Class 10

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ENGI-1500
Physics -2

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HUMBER

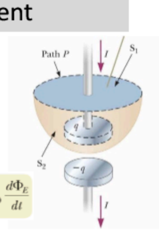
Reminder of the previous week

Displacement Current

$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0 I$

Ampere's law expanded / generalized

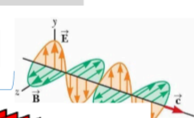
$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0(I + I_d) = \mu_0 I + \mu_0\epsilon_0 \frac{d\Phi_E}{dt}$



Maxwell's Equations

Plane EM Waves

$\frac{\partial^2 E}{\partial x^2} = \mu_0\epsilon_0 \frac{\partial^2 E}{\partial t^2}$ $\frac{\partial^2 B}{\partial x^2} = \mu_0\epsilon_0 \frac{\partial^2 B}{\partial t^2}$

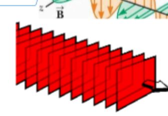


Solutions to the wave equation

$E = E_{max} \cos(kx - \omega t)$

$B = B_{max} \cos(kx - \omega t)$

$\frac{\omega}{k} = \frac{2\pi f}{2\pi/\lambda} = \lambda f = c$



$c = \frac{1}{\sqrt{(4\pi \times 10^{-7}\ \mathrm{T \cdot m/A})(8.854\,19 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2})}}$

$= 2.997\,92 \times 10^8\ \mathrm{m/s}$

Momentum & Radiation Pressure

EM waves transport energy as well as momentum. Absorption or reflection of EM waves results in momentum.

$p = \frac{2T_{ER}}{c}$ (complete reflection)

$P = \frac{2S}{c}$ (complete reflection)

Solar sailing

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q}{\epsilon_0}$$ Gauss's law

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$ Gauss's law in magnetism

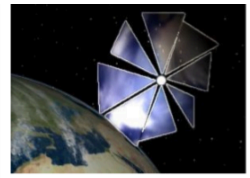
$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$ Faraday's law

$$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0 I + \epsilon_0 \mu_0 \frac{d\Phi_E}{dt}$$ Ampère–Maxwell law

Energy Carried by EM Waves

$$\vec{\mathbf{S}} = \frac{1}{\mu_0} \vec{\mathbf{E}} \times \vec{\mathbf{B}}$$ Poynting vector

$$I = S_{avg} = \frac{E_{max} B_{max}}{2\mu_0} = \frac{E_{max}^2}{2\mu_0 c} = \frac{c B_{max}^2}{2\mu_0}$$ Time average of S: wave intensity



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.
https://commons.wikimedia.org/wiki/File%3ACosmos_1_solar_sail.jpg
Source: https://en.wikipedia.org/wiki/Plane_wave

Week 12 / Class 10

Nature of Light and Ray Optics (Ch. 34)

Outline of Week 12 / Class 10

- Reminder of the previous week
- Nature of Light and Ray Optics (Ch. 34)
  - The Nature of Light
  - The Ray Approximation in Ray Optics
  - Analysis Model: Wave Under Reflection
  - Analysis Model: Wave Under Refraction
  - Huygen's Principle [Optional – Reading from Textbook]
  - Dispersion
  - Total Internal Reflection
- Examples
- Next week's topic

Nature of Light and Ray Optics (Ch. 34)

The Nature of Light

The Nature of Light

History

- Before the beginning of 19th century:
  - Light was considered to be a stream of particles either emitted by an object being viewed or emanated from the eyes of the viewer
- ***Newton***: chief architect of particle model of light
  - Believed that **the particles were emitted from the light source**
    - These particles stimulated a sense of sight upon entering the eye
- Using this idea: able to explain reflection and refraction
- Most scientists accepted Newton's particle model
- During Newton's lifetime another model was proposed:
  - Light might be **some sort of a wave motion**
- In 1678 ***Christian Huygens*** showed that wave model of light could also explain reflection and refraction

Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

The Nature of Light

History

- In 1801, ***Thomas Young*** provided the first clear experimental demonstration of wave nature of light
  - Light rays **interfere with one another** according to waves in interference model
  - Such behavior could not be explained by particle model
  - Not conceivable for particles to combine or cancel one another
- In 1873, ***Maxwell*** asserted that light was a form of high-frequency electromagnetic waves
- ***Hertz*** provided experimental confirmation of Maxwell's theory in 1887 by producing and detecting electromagnetic waves
- Results represented were convincing information that light has wave nature
  → Scientists accepted **wave nature of light**

The Nature of Light

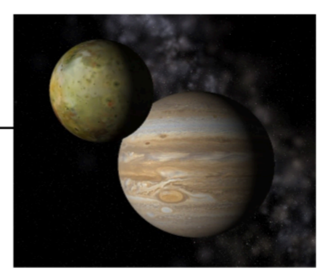
History

- Light travels at a high speed (**c ~= 3.00 × 10⁸ m/s**)

- Early attempts to measure speed were unsuccessful
  - Galileo attempted to measure speed of light by positioning two observers in towers separated by ≈ 10 km
  - Each observer carried a shuttered lantern
  - One observer would open his shutter first, then the other would open his shutter at the moment he saw light from the first lantern
  - Reasoning: calculating the light speed with the distance divided by the transit time of the light beams from one lantern to the other

- Measurement was not successful
  - Transit time: 10000 m/(3×10^8 m/s) = 33 μs
  - << reaction time of observers in opening the shutters

The Nature of Light



Measuring Speed of Light: Roemer's Method

- In 1675: ***Ole Roemer*** made observations that led to the first successful estimate of the speed of light

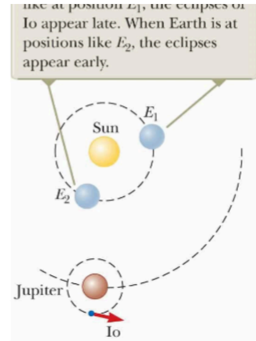
- After collecting data for more than a year, Roemer observed a systematic variation in ***Io***'s period (Io: one of the moons of Jupiter)

When Earth is far from Jupiter

- Longer than average - when Earth was at the opposite side of the Sun and far from Jupiter (E_1 in figure)
- Earlier than average - when Earth was on the same side of the Sun and close to Jupiter (E_2 in figure)

- Roemer attributed the variation in observed period to the extra time interval required for light for earth at different distances from Jupiter

- Using Roemer's data, ***Huygens*** estimated lower limit for speed of light ≈ 2.3×10^8 m/s



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The Nature of Light

Measuring Speed of Light: Fizeau's Method

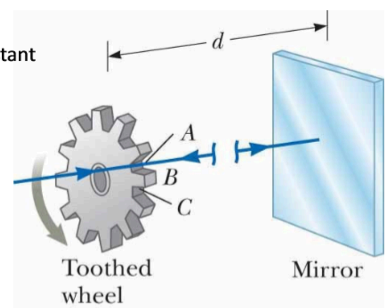
- First successful method for measuring the speed of light by purely terrestrial techniques was developed in 1849 by ***Armand H. L. Fizeau***

- Fizeau measured the total time interval during which light travels from some point to a distant mirror and back (*approximately 8kms away*)
  - *d* = distance between the light source and the mirror
  - Time interval for one round trip = Δt
  - Speed of light is $c = 2d/\Delta t$

- To measure the transit time: Fizeau used rotating toothed wheel
  - Converts continuous beam of light into series of light pulses
  - Wheel acts as light source and defines one end of distance ***d***
  - Observer looks through the teeth and determines whether or not the reflected light is observable

- At a great enough rate of rotation →
  - Opening at point *C* could move into position to allow reflected pulse to reach the observer

- Knowing distance *d*, number of teeth in wheel, and angular speed of wheel:
  - Fizeau arrived at a value of 3.1×10^8 m/s



More accurate $c = 2.99792458 \times 10^8$ *m/s*.

