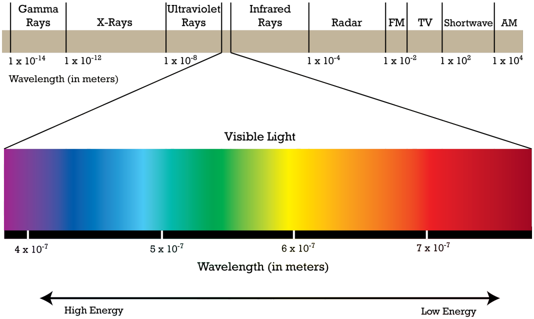
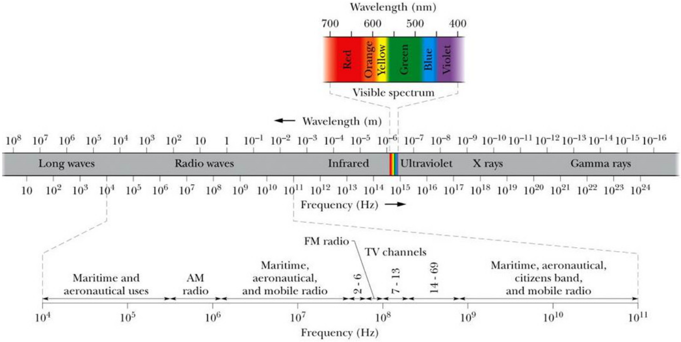
Chapter 1 - The Nature of Light



David J. Starling
Penn State Hazleton
PHYS 214

Traveling Waves

Electromagnetic radiation comes in many forms, differing only in wavelength, frequency or energy.



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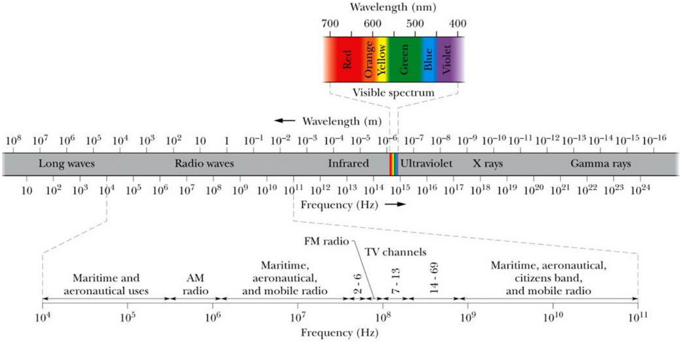
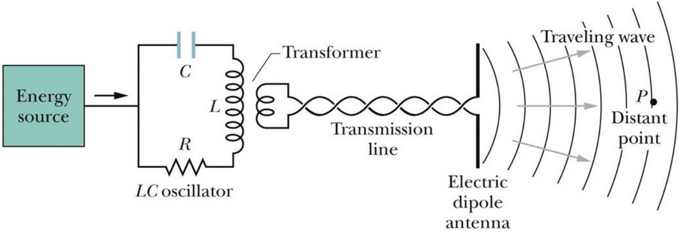


Visible light is only a small portion of the EM spectrum.

Traveling Waves

Electromagnetic radiation is a traveling wave that can be created with an antenna.



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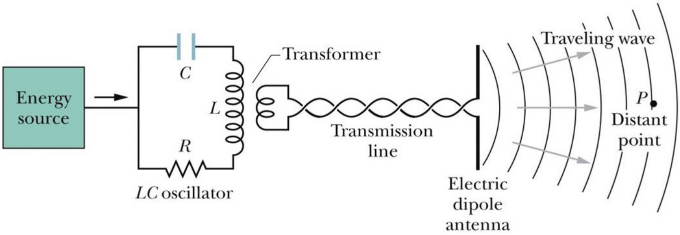
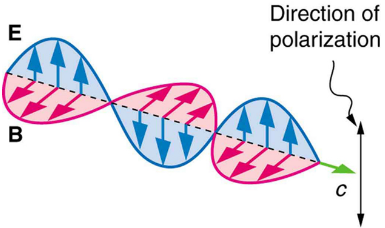


Oscillating electrons in the antenna create an oscillating EM wave that travels out in all directions.

Traveling Waves

The electric and magnetic fields are perpendicular to each other and are transverse to the direction of propagation.



