OPTICS

Reflection and Refraction

Chapter 33

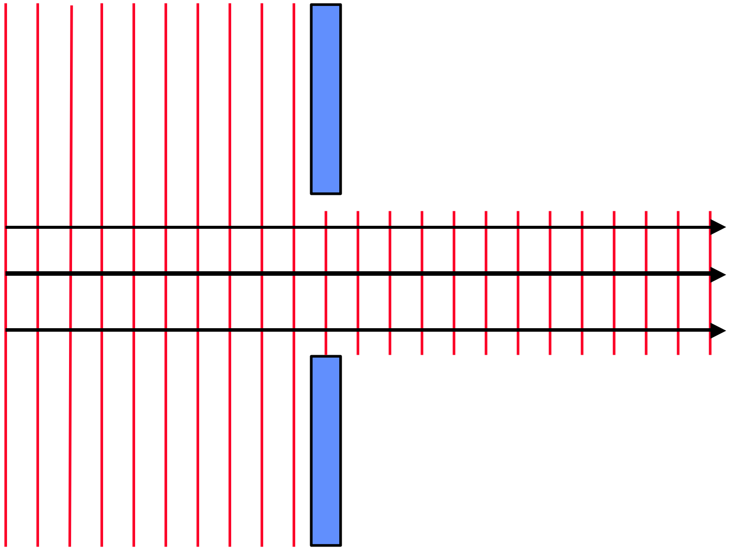
Geometrical Optics

- Optics is the study of the behavior of light (not necessarily visible light).
- This behavior can be described by Maxwell's equations.
- However, when the objects with which light interacts are larger that its wavelength, the light travels in straight lines called rays, and its wave nature can be ignored.
- This is the realm of geometrical optics.
- The wave properties of light show up in phenomena such as interference and diffraction.

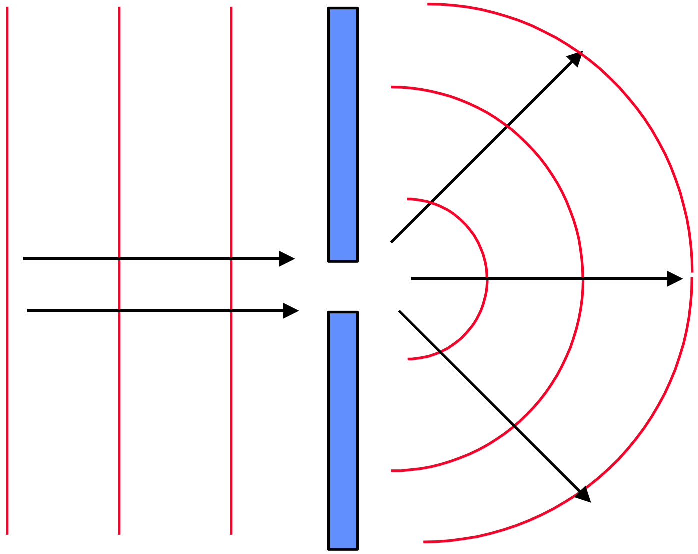
Geometrical Optics

Light can be described using geometrical optics, as long as the objects with which it interacts, are much larger than the wavelength of the light.

This can be described using geometrical optics



This requires the use of full wave optics (Maxwell's equations)



Reflection and Transmission

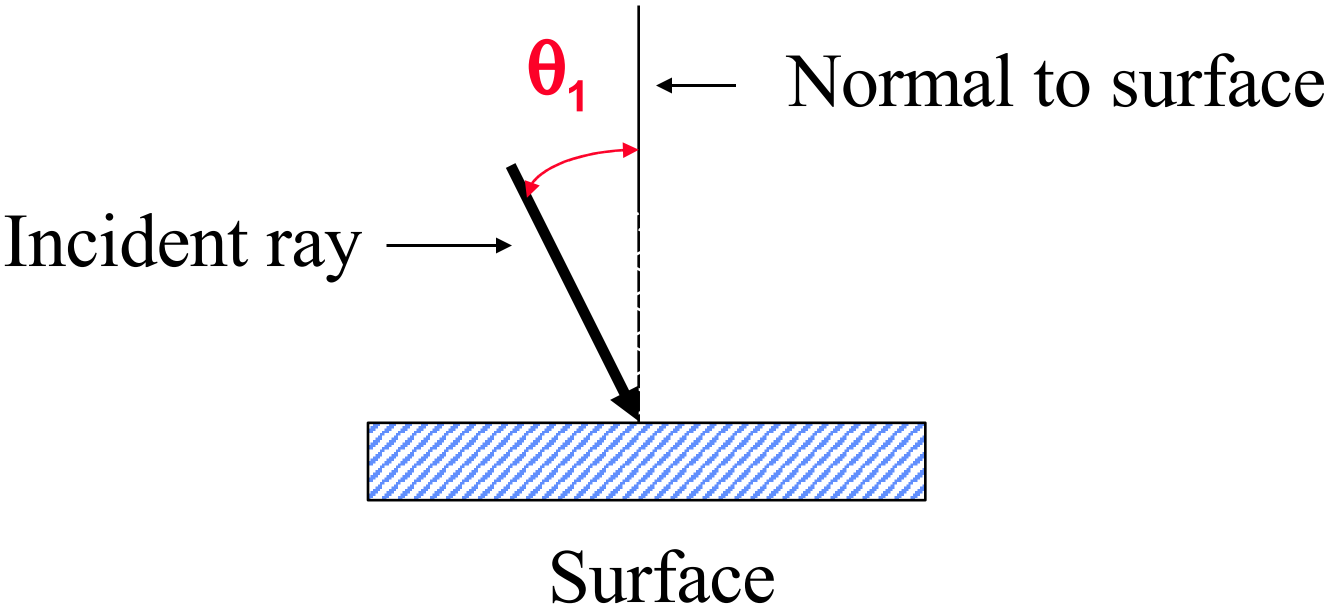
Some materials reflect light. For example, metals reflect light because an incident oscillating light beam causes the metal's nearly free electrons to oscillate, setting up another (reflected) electromagnetic wave.