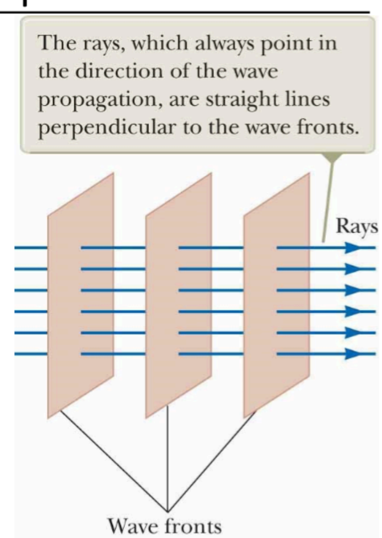
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Nature of Light and Ray Optics (Ch. 34)

The Ray Approximation in Ray Optics

The Ray Approximation in Ray Optics

- **Ray optics** (*geometric optics*): involves the study of propagation of light
  - Assumes light travels in a fixed direction in a straight line as it passes through a uniform medium
  - Changes direction when it meets a surface of a different medium or if the optical properties of a medium is nonuniform in either space or time
- **Ray approximation**: recall that the rays of a given wave are straight lines that are perpendicular to the wave fronts for plane waves (figure)
  - Wave moving through a uniform medium travels in a straight line in the direction of its rays



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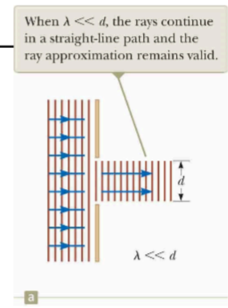
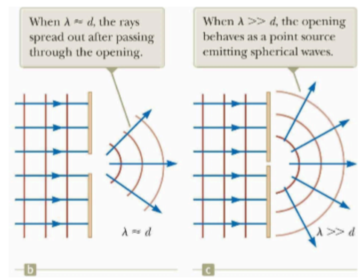
The Ray Approximation in Ray Optics

If the wave meets a barrier in which there is a circular opening;

- **Figure (a)**: diameter of the opening >> (much larger than) wavelength
  - Wave emerging from the opening continues to move in a straight line (apart from some small edge effects)
  - Ray approximation is valid
- **Figure (b)**: diameter of the opening ~ (comparable to) wavelength
  - Waves spread out from the opening in all directions: ***diffraction***
- **Figure (c)**: opening << (much smaller than) wavelength
  - Waves to the right of the barrier can be approximated as if there is a point source at the opening
- Similar effects can be seen when the waves encounter an opaque object of dimension ***d***
- Ray approximation and the assumption $\lambda \ll d$ is used in this chapter.
  - Appropriate for study of mirrors, lenses, prisms, and associated optical instruments such as telescopes, cameras, and eyeglasses





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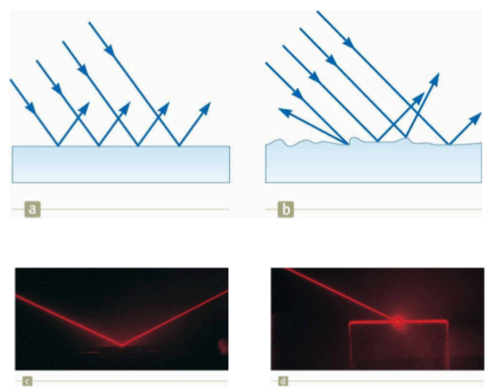
Nature of Light and Ray Optics (Ch. 34)

Analysis Model: Wave Under Reflection

Analysis Model: Wave Under Reflection

- When a light ray traveling in one medium encounters a boundary with another medium:
  - Part of the incident light gets reflected from the smooth, mirror-like, reflecting surface (figures (a) & (c))
  - Reflected rays are parallel to one another
  - Direction of reflected rays are in a plane perpendicular to the reflecting surface
- Reflection of light from smooth surfaces: ***specular reflection***
- If the reflecting surface is rough (figures (b) & (d)):
  - Surface reflects rays in various directions
- Reflection from any rough surface: ***diffuse reflection***
- A surface behaves as a smooth surface as long as the surface variations are << wavelength of the incident light
- For the scope of this course, we restrict our study to specular reflection and use the term ***reflection*** to mean ***specular reflection***



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Analysis Model: Wave Under Reflection

- Consider a light ray traveling in the air and it's incident at an angle on a flat, smooth surface as shown in the figure

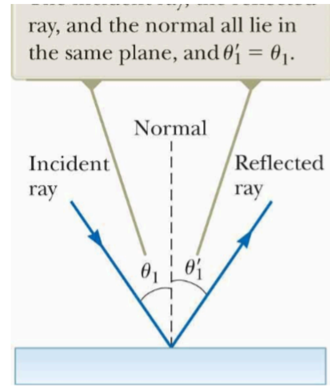
The incident ray, the reflected

surface as shown in the figure.

- Incident and reflected rays make angles $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_1'}$, respectively
  - The angles are measured between the normal and the rays
  - ***Normal*** = a line drawn perpendicular to the surface at the point where the incident ray strikes the surface
- Experiments and theory show that the angle of reflection = the angle of incidence

$$\theta_1' = \theta_1$$

Law of Reflection



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Quick Quiz

Quick Quiz

In the movies, you sometimes see an actor looking in a mirror and you can see his face in the mirror. It can be said with certainty that during the filming of such a scene, the actor sees in the mirror:

(a) his face
(b) your face
(c) the director's face
(d) the movie camera
(e) impossible to determine

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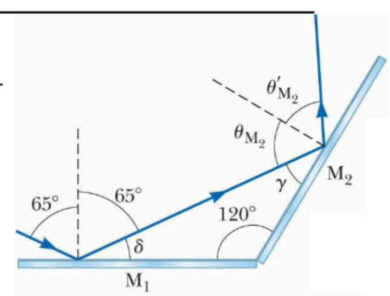
The Double-Reflected Light Ray

Example 34.2

Two mirrors make an angle of **120°** with each other as illustrated in the figure. A ray is incident on mirror **M_1** at an angle of **65°** to the normal. Find the direction of the ray after it is reflected from mirror **M_2**.