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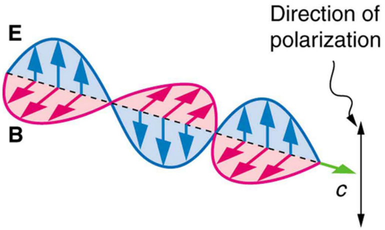
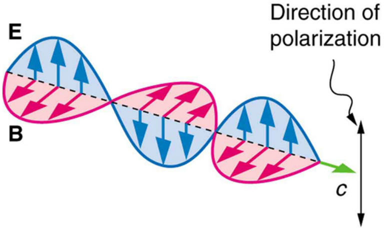


This is called a **transverse wave** and the “polarization” points along the electric field.

Traveling Waves

The wave's direction is given by the **Poynting vector***:*

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B} \tag{1}$$



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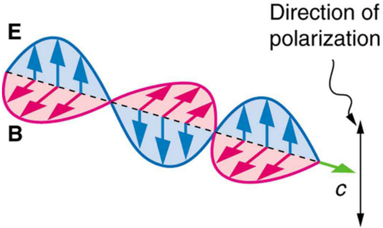

The Poynting vector $\vec{S}$ gives the energy per time per area that the EM wave transmits.

Traveling Waves

The speed of an electromagnetic wave is constant (in vaccuum) and is given by

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3.0 \times 10^8 \text{ m/s}$$

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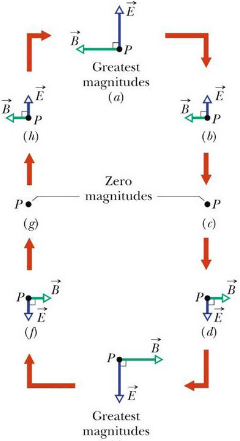
In a material, use the material's permitivity ϵ instead of ϵ_0. For example, in water, $v_l = 2.25 \times 10^8$ m/s.

Traveling Waves

As the wave travels past a point in space, the electric and magnetic fields oscillate in phase.



Traveling Waves

The oscillations of the EM wave tend to be sinusoidal:

$$
\begin{aligned}
E(x,t) &= E_m \sin(kx - \omega t) \\
B(x,t) &= B_m \sin(kx - \omega t)
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Recall that the speed of a traveling wave is given by $c = \omega/k$ and that $k = 2\pi/\lambda$ is the spatial frequency.

Energy and Pressure

Using the Poynting vector, we can calculate the average rate of energy transmitted by plane waves for a unit area:

$$\begin{aligned} I &= \left\langle \frac{E}{\mu_0} B \right\rangle \\ &= \left\langle \frac{E}{\mu_0} \frac{E}{c} \right\rangle \\ &= \left\langle \frac{E^2}{\mu_0 c} \right\rangle \\ &= \frac{1}{2c\mu_0} E_m^2 \end{aligned}$$

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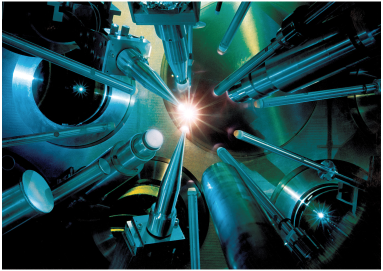
For plane waves, Maxwell's Equations require $B = E/c$.

Energy and Pressure

Intensity is a measure of how much power is concentrated into a certain area:

$$I = \frac{\text{power}}{\text{area}}$$



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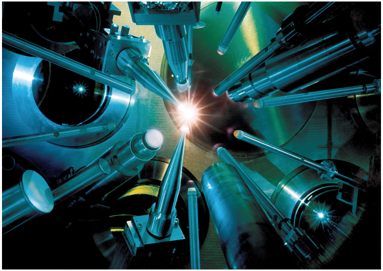
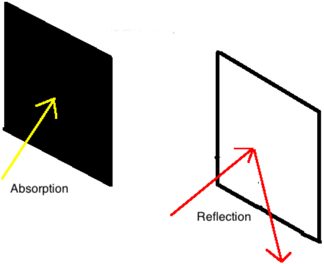


For a spherical wave, $I = P/4\pi r^2$.

Energy and Pressure

Power and force are related by speed ($P = Fv$), and this relationship holds for light as well.

$$F = \frac{P}{c} = \frac{IA}{c}$$



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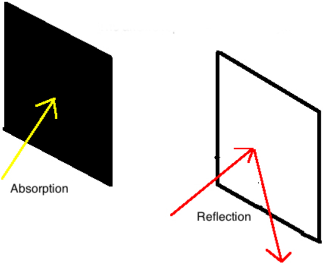
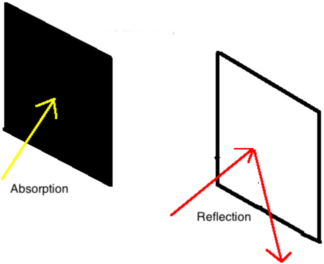


If the light is reflected, then force is doubled: $F = 2IA/c$.