Opaque materials absorb light (by, say, moving electrons into higher atomic orbitals).

Transparent materials are usually insulators whose electrons are bound to atoms, and which would require more energy to move to higher orbitals than in materials which are opaque.

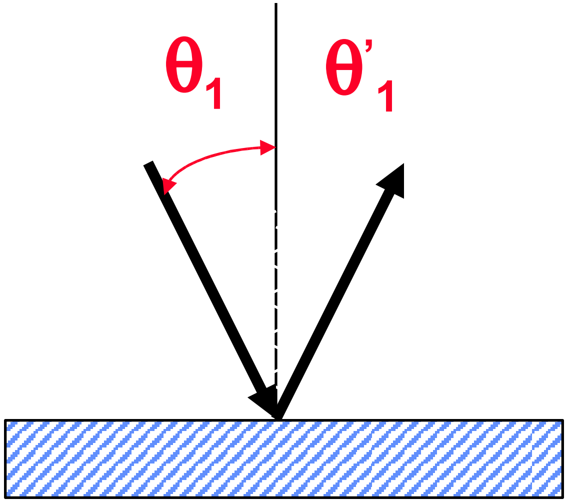
Geometrical Optics

θ_1 = angle of incidence



Angles are measured with respect to the normal to the surface

Reflection



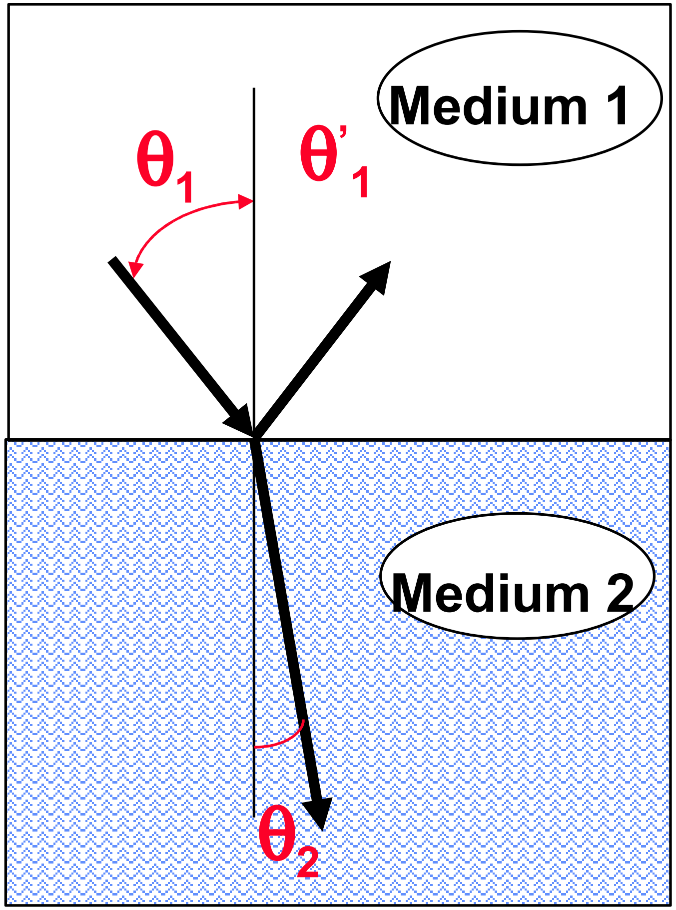
$$\theta_1 = \theta'_1$$

This is called
“specular” reflection

The Law of Reflection:

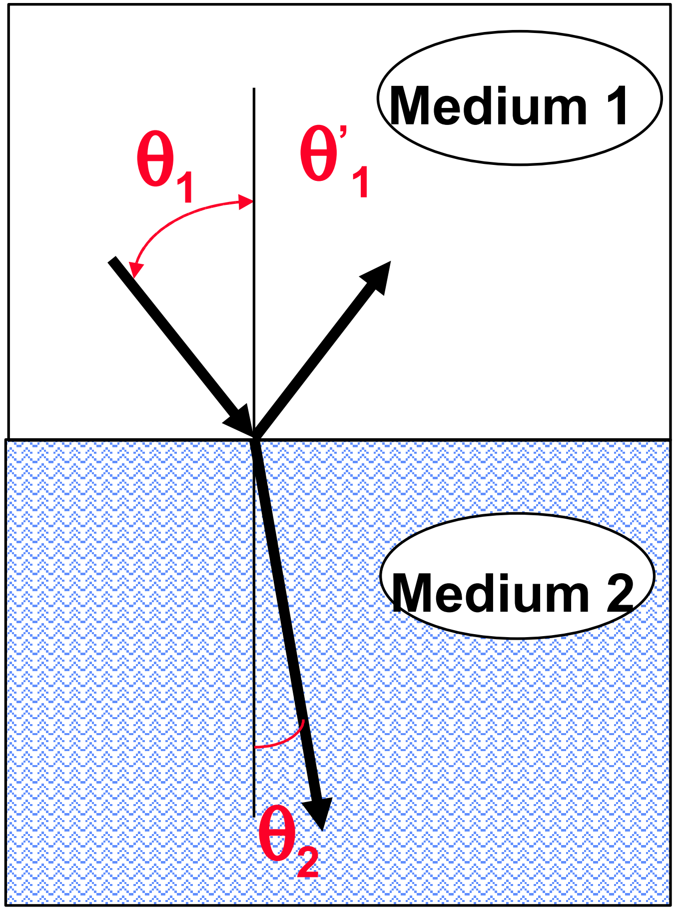
Light reflected from a surface stays in the plane formed by the incident ray and the surface normal; and the angle of reflection equals the angle of incidence (measured to the normal)

Refraction



More generally, when light passes from one transparent medium to another, part is reflected and part is transmitted. The reflected ray obeys $\theta_1 = \theta'_1$.

