of Light, Total Internal Reflection

Maxwell’s Equations and Electromagnetic Waves

Introduction

- In previous chapters we have learned that when the fields don't vary with time, such as an electric field produced by charges at rest or the magnetic field of a steady current, we can analyze the electric and magnetic fields independently without considering interactions between them. But when the fields vary with time, they are no longer independent.
- Faraday's law tells us that a time-varying magnetic field acts as a source of electric field, as shown by induced emfs in inductors and transformers.
- Ampere's law, including the displacement current discovered by Maxwell, shows that a time-varying electric field acts as a source of magnetic field. This mutual interaction between the two fields is summarized in Maxwell's equations.
- Thus, when either an electric or a magnetic field is changing with time, a field of the other kind is induced in adjacent regions of space. We are led (as Maxwell was) to consider the possibility of an electromagnetic disturbance, consisting of time-varying electric and magnetic fields, that can propagate through space from one region to another, even when there is no matter in the intervening region

Maxwell's Equations and Electromagnetic Waves

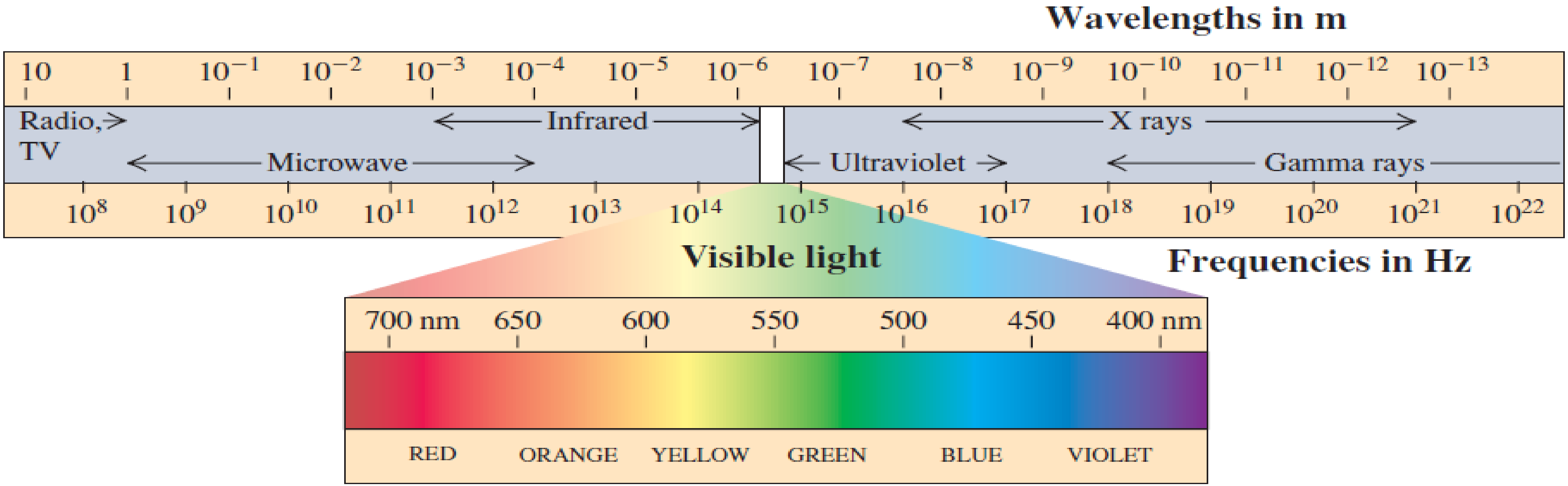
- Maxwell in 1865 proved that an electromagnetic disturbance should propagate in free space with a speed equal to that of light and hence that light waves were likely to be electromagnetic in nature. At the same time, he discovered that the basic principles of electromagnetism can be expressed in terms of the four equations that we now call **Maxwell's equations**
- These equations apply to electric and magnetic fields in *vacuum*.