Energy and Pressure

This force can result in a pressure, known as radiation pressure ($p_r = F/A$)*:*

$$p_r = \frac{I}{c}$$



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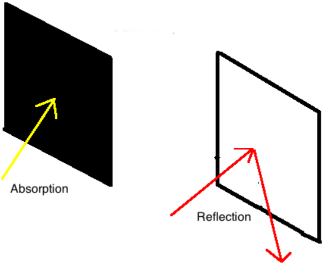


If the light is reflected, then *pressure* is doubled: $p_r = 2I/c$.

Energy and Pressure

Lecture Question 1.1

Monochromatic electromagnetic radiation illuminates a surface. The electric and magnetic fields of the waves are then doubled in magnitude. How is the total energy incident on the surface, per unit time, affected by this increase?

(a) The total energy is not affected by this change.

(b) The total energy will increase by a factor of two.

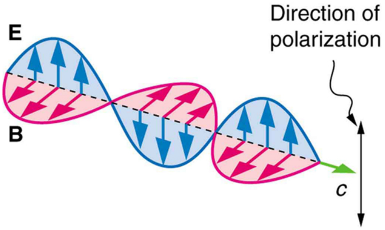
(c) The total energy will increase by a factor of four.

(d) The total energy will decrease by a factor of two.

(e) The total energy will decrease by a factor of four.

Polarization

The direction of the electric field is the direction of polarization of the EM wave.



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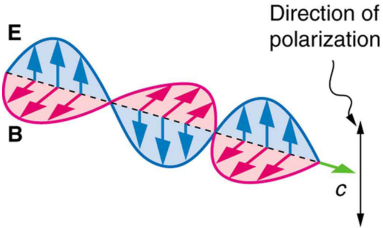
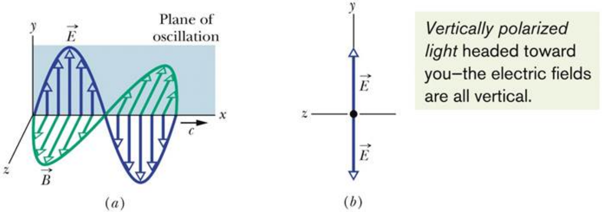


However, the direction of the polarization may change with time, resulting in a variety of possibilities.

Polarization

Linearly polarized light means the polarization direction is a constant in time.



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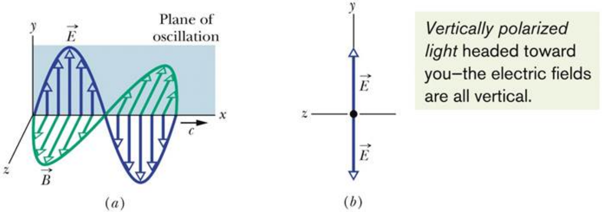
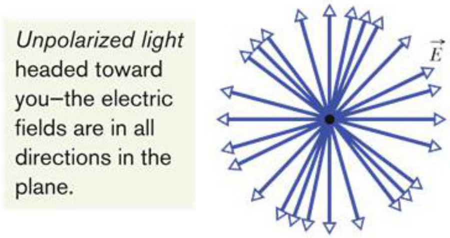


Light coming from most lasers is linearly polarized.

Polarization

Unpolarized light means the polarization direction changes randomly in time.



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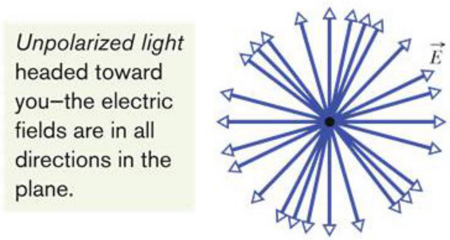
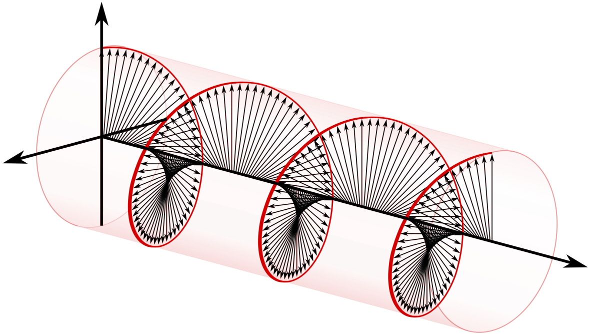


Light coming from fire or the sun is unpolarized.