Refraction



More generally, when light passes from one transparent medium to another, part is reflected and part is transmitted. The reflected ray obeys $\theta_1 = \theta'_1$.

The transmitted ray obeys

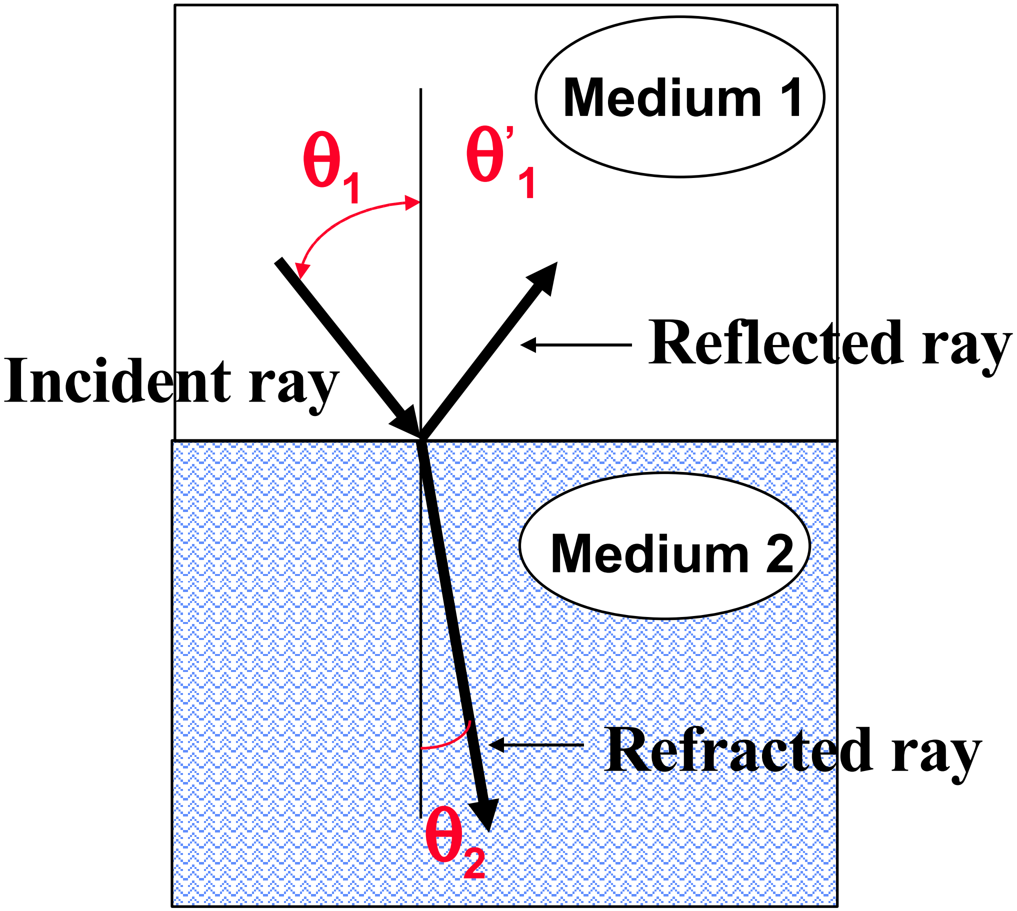
Snell's Law of Refraction:

It stays in the plane, and the angles are related by

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Here n is the "index of refraction" of a medium.

Refraction



θ_1 = angle of incidence

θ'_1 = angle of reflection

θ_2 = angle of refraction

Law of Reflection

$\theta_1 = \theta'_1$

Law of Refraction

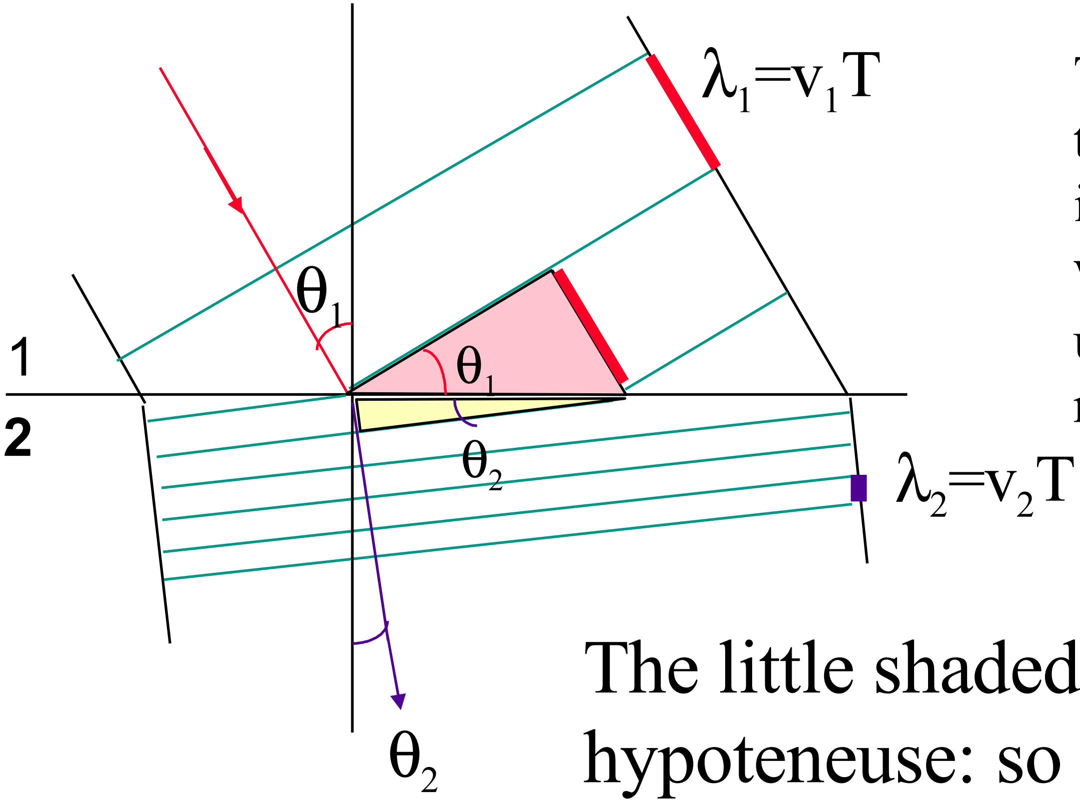
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$n \equiv$ index of refraction