Name	Equation	
Gauss' law for electricity	$\oint \vec{E} \cdot d\vec{A} = q_{enc}/\varepsilon_0$	Relates net electric flux to net enclosed electric charge
Gauss' law for magnetism	$\oint \vec{B} \cdot d\vec{A} = 0$	Relates net magnetic flux to net enclosed magnetic charge
Faraday's law	$\oint \vec{E} \cdot d\vec{s} = -\dfrac{d\Phi_B}{dt}$	Relates induced electric field to changing magnetic flux
Ampere–Maxwell law	$\oint \vec{B} \cdot d\vec{s} = \mu_0\varepsilon_0 \dfrac{d\Phi_E}{dt} + \mu_0 i_{enc}$	Relates induced magnetic field to changing electric flux and to current

- According to Maxwell's equations, a point charge at rest produces a static **E** field but no **B** field; a point charge moving with a constant velocity produces both **E** and **B** fields. Maxwell's equations can also be used to show that in order for a point charge to produce electromagnetic waves, the charge must accelerate.
- In fact, it's a general result of Maxwell's equations that *every* accelerated charge radiates electromagnetic energy

The Electromagnetic Spectrum

- The **electromagnetic spectrum** encompasses electromagnetic waves of all frequencies and wavelengths.
- Figure shows approximate wavelength and frequency ranges for the most commonly encountered portion of the spectrum. Despite vast differences in their uses and means of production, these are all electromagnetic waves with the same propagation speed (in vacuum).
- Electromagnetic waves may differ in frequency and wavelength but the relationship in vacuum holds for each.