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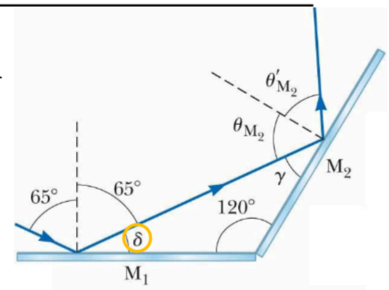

Solution

From the law of reflection, the first reflected ray makes an angle of 65° with the normal.

Find the angle the first reflected ray makes with the horizontal: $\delta = 90° - 65° = 25°$

The Double-Reflected Light Ray

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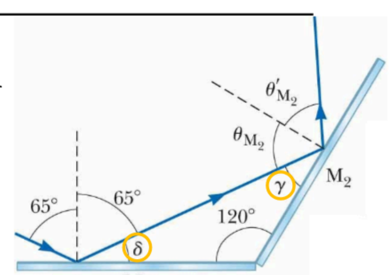

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Find the angle the first reflected ray makes with the horizontal: $\delta = 90° - 65° = 25°$

From the triangle made by the first reflected ray and the two mirrors, find the angle the reflected ray makes with M_2: $\gamma = 180° - 25° - 120° = 35°$

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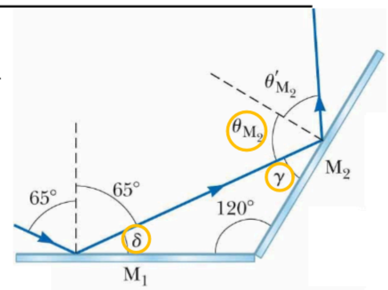

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Find the angle the first reflected ray makes with the normal to M_2: $\theta_{M_2} = 90° - 35° = 55°$

The Double-Reflected Light Ray

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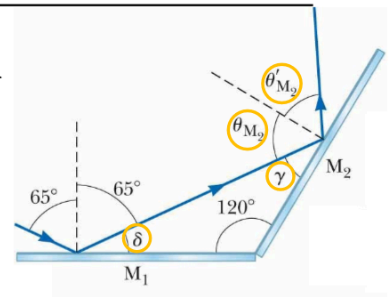

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Find the angle the first reflected ray makes with the normal to M_2: $\theta_{M_2} = 90° - 35° = 55°$

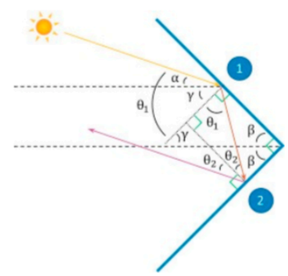
From the law of reflection, find the angle the second reflected ray makes with the normal to M_2: $\theta'_{M_2} = \theta_{M_2} = \boxed{55°}$

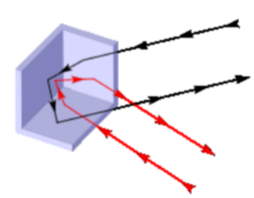
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Analysis Model: Wave Under Reflection

Retroreflection

- If the angle between two mirrors is 90°, the reflected beam returns to the source parallel to its original path.
- This phenomenon, called ***retroreflection***, has many practical applications:
  - If a third mirror is placed perpendicular to first two:
    - A cube corner for 3D retroreflection



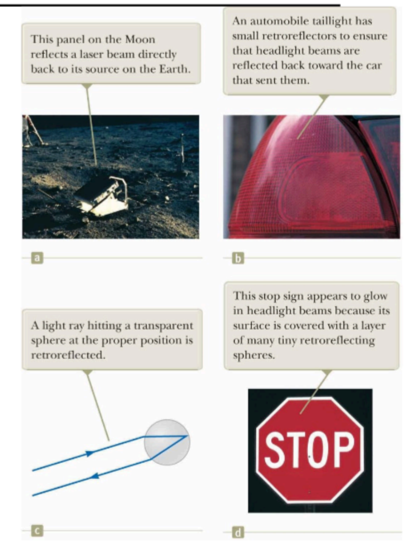


Source:
https://www.sciencedirect.com/science/article/abs/pii/S0927024819304465
https://en.wikipedia.org/wiki/Retroreflector

Analysis Model: Wave Under Reflection

Retroreflection

- Applications:
  - In 1969: retroreflectors were placed on the Moon (figure (a)) to reflect a laser beam from Earth in order to determine the distance to the Moon within certainty of 15 cm
  - Automobile taillights consist of many tiny cube corners (figure (b)) or small spherical bumps (figure (c)) to reflect headlight beams from cars approaching in the back
  - Road signs coated with tiny clear spheres appear much brighter due to retroreflection
  - Retroreflectors are used for reflective panels on running shoes and running clothing for joggers to be seen at night



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Nature of Light and Ray Optics (Ch. 34)

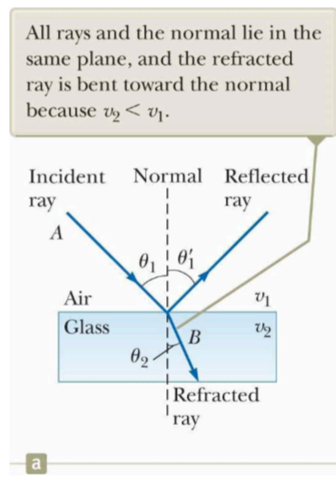
Analysis Model: Wave Under Refraction

Analysis Model: Wave Under Refraction

- When a ray of light travels through one transparent medium to another transparent medium(figure), at the boundary;
  - Part of the light energy is reflected:
  - Part of the energy enters (is refracted into) the second medium:
- The ray that enters the second medium (transmitted) changes its direction of propagation at the boundary and is said to be ***refracted.***
- The incident ray, the reflected ray, and the refracted ray all lie in the same plane.
- The angle of refraction $\boldsymbol{\theta_2}$ depends on the properties of the two media and on the angle of incidence $\boldsymbol{\theta_1}$ through the relationship
  - θ_2: **angle of refraction**
  - v_1: speed of light in the first medium
  - v_2: speed of light in the second medium

$$\theta_1' = \theta_1$$

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$



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Quick Quiz

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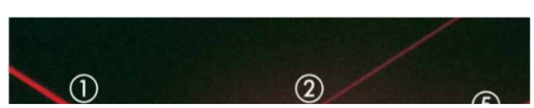
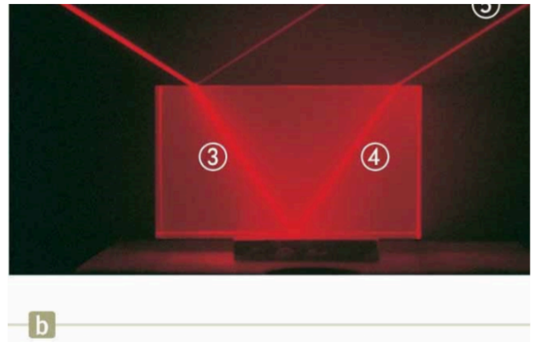
If beam 1 is the incoming beam in the figure, which of the other four red lines are reflected beams and which are refracted beams?