$n_i = c / v_i$

v_i = velocity of light in medium i

Refraction



The period T doesn’t change, but the speed of light can be different. in different materials. Then the wavelengths λ_1 and λ_2 are unequal. This also gives rise to refraction.

The little shaded triangles have the same hypoteneuse: so $\lambda_1/\sin\theta_1 = \lambda_2/\sin\theta_2$, or

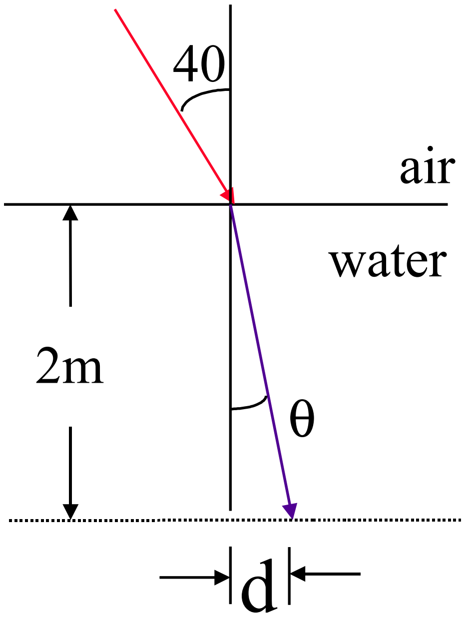
$$v_1/\sin\theta_1 = v_2/\sin\theta_2$$

Define the index of refraction: $n=c/v$.
Then Snell’s law is: $n_1\sin\theta_1 = n_2\sin\theta_2$

Example: air-water interface

If you shine a light at an incident angle of 40^o onto the surface of a pool 2m deep, where does the beam hit the bottom?

Air: n=1.00 Water: n=1.33



Example: air-water interface

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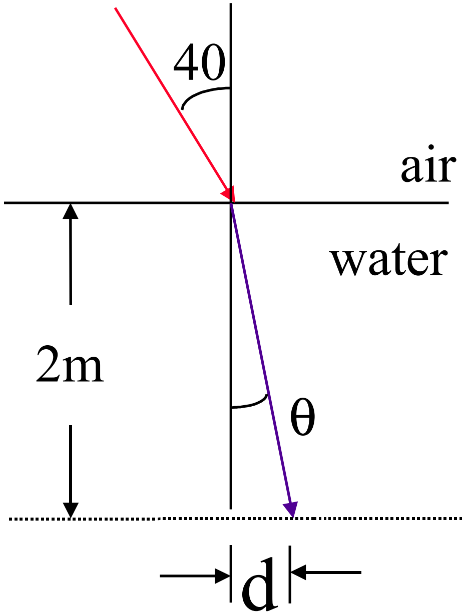


Air: n=1.00 Water: n=1.33

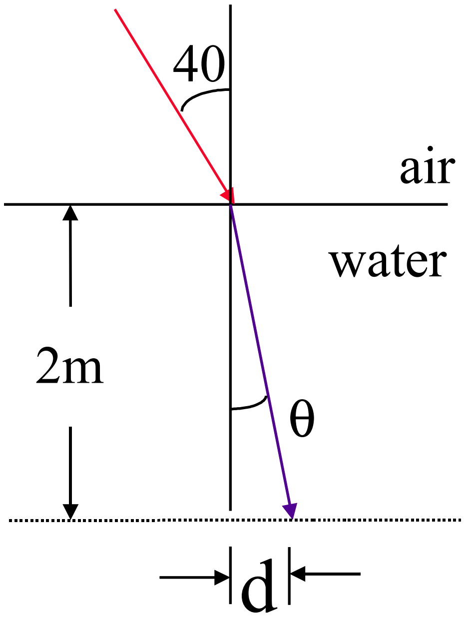
$(1.00)\sin 40 = (1.33)\sin\theta$

$\sin\theta=\sin 40/1.33$ so $\theta=28.9^{o}$

Then $d/2=\tan 28.9^{o}$ which gives $d=1.1$ m.

Example: air-water interface

If you shine a light at an incident angle of 40° onto the surface of a pool 2m deep, where does the beam hit the bottom?