Polarization

Circularly polarized light means the polarization direction rotates in a circle at a constant rate.



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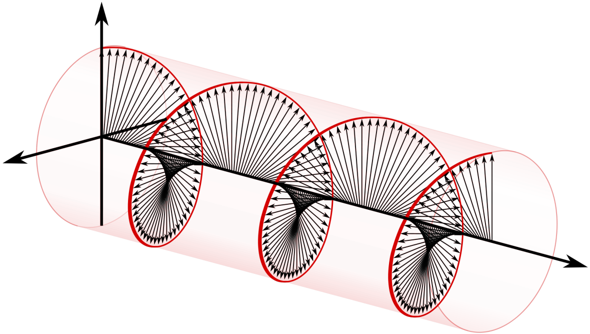
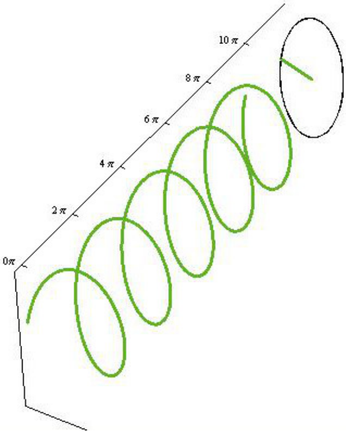
Circularly polarized light means the polarization direction rotates in a circle at a constant rate.



This can be created with optics in a lab.

Polarization

Elliptically polarized light means the electric field rotates, tracing out an ellipse.



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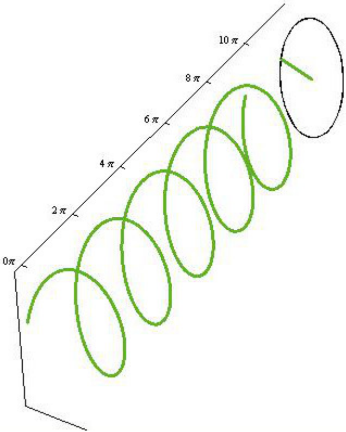
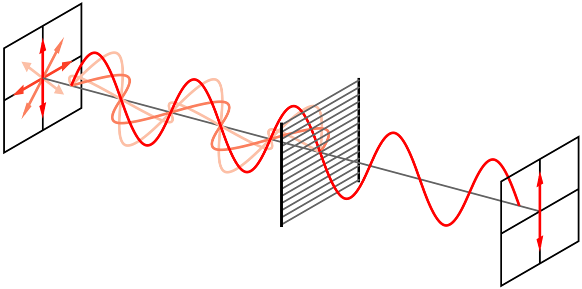


This can also be created with optics in a lab.

Polarization

When light passes through a linear polarizer, only some of the light is transmitted.



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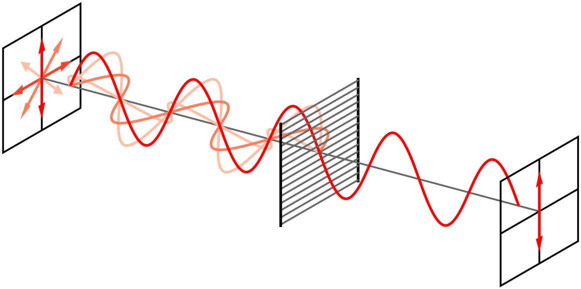
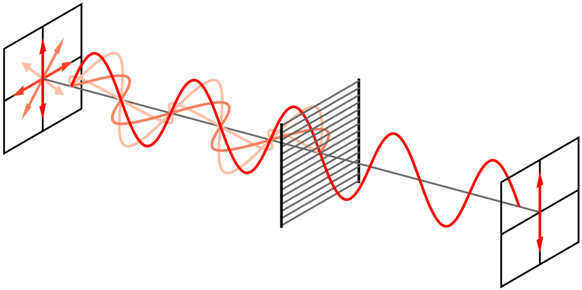


For unpolarized light, the light that passes through becomes linearly polarized and its intensity drops to

$$I = I_0/2$$

Polarization

The light always takes on the polarization direction of the polarizing material.