1) Incident
2)
3)
4)
5)



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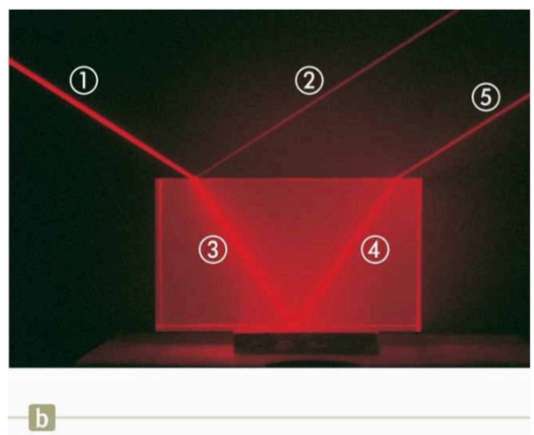
1) Incident
2) Reflected
3) Refracted
4) Reflected
5) Refracted

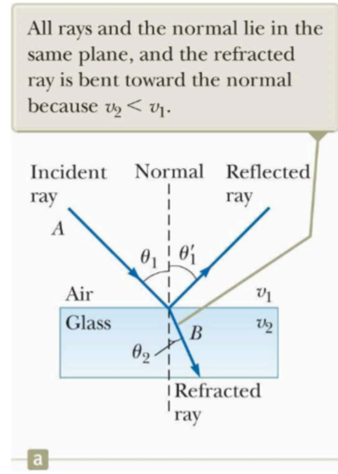


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Analysis Model: Wave Under Refraction

Reversible path

- The path of a light ray through a refracting surface is ***reversible***
- For example: the ray shown in the figure travels from point *A* to point *B*
  - If the ray originated at *B* →
    - It would travel upward to the point of incidence at the surface
    - Then bends away from the normal
    - Then reaches point *A*



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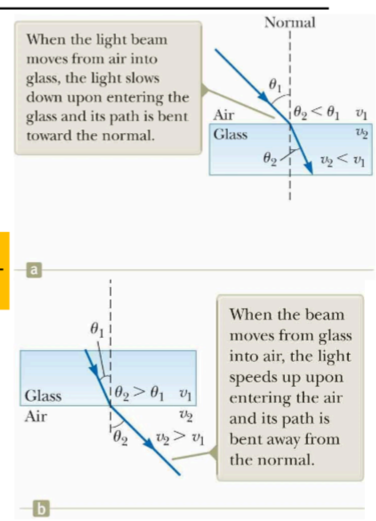
Analysis Model: Wave Under Refraction

- When light moves from the 1st material with a higher speed to the 2nd material with a slower speed (figure (a)):
  - Angle of refraction θ_2 < angle of incidence θ_1
  - Ray bent *toward* surface normal
- If light moves from the 1st material with a lower speed to the 2nd material with a higher speed (figure (b)):
  - $\theta_2 > \theta_1$
  - Ray is bent *away* from the surface normal

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$



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Analysis Model: Wave Under Refraction

Index of refraction

- In general: speed of light in any material is *less* than its speed in vacuum
  - *Light travels at its maximum speed **c** in vacuum.*
- **Index of refraction** *n* of a medium is:

$$n \equiv \frac{\text{speed of light in vacuum}}{\text{speed of light in a medium}} \equiv \frac{c}{v}$$

- Index of refraction: dimensionless number > 1 (because v always < c)
- $n = 1$ for vacuum

TABLE 34.1 Indices of Refraction

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

Note: All values are for light having a wavelength of 589 nm in vacuum.

- Table: indices of refraction for various substances
  - Use $n = 1$ for air

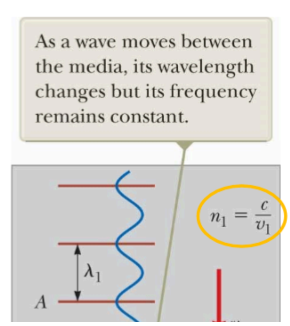
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Analysis Model: Wave Under Refraction

Index of refraction

- As light travels from one medium to another, its frequency does not change but its wavelength does.

$$v = \lambda f$$
$$f_1 = f_2 = f$$
$$v_1 = \lambda_1 f \quad \text{and} \quad v_2 = \lambda_2 f$$
$$\frac{\lambda_1}{} = \frac{v_1}{} = \frac{c/n_1}{} = \frac{n_2}{}$$



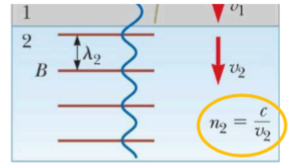
$\lambda_2 \quad v_2 \quad c/n_2 \quad n_1$

$\lambda_1 n_1 = \lambda_2 n_2$

$n = \frac{\lambda}{\lambda_n}$

λ = wavelength of light in vacuum
λ_n = wavelength of light in medium with index of refraction ***n***

Because n>1, $\lambda_n < \lambda$



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Analysis Model: Wave Under Refraction

Snell's Law

- With the definition of '***index of refraction***', we can have an alternative formula:

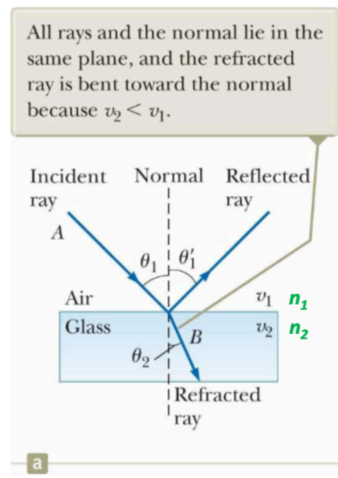
$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

n=c/v
$v_2/v_1 = n_1/n_2$

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

Snell's Law of Refraction

- Experimental discovery of this relationship was credited to ***Willebrord Snell***
- Other waves (e.g., seismic waves and sound waves) also exhibit refraction according to this model.



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Angle of Refraction for Glass

TABLE 34.1 Indices of Refraction

Example 34.3

A light ray of wavelength λ=***589nm*** traveling through air is incident on a smooth, flat slab of crown glass at an angle of θ_1**=30.0°** to the normal.

(A) Find the angle of refraction.
(B) Find the speed of this light once it enters the glass.
(C) What is the wavelength of this light in the glass?

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

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

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Polystyrene	1.49	Air	1.000 293
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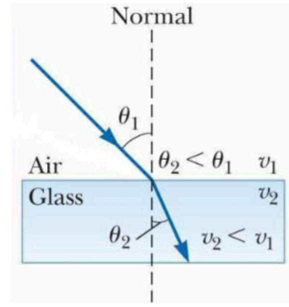
Note: All values are for light having a wavelength of 589 nm in vacuum.



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Angle of Refraction for Glass

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Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

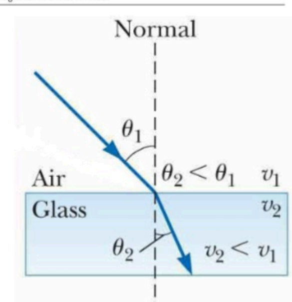
Note: All values are for light having a wavelength of 589 nm in vacuum.