Air: n=1.00 Water: n=1.33

$(1.00)\ \sin(40) = (1.33)\ \sin\theta$

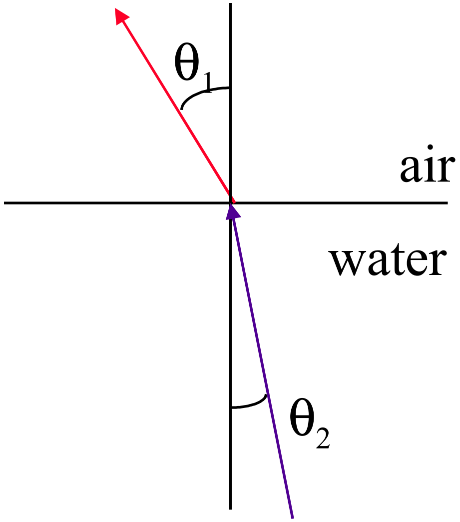
$\sin\theta = \sin(40)/1.33$ so $\theta = 28.9^{\circ}$

Then $d/2 = \tan(28.9^{\circ})$

which gives $\Rightarrow$ d=1.1 m.

Turn this around: if you shine a light from the bottom at this position it will look like it's coming from further right.

Air-water interface



Air: $n_1 = 1.00$ Water: $n_2 = 1.33$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n_1/n_2 = \sin\theta_2 / \sin\theta_1$$

When the light travels from air to water ($n_1 < n_2$) the ray is bent towards the normal.

When the light travels from water to air ($n_2 > n_1$) the ray is bent away from the normal.

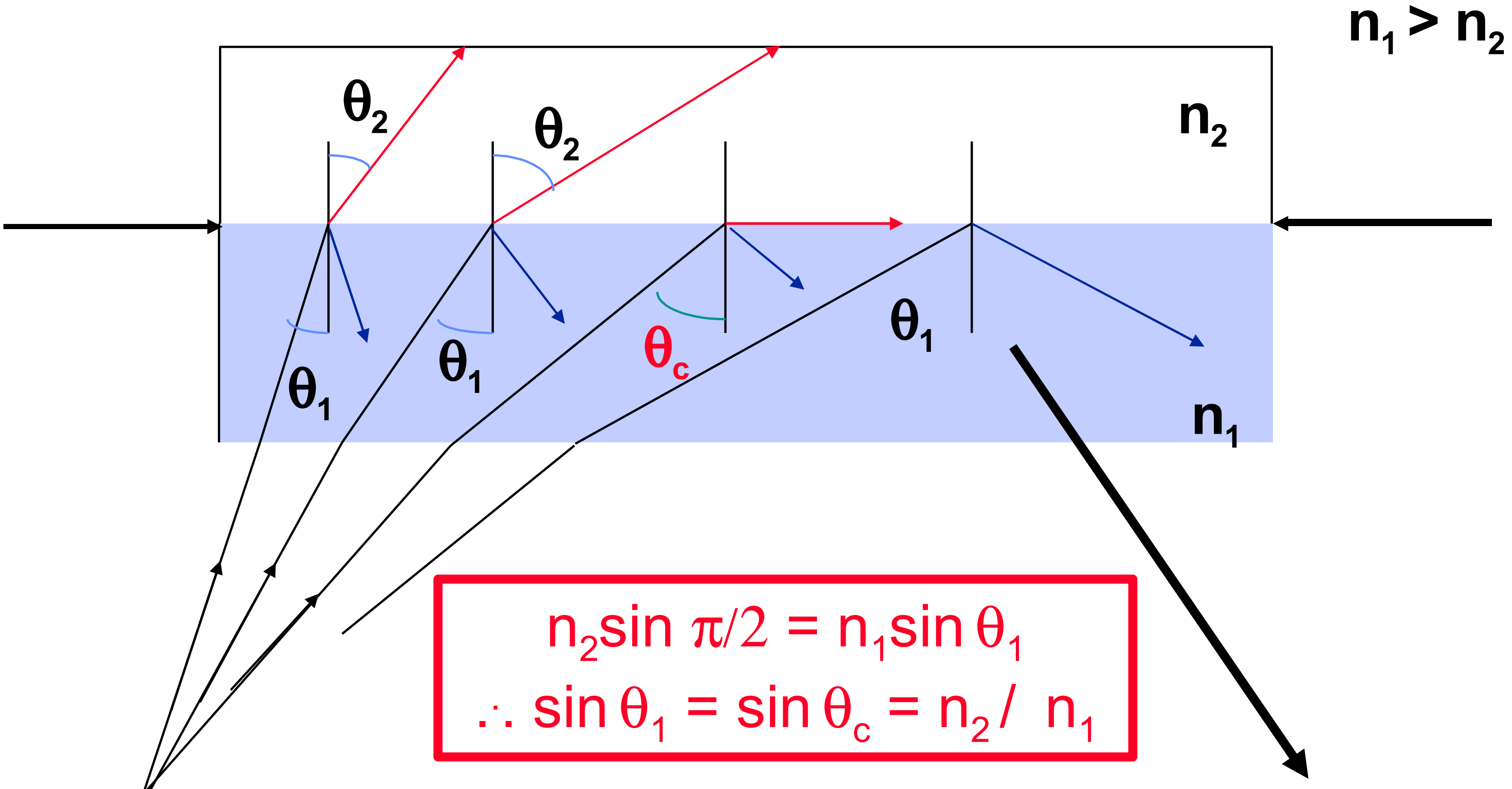
This is valid for any pair of materials with $n_1 < n_2$

Total Internal Reflection

- Suppose the light goes from medium 1 to 2 and that $n_2<n_1$ (for example, from water to air).
- Snell's law gives $\sin \theta_2 = (n_1 / n_2) \sin \theta_1$.
- Since $\sin \theta_2 <= 1$ there must be a maximum value of θ_1.
- At angles bigger than this "critical angle", the beam is totally reflected.
- The critical angle is when $\theta_2=\pi/2$, which gives

  $\theta_c=\sin^{-1}(n_2/n_1)$.