Optics

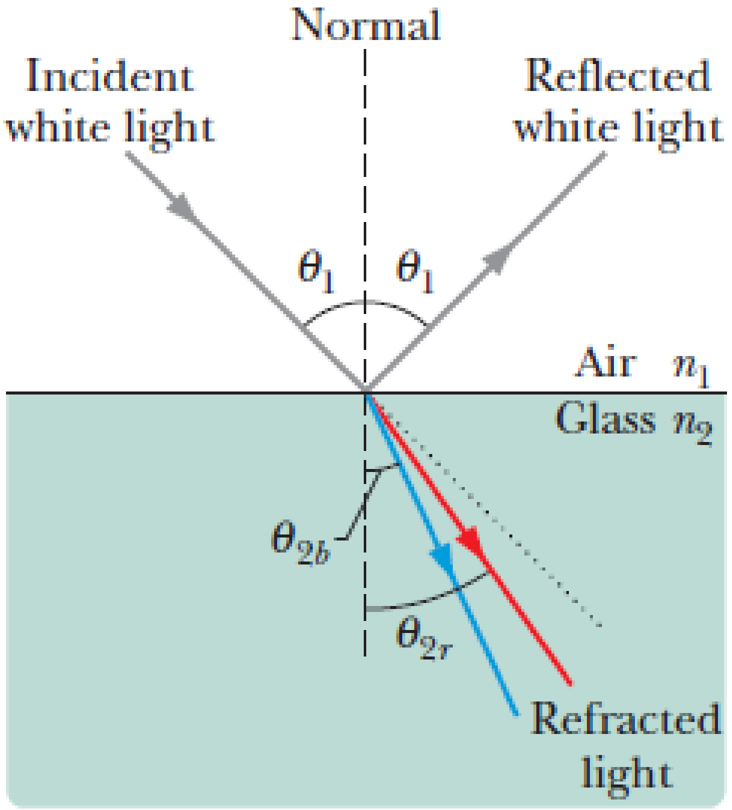
Geometrical optics

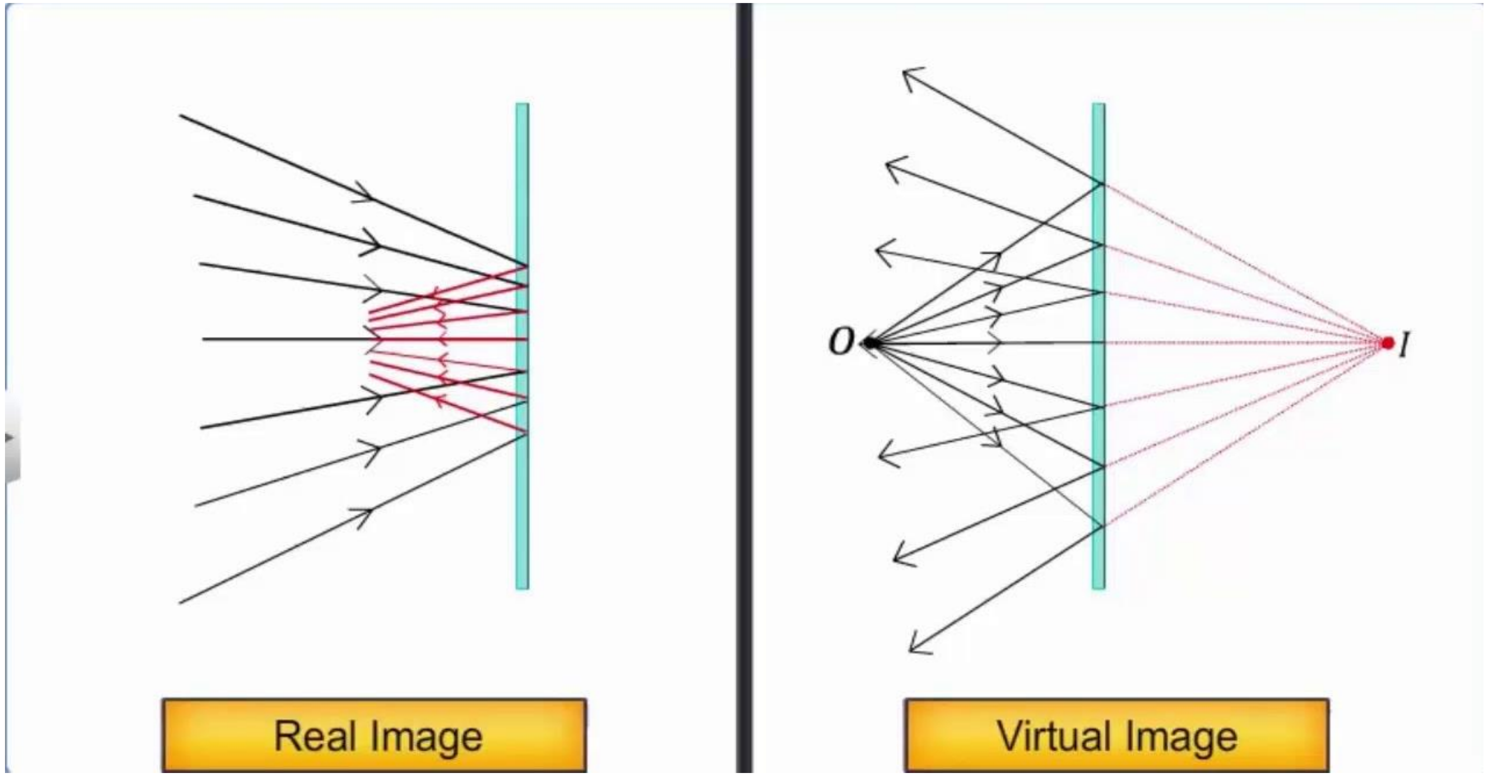
A ray is an imaginary line along the direction of travel of the wave

Although a light wave spreads as it moves away from its source, we can often approximate its travel as being in a straight line, called ray.

The study of the properties of light waves under that approximation is

called ***geometrical optics***


Normal
Incident
white light
Reflected
white light
θ_1
θ_1
Air n_1
Glass n_2
θ_{2b}
θ_{2r}
Refracted
light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Reflection and Refraction of Light