Solution

Solution for (A)

Rearrange Snell's law:

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



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Angle of Refraction for Glass

Example 34.3

A light ray of wavelength λ=***589nm*** traveling through air is incident on a smooth, flat slab of crown glass at an angle of $\boldsymbol{\theta_1=30.0°}$ to the normal.

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(B) Find the speed of this light once it enters the glass.
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$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

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Note: All values are for light having a wavelength of 589 nm in vacuum.

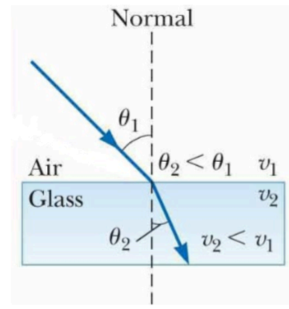
Solution

Solution for (A)

Rearrange Snell's law: $$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1$$

Solve for $\boldsymbol{\theta_2}$: $$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right)$$

Substitute values: $$\theta_2 = \sin^{-1}\left(\frac{1.00}{1.52}\sin 30.0°\right) = \ ?$$



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Angle of Refraction for Glass

Example 34.3

A light ray of wavelength λ=***589nm*** traveling through air is incident on a smooth, flat slab of crown glass at an angle of $\boldsymbol{\theta_1=30.0°}$ to the normal.

(A) Find the angle of refraction.
(B) Find the speed of this light once it enters the glass.
(C) What is the wavelength of this light in the glass?

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

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

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Note: All values are for light having a wavelength of 589 nm in vacuum.

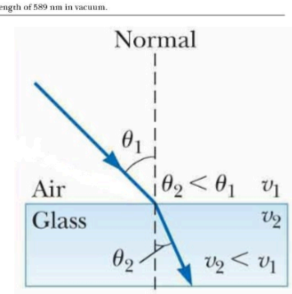
Solution

Solution for (A)

Rearrange Snell's law: $$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1$$

Solve for $\boldsymbol{\theta_2}$: $$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right)$$

Substitute values: $$\theta_2 = \sin^{-1}\left(\frac{1.00}{1.52}\sin 30.0°\right) = \boxed{19.2°}$$



Angle of Refraction for Glass

Example 34.3

A light ray of wavelength **λ=589nm** traveling through air is incident on a smooth, flat slab of crown glass at an angle of **θ_1=30.0°** to the normal.

(A) Find the angle of refraction.
(B) Find the speed of this light once it enters the glass.
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$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

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Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

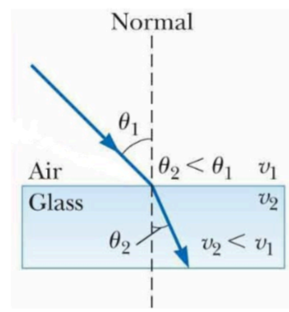
Note: All values are for light having a wavelength of 589 nm in vacuum.

Solution

Solution for (B)

$$v = \frac{c}{n}$$

$$v = \frac{3.00 \times 10^8 \text{ m/s}}{1.52} = \boxed{1.97 \times 10^8 \text{ m/s}}$$



Angle of Refraction for Glass

Example 34.3

A light ray of wavelength **λ=589nm** traveling through air is incident on a smooth, flat slab of crown glass at an angle of **θ_1=30.0°** to the normal.

(A) Find the angle of refraction.
(B) Find the speed of this light once it enters the glass.
(C) What is the wavelength of this light in the glass?

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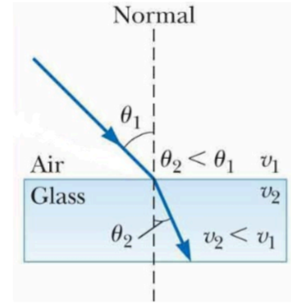
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

Note: All values are for light having a wavelength of 589 nm in vacuum.

Solution

Solution for (C)

$$\lambda_n = \frac{\lambda}{n} = \frac{589\text{ nm}}{1.52} = \boxed{388\text{ nm}}$$



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Angle of Refraction for Glass

Example 34.3

A light ray of wavelength λ=***589nm*** traveling through air is incident on a smooth, flat slab of crown glass at an angle of **θ$_1$=30.0°** to the normal.

(A) Find the angle of refraction.
(B) Find the speed of this light once it enters the glass.
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$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

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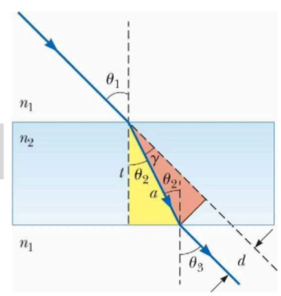
Note: All values are for light having a wavelength of 589 nm in vacuum.

Example 34.4

What would happen if the light beam was passing through a thick slab of material whose index of refraction is n$_2$? Show that the beam emerging into medium 1 from the other side is parallel to the incident beam.

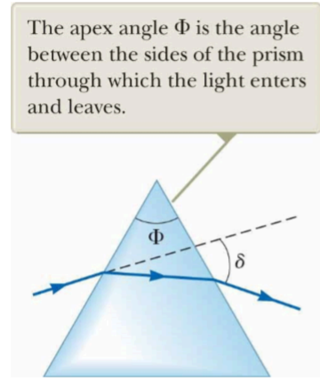


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Analysis Model: Wave Under Refraction

Prisms

- We talked about a slab of material with parallel sides.
- What happens when light strikes a prism with nonparallel sides as shown in the figure?
- In this case, the outgoing ray does not propagate in the same direction as the incoming ray. A ray of single-wavelength light incident on the prism from the left emerges at angle δ from its original direction of travel.
- This angle δ is called the ***angle of deviation***.
- The ***apex angle Φ*** of the prism, shown in the figure, is defined as the angle between the surface at which the light enters the prism and the second surface that the light encounters.



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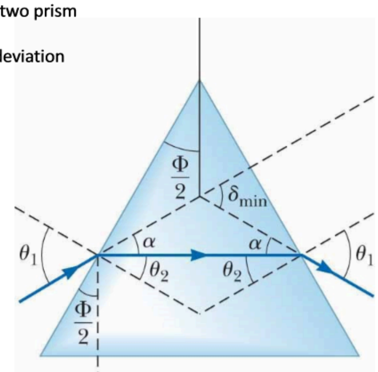
Angle of Refraction for Glass

Example 34.5

Although we do not prove it here, the minimum angle of deviation δ_{min} for a prism occurs when the angle of incidence θ_1 is such that the refracted ray inside the prism makes the same angle with the normal to the two prism faces as shown in the figure.
Obtain an expression for the index of refraction of the prism material in terms of the minimum angle of deviation **(δ_{min})** and the apex angle **(Φ)**.