Total Internal Reflection



$$n_2 \sin \pi/2 = n_1 \sin \theta_1$$

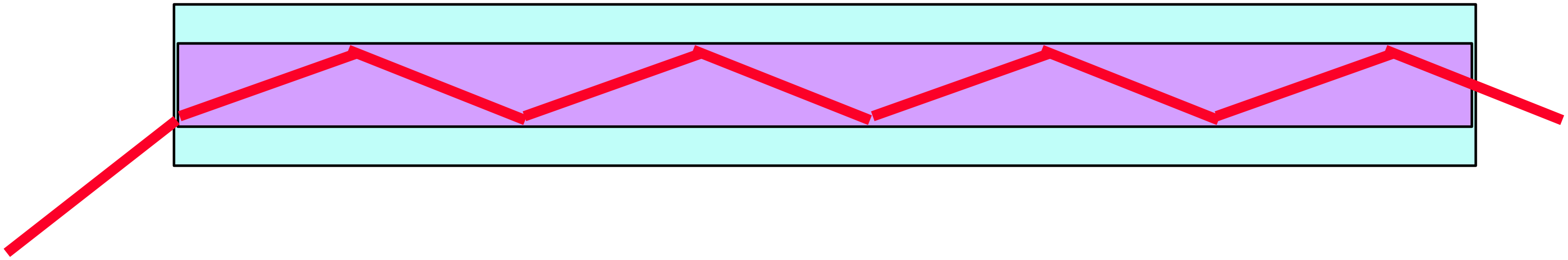
$$\therefore \sin \theta_1 = \sin \theta_c = n_2 / n_1$$

Some light is refracted and some is reflected

Total internal reflection: no light is refracted

Example: Fiber Optics

An optical fiber consists of a core with index n_1 surrounded by a cladding with index n_2, with $n_1 > n_2$. Light can be confined by total internal reflection, even if the fiber is bent and twisted.



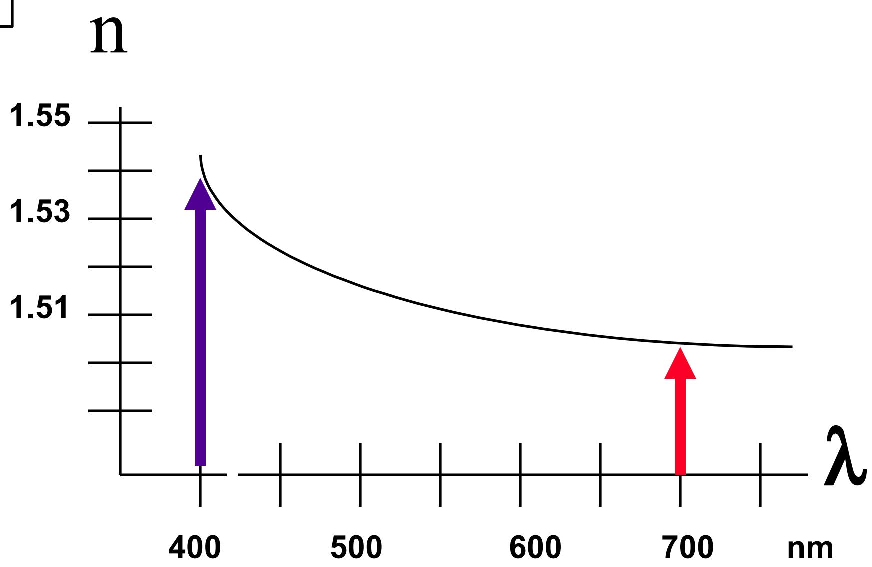
Exercise: For $n_1 = 1.7$ and $n_2 = 1.6$ find the minimum angle of incidence for guiding in the fiber.

Answer: $\sin\theta_C = n_2 / n_1 \Rightarrow \theta_C = \sin^{-1}(n_2 / n_1) = \sin^{-1}(1.6/1.7) = 70^o$.

(Need to graze at $< 20^o$)