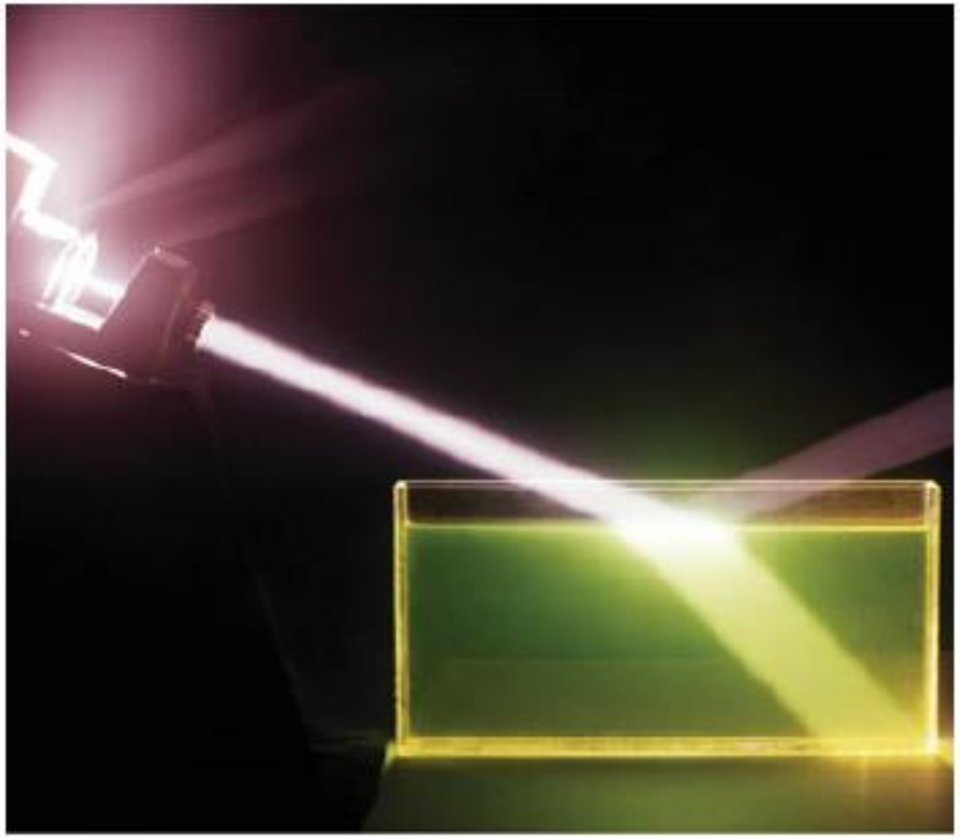
When a light wave strikes a smooth interface separating two transparent materials (such as air and glass or water and glass), a part of it turns back in the same medium and the rest of the light travels through the surface and into the other medium.

*The phenomenon in which the part of light bounces back is called **reflection.***