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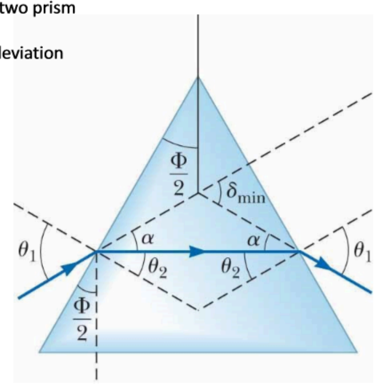

Solution

First, can we observe:

$$\theta_1 = \theta_2 + \alpha$$

$$\theta_2 = \Phi/2$$

$$\delta_{\text{min}} = 2\alpha$$

Angle of Refraction for Glass

Example 34.5

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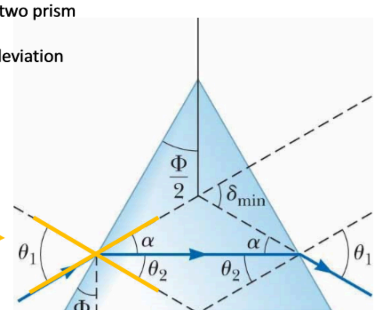
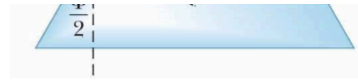


$\delta_{\text{min}} = 2\alpha$



Angle of Refraction for Glass

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Solution

First, can we observe:

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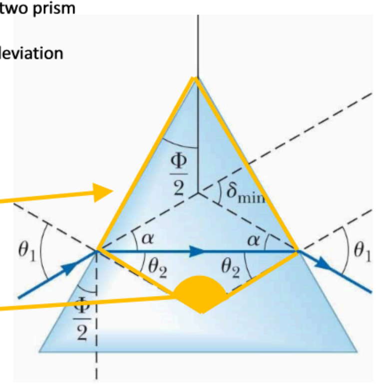
$$\theta_2 = \Phi/2$$

$$\delta_{\text{min}} = 2\alpha$$

=360-90-90-Φ
=180-Φ
=180-(2xθ_2)
→Φ=2xθ_2



Angle of Refraction for Glass

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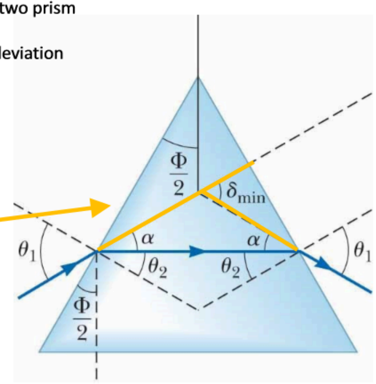

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$$\theta_2 = \Phi/2$$

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Angle of Refraction for Glass

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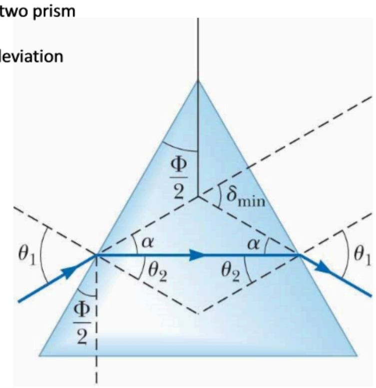


Solution

First, can we observe:

$$\theta_1 = \theta_2 + \alpha$$

$$\theta_2 = \Phi/2$$

$$\delta_{\text{min}} = 2\alpha$$

$$\theta_1 = \theta_2 + \alpha = \frac{\Phi}{2} + \frac{\delta_{\text{min}}}{2} = \frac{\Phi + \delta_{\text{min}}}{2}$$

$$(1.00)\sin\theta_1 = n\sin\theta_2 \rightarrow n = \frac{\sin\theta_1}{\sin\theta_2}$$

$$n = \boxed{\frac{\sin\left(\dfrac{\Phi + \delta_{\text{min}}}{2}\right)}{\sin(\Phi/2)}}$$

Nature of Light and Ray Optics (Ch. 34)

Huygen's Principle [Optional – Reading from text book]

Nature of Light and Ray Optics (Ch. 34)

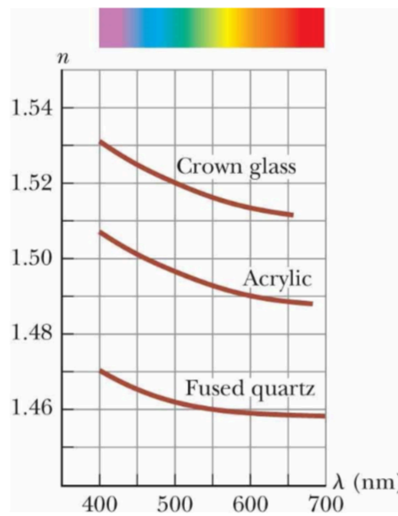
Dispersion

Dispersion

- **Dispersion:** For a given material, index of refraction varies with wavelength of light passing through the material (figure):
  - ***n*** *is a* function of wavelength →
  - Snell's law of refraction indicates that light of different wavelengths refracts at different angles

- Figure: shows that index of refraction generally decreases with increasing wavelength

- Example:
  - Violet light refracts more than red light does when passing into a material



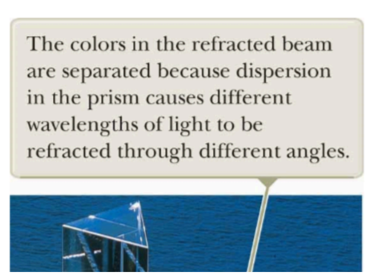
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Dispersion

- Figure: a beam of ***white light*** (combination of all visible wavelengths) is incident onto a prism from the left

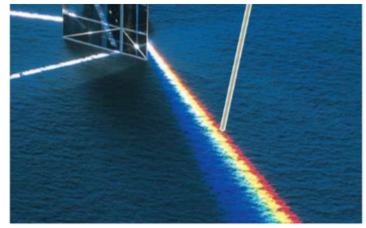
- Angle of deviation depends on the index of refraction →
  - Angle depends on the wavelength

- Rays that emerge spread out in series of colors (**visible**



spectrum)
- In order of decreasing wavelength: red, orange, yellow, green, blue, and violet

- Newton showed:
  - Each color has a particular angle of deviation
  - Colors can be recombined to form original white light



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Dispersion

Rainbows

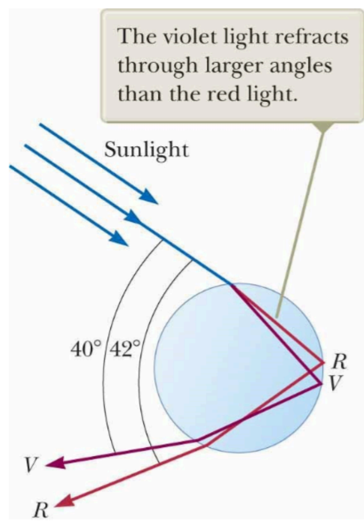
- **Rainbow**: dispersion of light into spectrum
  - Often seen by an observer positioned between the Sun and a rain shower