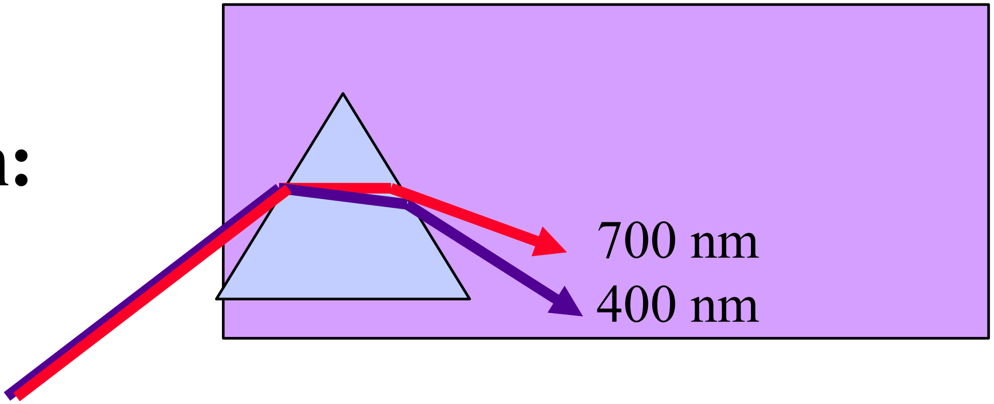
Dispersion

The index of refraction depends on frequency or wavelength: $n = n(\lambda)$



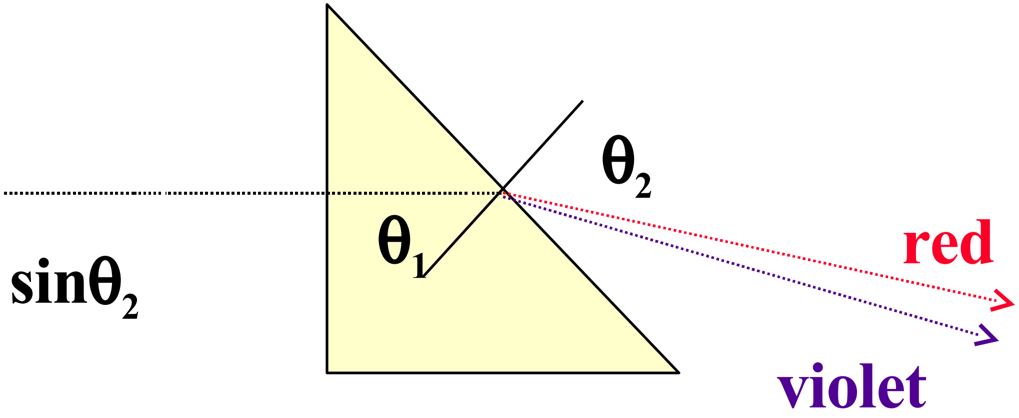
Typically many optical materials, (glass, quartz) have decreasing n with increasing wavelength in the visible region of spectrum

Dispersion by a prism:



Example: dispersion at a right angle prism

Find the angle between outgoing red (λr = 700nm) and violet (λv = 400nm) light [n_{400} =1.538, n_{700} = 1.516, θ_1 = 40°].



$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$n_2 = 1$ (air)

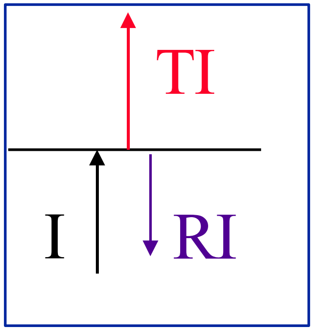
Red: $1.538 \sin(40°) = 1 \sin\theta_{400} \Rightarrow \theta_{400} = \sin^{-1}(1.538\ 0.643) = 81.34°$

Violet: $1.516 \sin(40°) = 1 \sin\theta_{700} \Rightarrow \theta_{700} = \sin^{-1}(1.516\ 0.643) = 77.02°$

$\Rightarrow\ \Delta = 4.32° \equiv$ angular dispersion of the beam

Reflection and Transmission at Normal Incidence

Geometrical optics can’t tell how much is reflected and how much transmitted at an interface. This can be derived from Maxwell’s equations. These are described in terms of the reflection and transmission coefficients R and T, which are, respectively, the fraction of incident intensity reflected and transmitted. For the case of normal incidence, one finds:

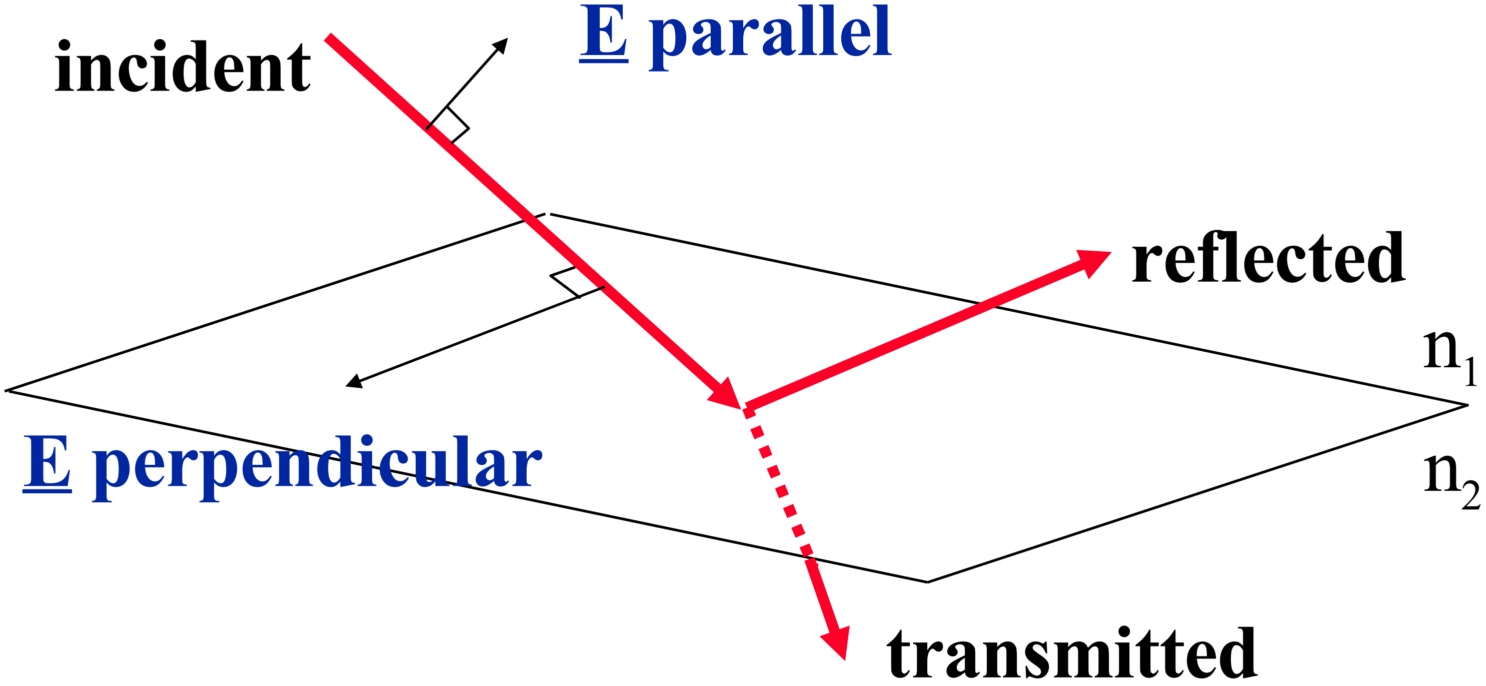


$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2, \quad T = 1 - R = \frac{4n_1 n_2}{(n_2 + n_1)^2}$$