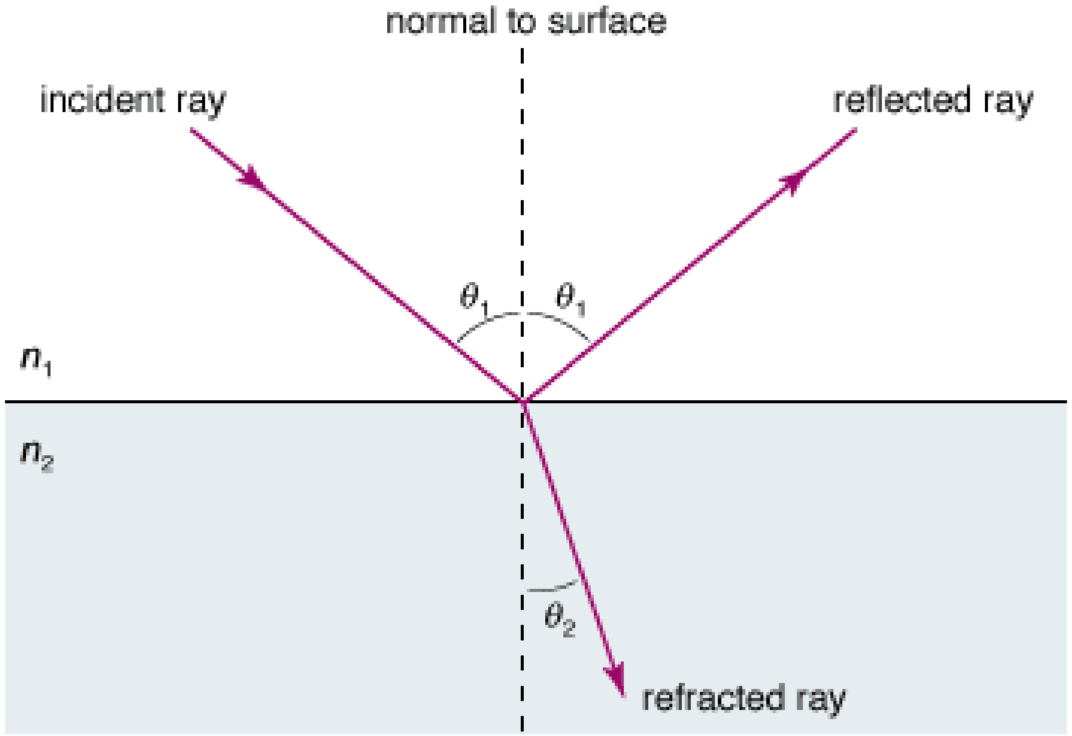
And

*The phenomenon in which the rest of the light travels through (or transmitted) the other medium is called **refraction.***

(a)



(b)

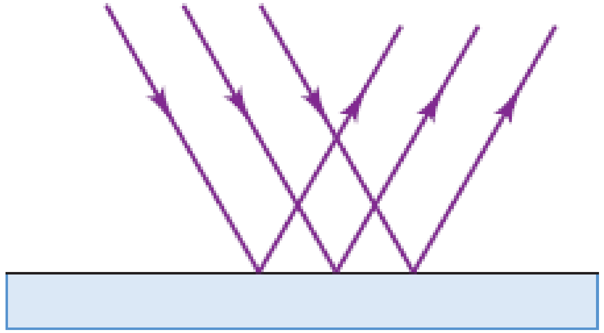

normal to surface
incident ray
reflected ray
θ_1
θ_1
n_1
n_2
θ_2
refracted ray

Types of reflection

Specular Reflection

- Reflection at a definite angle from a very smooth surface
- Reflection at a definite angle