- Apply both '*wave under reflection*' and '*wave under refraction'* models

- Rays of sunlight (white light) strike a drop of water in atmosphere (figure)

- Light ***refracted*** and ***reflected*** as shown:
  - First refracted at the front surface of the drop
    - Violet light deviating most and red light least.
  - At the back surface of the drop:
    - Light is reflected and returns to front surface
    - Again undergoes refraction as it moves from water into air

- Small angular difference between returning rays: causes us to see a colored bow



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Dispersion

Dispersion

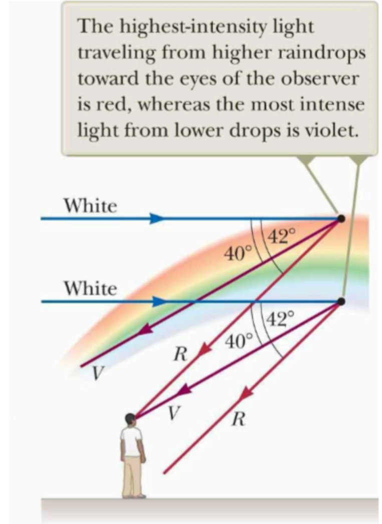
Rainbows

- Figure: observer viewing a rainbow

- If raindrop high in the sky is being observed:
  - Most intense red light returning from drop reaches the observer →
    - Because it deviated the least
  - Most intense violet light from this drop passes over observer →
    - Because it deviated the most
  - Observer sees red light coming from drop

- Drop lower in sky directs most intense violet light toward observer
  - Appears violet
    - Most intense red light from this drop passes below observer's eye

- Most intense light from other colors of spectrum reaches observer from raindrops lying between these two extreme positions



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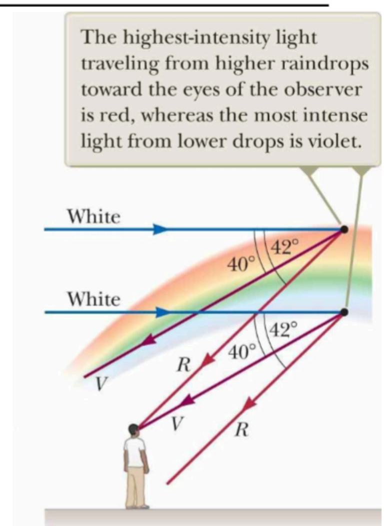
Dispersion

Rainbows



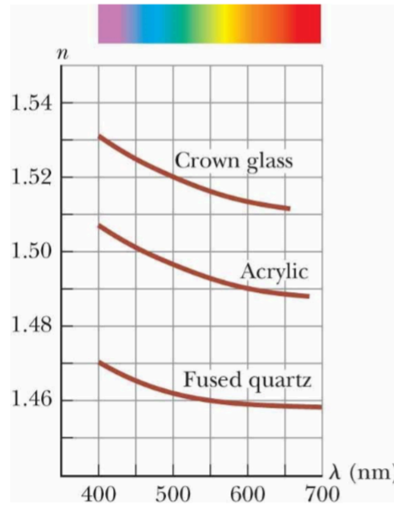
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018
https://en.wikipedia.org/wiki/Rainbow

Quick Quiz

Quick Quiz

In photography, lenses in a camera use refraction to form an image on a light-sensitive surface. Ideally, you want all the colors in the light from the object being photographed to be refracted by the same amount. Of the materials shown in the figure, which would you choose for a single-element camera lens?

(a) crown glass
(b) acrylic
(c) fused quartz
(d) impossible to determine



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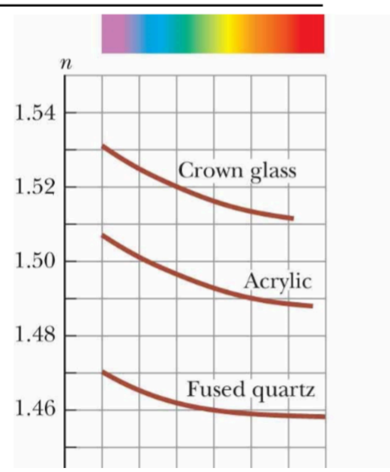
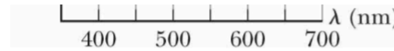
(a) crown glass
(b) acrylic
(c) fused quartz
(d) impossible to determine

An ideal camera lens would have an index of refraction that does not vary with wavelength so that all colors would be bent through the same angle by the lens. Of the three choices, fused quartz has the least variation in n across the visible spectrum.
A lens designer can do even better by ***stacking*** two lenses of different materials together to make an ***achromatic double***





Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Nature of Light and Ray Optics (Ch. 34)

Total Internal Reflection

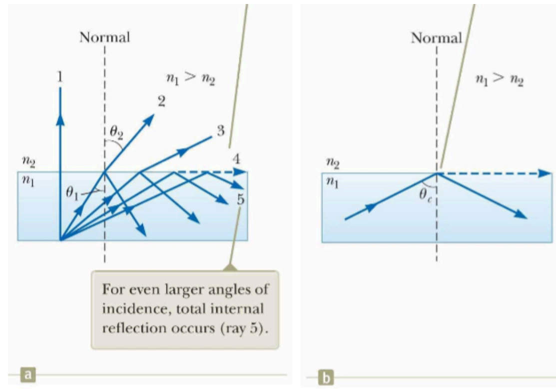
Total Internal Reflection

- **Total internal reflection**: can occur when light travels from a higher index of refraction medium to a lower index of refraction medium

As the angle of incidence θ_1 increases, the angle of refraction θ_2 increases until θ_2 is 90° (ray 4). The dashed line indicates that no energy actually propagates in this direction.

The angle of incidence producing an angle of refraction equal to 90° is the critical angle θ_c. For angles greater than θ_c, all the energy of the incident light is reflected.

- Figure (a): Labels 1 to 5 indicate various possible directions of ray consistent with wave under refraction model.
  - As θ_1 increases → θ_2 becomes larger
  - Refracted ray bends away from normal so much that it approaches direction parallel to interface
- At the particular angle of incidence θ_c (**critical angle**):
  - Refracted light ray reaches this condition that it is parallel to the boundary → θ_2 = 90° (ray 4 figure (a), and figure (b))



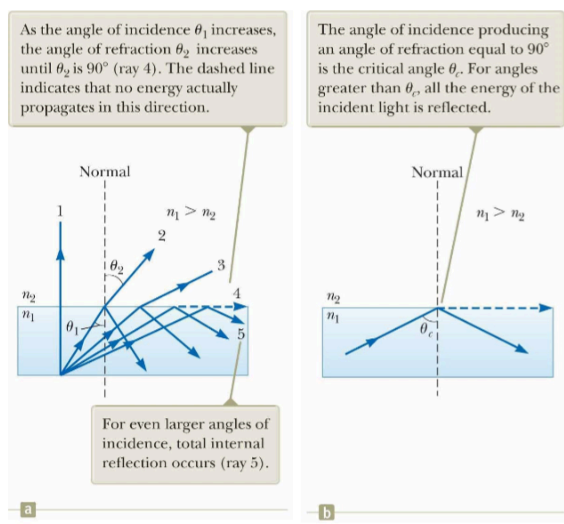
Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Total Internal Reflection

- For angles of incidence > θ_c:
  - Rays cannot escape from the material and will be entirely reflected at boundary (ray 5 figure (a))
- Use Snell's law of refraction to find the ***critical angle***
  - When $\theta_1 = \theta_c$, θ_2 = 90°:

$$\sin\theta_c = \frac{n_2}{n_1} \quad (\text{for } n_1 > n_2)$$

- Total internal reflection **occurs only when** light travels from a higher index of refraction medium to a lower index of refraction medium
- If $n_1 < n_2$ → equation gives $\sin\theta_c > 1$
  - impossible situation!



Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Total Internal Reflection

Diamonds

- Critical angle for a diamond in air = 24° (n: ~2.4)
  - Any ray inside the diamond that approaches surface at angle > 24° completely is reflected back into the crystal
  - This property, combined with proper faceting, causes diamonds to sparkle
- Angles of the facets cut so that light is "caught" inside the crystal through multiple internal reflections
  - Multiple reflections give light long path through medium
  - Substantial dispersion of colors occurs
- By the time light exits through the top surface of the crystal:
  - Rays associated with different colors widely separated from one another

<u>Source:</u> Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.
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Total Internal Reflection

Cubic Zirconia

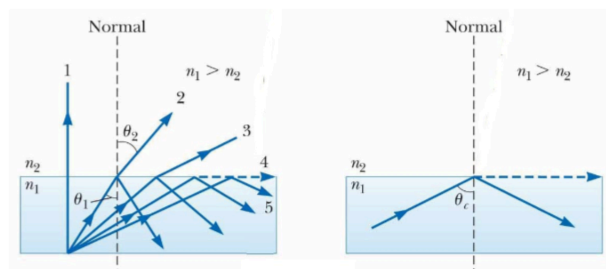
- Cubic zirconia: high index of refraction (n: ~2.2)
  - Can be made to sparkle like diamond.
- If a suspect jewel is immersed in corn syrup →
  - Difference in n for cubic zirconia and that for corn syrup (n: ~1.5) is small.
  - Critical angle is great.
  - More rays escape sooner →
    - Sparkle completely disappears
- Real diamond does not lose all its sparkle when placed in corn syrup

<u>Source:</u> Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Angle of Refraction for Glass

Example 34.6

Find the critical angle for an air–water boundary. (Assume the index of refraction of water is ***1.33***.)



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Angle of Refraction for Glass

Example 34.6

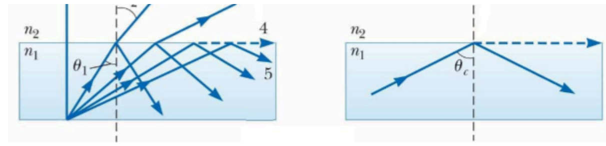
Find the critical angle for an air–water boundary. (Assume the index of refraction of water is ***1.33***.)

Solution

$\sin \theta_c = \frac{n_2}{\ } = \frac{1.00}{\ } = 0.752$

$n_1 \quad 1.33$

$\theta_c = \boxed{48.8°}$

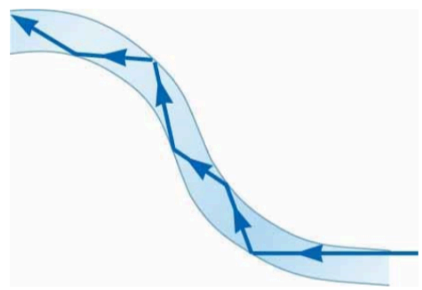


Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Total Internal Reflection

Optical Fibers

- A great application example of total internal reflection
- Use of glass or transparent plastic rods to "pipe" light from one place to another
- Figure: light is confined to travel within the rod (even around curves)
  - Result of successive total internal reflections
- Light pipe: flexible with thin fibers rather than thick rods
  - Flexible light pipe: **optical fiber**
- Part of the 2009 Nobel Prize in Physics was awarded to ***Charles K. Kao*** for his discovery of how to transmit light signals over long distances through thin glass fibers
  - Discovery led to the development of sizable industry known as ***fiber optics***



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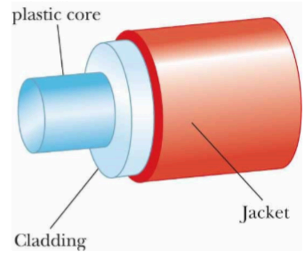
Total Internal Reflection

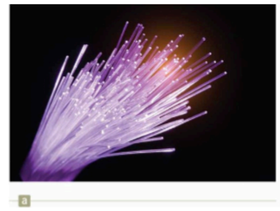
Glass or

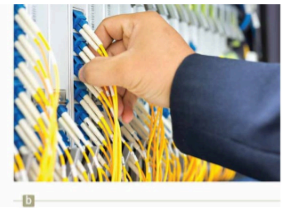
Optical Fibers

- Figure: cutaway view of an optical fiber



- An optical fiber consists of a transparent core surrounded by a ***cladding*** (material that has lower index of refraction than the core)
  - Combination may be surrounded by plastic ***jacket*** to prevent mechanical damage
- Because index of refraction of the cladding < that of the core →
  - Light traveling in the core experiences total internal reflection if it arrives at interface between core and cladding at angle of incidence > θ_c
  - Light "***bounces***" along the core of an optical fiber
- Optical fiber cables replacing copper wiring and coaxial cables for telecommunications →
  - Fibers can carry much greater volume of telephone calls or other forms of communication than electrical wires can

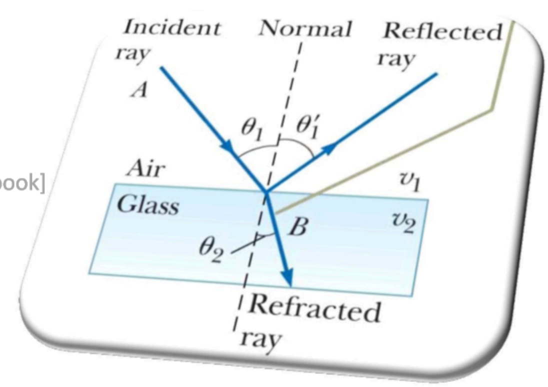




Source: Serway, Raymond A., and John W. Jewett. *Physics for scientists and engineers*. 10th Edition. Cengage learning, 2018.

Summary of Week 12, Class 10

- Reminder of the previous week
- Nature of Light and Ray Optics (Ch. 34)
  - The Nature of Light
  - The Ray Approximation in Ray Optics
  - Analysis Model: Wave Under Reflection
  - Analysis Model: Wave Under Refraction
  - Huygen's Principle [Optional – Reading from Textbook]
  - Dispersion
  - Total Internal Reflection
- Examples
- Next week's topic



Reading / Preparation for Next Week

Topics for next week:

- Image Formation (Ch. 35)