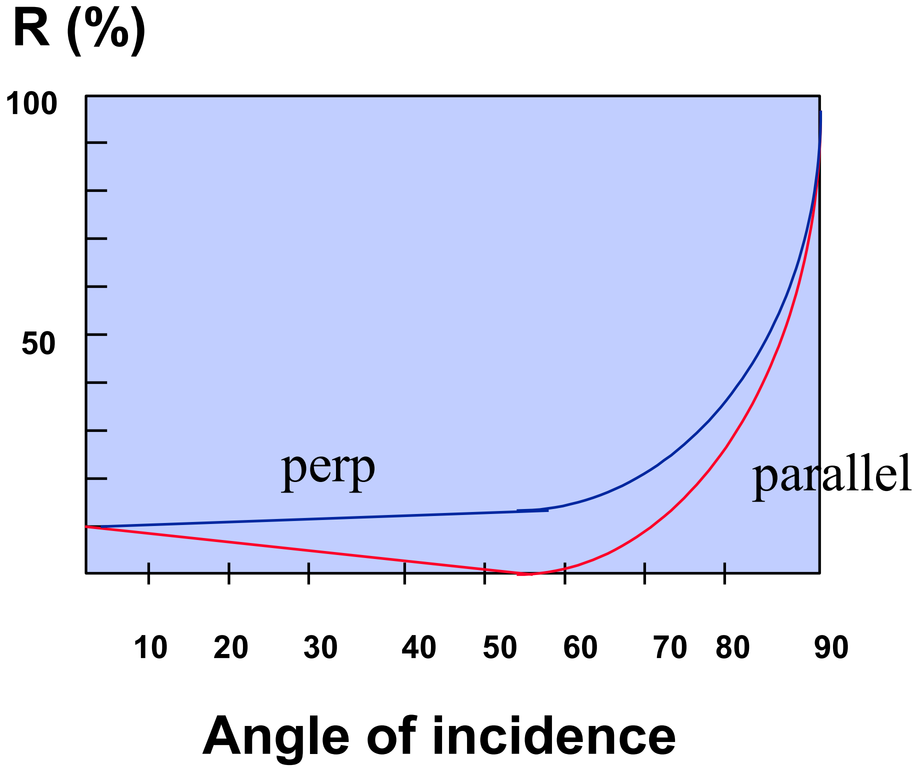
Notice that when $n_1 = n_2$ (so that there is not really any interface), R=0 and T=1.

Reflection and Transmission at Oblique Incidence

In this case R and T depend on the angle of incidence in a complicated way – and on the polarization of the incident beam. We relate polarization to the plane of the three rays.



Reflection and Transmission at Oblique Incidence

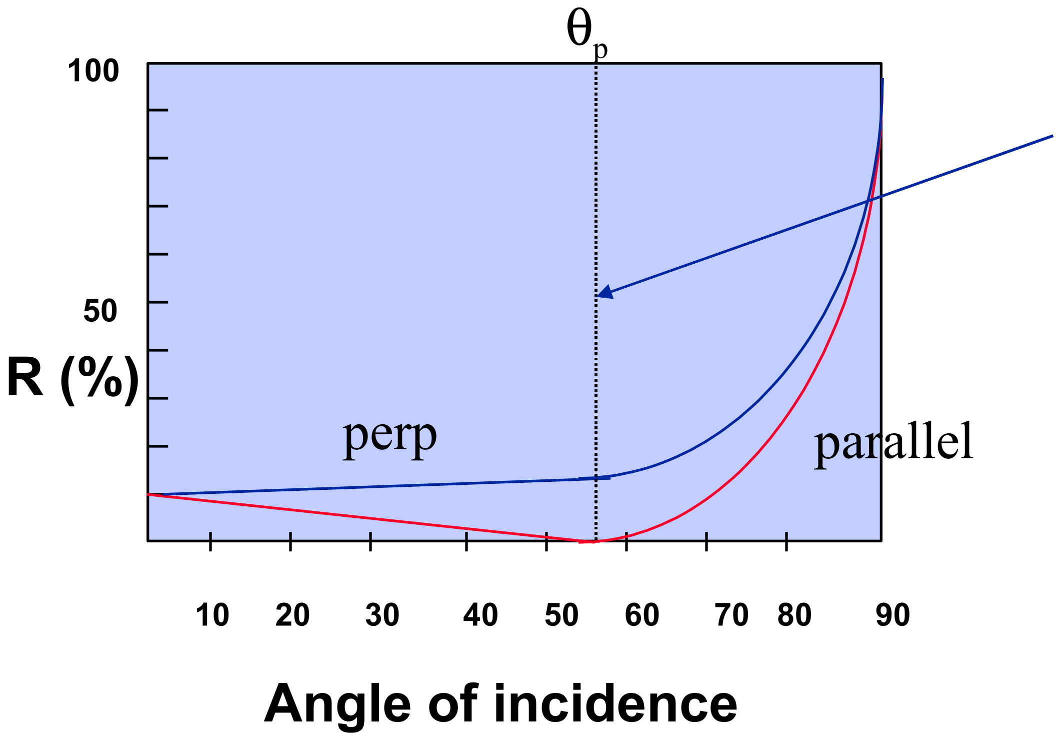


Light with the perpendicular polarization is reflected more strongly than light with the parallel polarization.

Hence if unpolarized light is incident on a surface, the reflected beam will be partially polarized.

Notice that at grazing incidence everything is reflected.

Reflection and Transmission at Oblique Incidence



Polarizing angle, or “Brewster’s angle”

$$\tan\theta_p = \frac{n_2}{n_1}$$

Brewster’s angle of incidence is the angle at which light polarized in the plane is not reflected but transmitted 100%
All the reflected light has perpendicular polarization.