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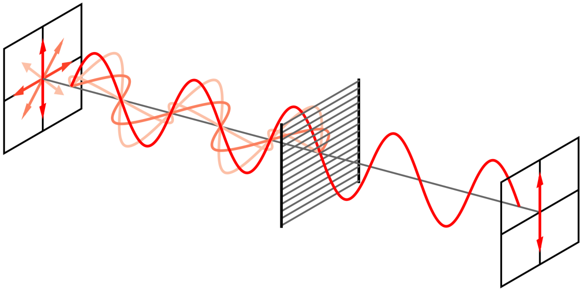


The intensity always drops as

$$I = I_0 \cos^2(\theta)$$

where θ is the angle between the light's polarization and the polarizer.

Polarization

Lecture Question 1.2

Unpolarized light with intensity S is incident on a series of polarizing sheets. The first sheet has its transmission axis oriented at $0°$. A second polarizer has its transmission axis oriented at $45°$ and a third polarizer oriented with its axis at $90°$. Determine the fraction of light intensity exiting the third sheet with and without the second sheet present.

(a) $S/2$, S

(b) $S/2$, 0

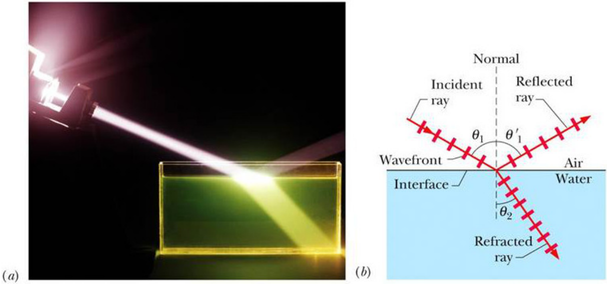
(c) $S/4$, 0

(d) $S/3$, $S/2$

(e) S, $S/2$

Reflection and Refraction

When light interacts with a surface, it can reflect off of or refract into the material.



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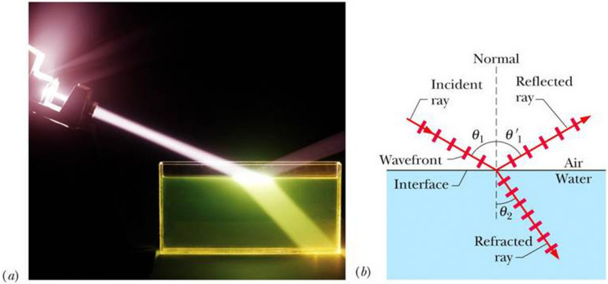
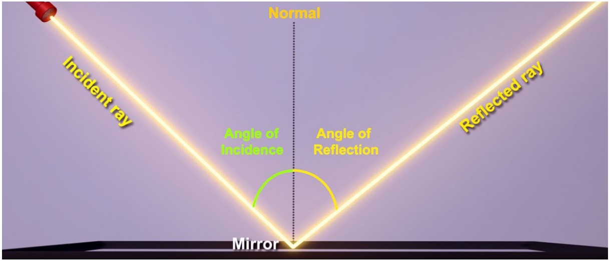


How does the light behave? (Can derive completely from Maxwell's Equations...)

Reflection and Refraction

A reflected ray lies in the plane of incidence and has an angle of reflection equal to the angle of incidence.

$$\theta_1 = \theta_1'$$



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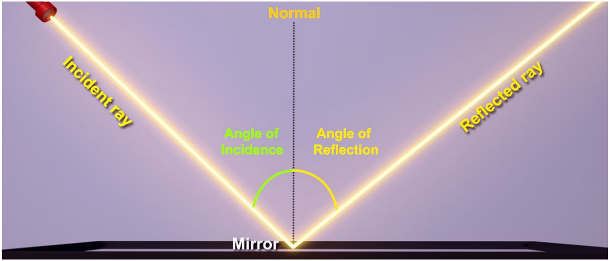
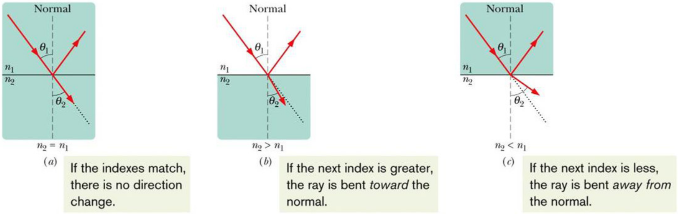


This is the Law of Reflection.