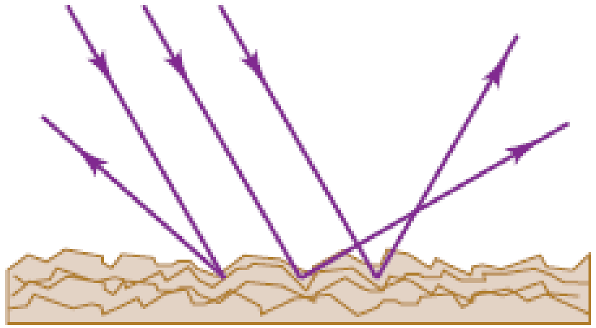
(a) Specular reflection



Diffuse reflection

- Scattered reflection from a rough surface
- No single angle of reflection

(b) Diffuse reflection

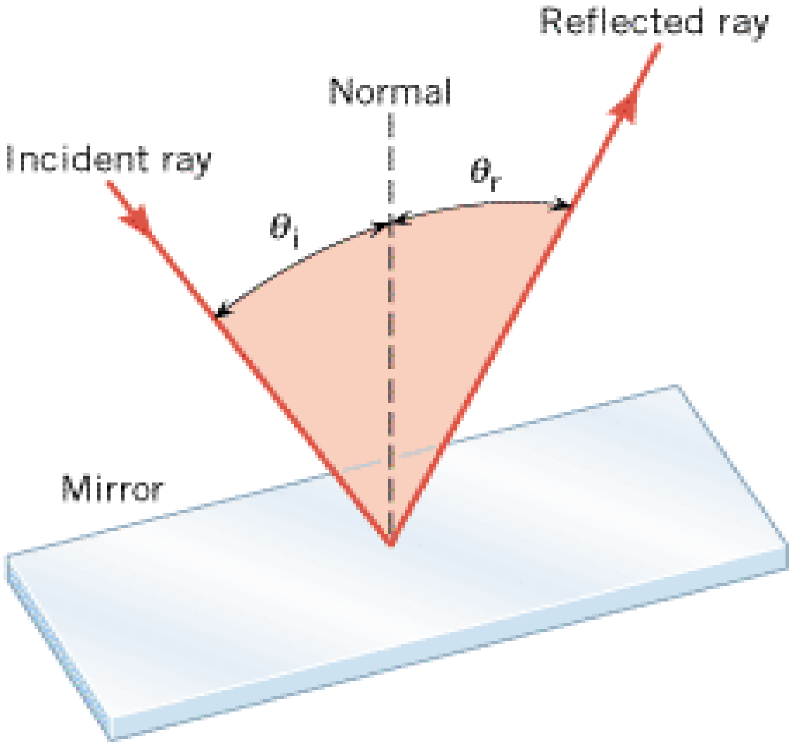


Laws of Reflection and Refraction

Experiment shows that reflection and refraction are governed by two laws:

Law of Reflection

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



Law of Refraction or Snell's law

A refracted ray lies in the plane of incidence and has an angle of refraction θ_2 that is related to the angle of incidence θ_1 by

$$n_2 \sin \theta_2 = n_1 \sin \theta_1 \quad \text{(refraction)}$$

Where the symbols n_1 and n_2 is a dimensionless constant, called the index of refraction, that is associated with a medium involved in the refraction

$$n_i = \frac{c}{v_i}$$

where v is the speed of light in that medium and c is its speed in vacuum.

- Nothing has index of refraction less than 1.

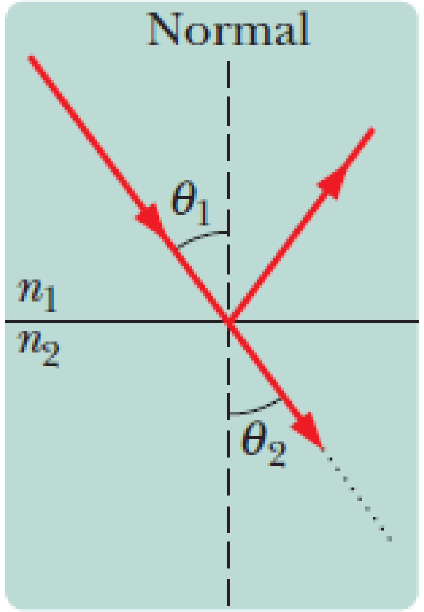
We can rearrange the above equation as

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1$$

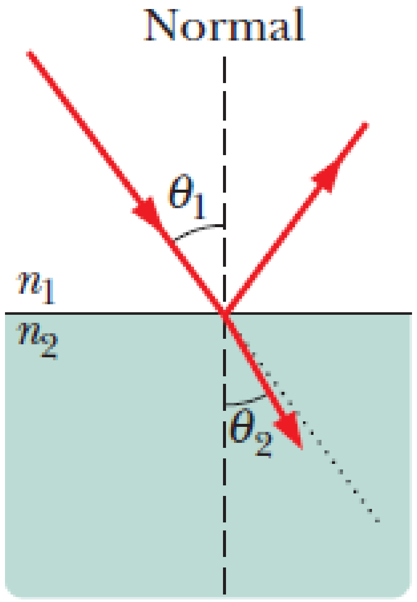
To compare the angle of refraction θ_2 with the angle of incidence θ_1. We can then see that the relative value of θ_2 depends on the relative values of n_2 and n_1

1. If n_2 is equal to n_1, then θ_2 is equal to θ_1 and refraction does not bend the light beam, which continues in the *undeflected direction as in figure (a)*

2. If n_2 is greater than n_1, then θ_2 is less than θ_1. In this case, refraction bends the light beam away from the undeflected direction and toward the normal