Reflection and Refraction

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

$$n_2 \sin\theta_2 = n_1 \sin\theta_1 \text{ (Snell's Law)}$$



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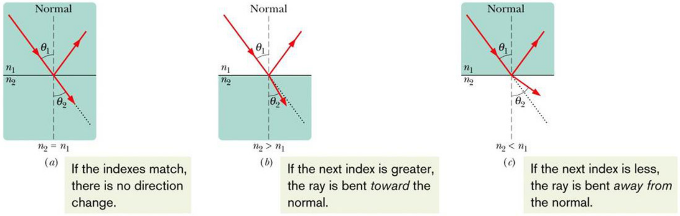
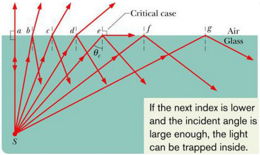


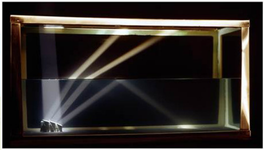
n is the index of refraction and is related to the speed of light in the material ($v_1 = c/n_1$).

Reflection and Refraction

Snell's Law results in total internal reflection when light shines from high index (n_1) to low index (n_2).

$$n_2 \sin 90^\circ = n_1 \sin \theta_c \rightarrow \theta_c = \sin^{-1}(n_2/n_1)$$





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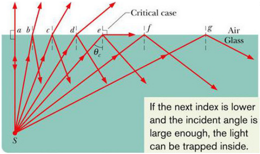
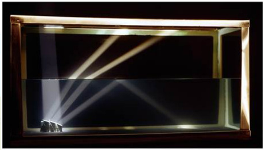
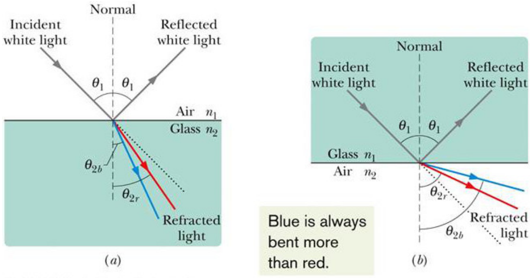




At this critical angle, all light is reflected. (e.g. in a pool, or a fiber optic cable)

Reflection and Refraction

For every material, the index of refraction varies with the color of light. This gives rise to **chromatic dispersion**.



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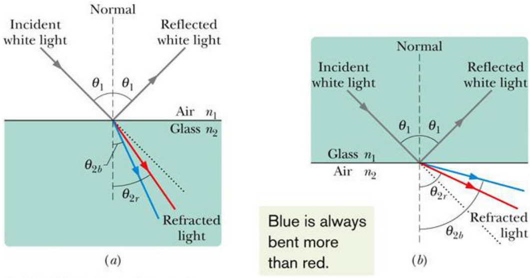
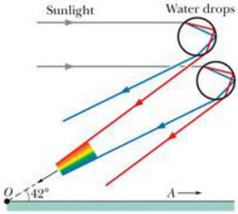
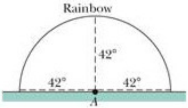


This is the principle behind prisms and rainbows.

Reflection and Refraction

Water droplets act as a dispersive material for sunlight and a rainbow forms given a certain geometry.





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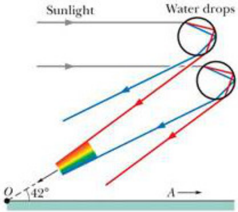
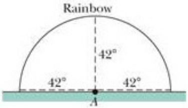


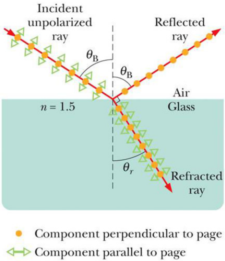


Inside the droplet the light refracts, is totally internally reflected and then refracts again.

Reflection and Refraction

When unpolarized light reflects off of a surface at the Brewster angle θ_B, it becomes polarized in the plane of the surface.

$$\theta_B = \tan^{-1}(n_2/n_1)$$



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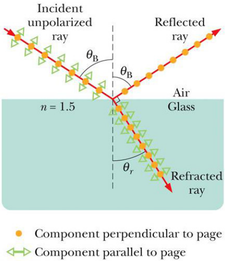

This is the result of solving Maxwell's Equations at the boundary.

Lecture Question 1.3

Is light bent more, less, or not at all when entering a medium with a smaller index of refraction than that of the incident medium?

(a) more

(b) less

(c) not at all