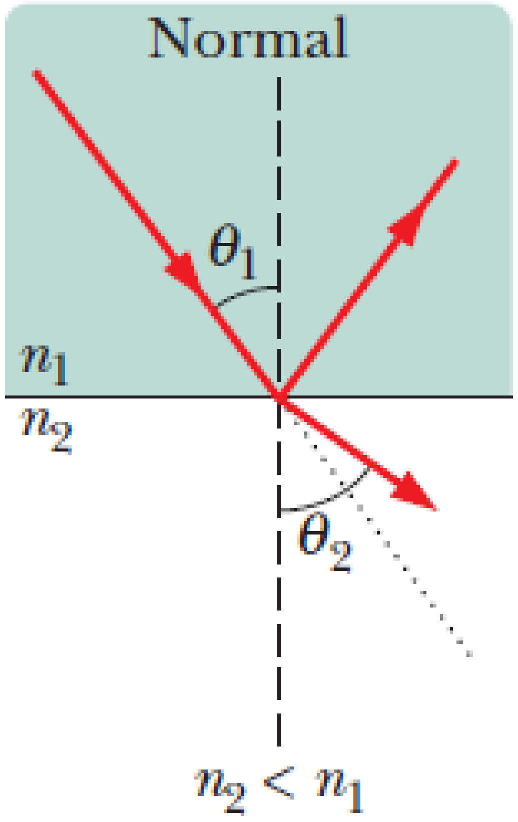


$n_2 = n_1$

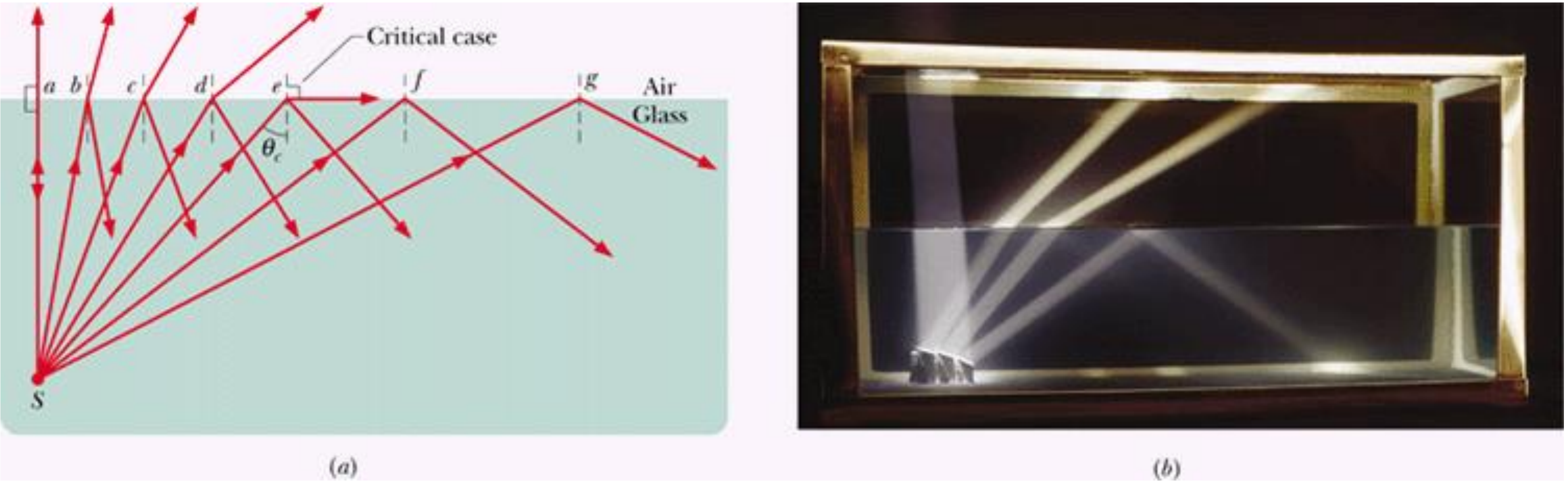


$n_2 > n_1$

3. If n_2 is less than n_1, then θ_2 is greater than θ_1. In this case, refraction bends the light beam away from the undeflected direction and away from the normal, as in Figure (c)



Total Internal Reflection



$$n_1 \sin \theta_c = n_2 \sin 90^\circ.$$

$$\theta_c = \sin^{-1} \frac{n_2}{n_1} \quad \text{(critical angle).}$$

Because the sine of an angle cannot exceed unity, n_2 cannot exceed $n1$ in this equation. This restriction tells us that total internal reflection cannot occur when the incident light is in the medium of lower index of refraction.