General Physics (PHY 2130)

Lecture XII

- Sound
  - sound waves
  - Doppler effect
  - Standing waves
- Light
  - Reflection and refraction

WAYNE STATE UNIVERSITY

Lightning Review

Last lecture:

1. Vibration and waves
   - ✓ Hooke's law
   - ✓ Potential energy of an oscillator
   - ✓ Simple harmonic motion, pendulums
   - ✓ waves

Review Problem: The speed of a wave on a string depends on

1. the amplitude of the wave
2. the material properties of the string
3. both of the above
4. neither of the above

If you want to know your detailed progress…

e-mail your request to apetrov@physics.wayne.edu

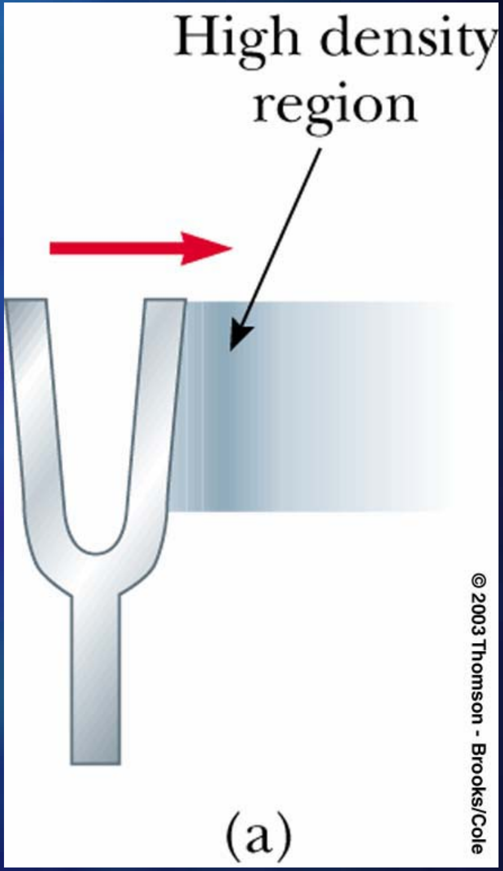
Sound

Producing a Sound Wave

- Sound waves are longitudinal waves traveling through a medium
- A tuning fork can be used as an example of producing a sound wave

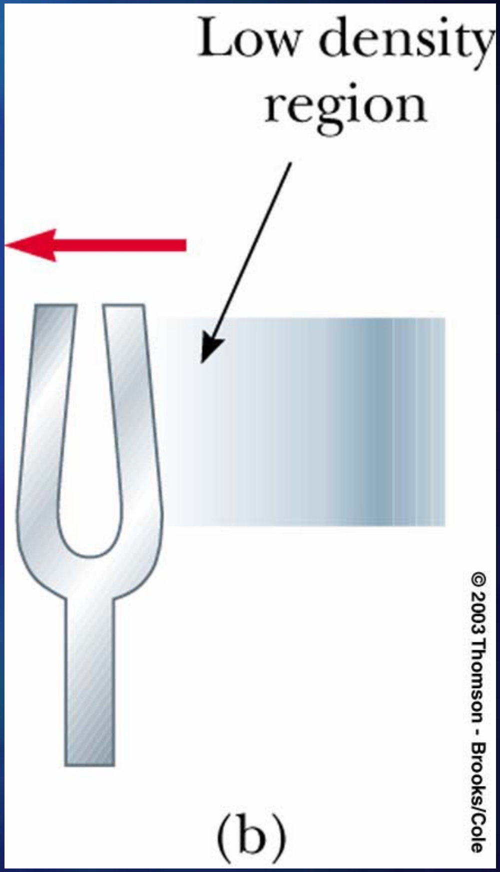
Using a Tuning Fork to Produce a Sound Wave

- A tuning fork will produce a pure musical note
- As the tines vibrate, they disturb the air near them
- As the tine swings to the right, it forces the air molecules near it closer together
- This produces a high density area in the air
  - This is an area of compression

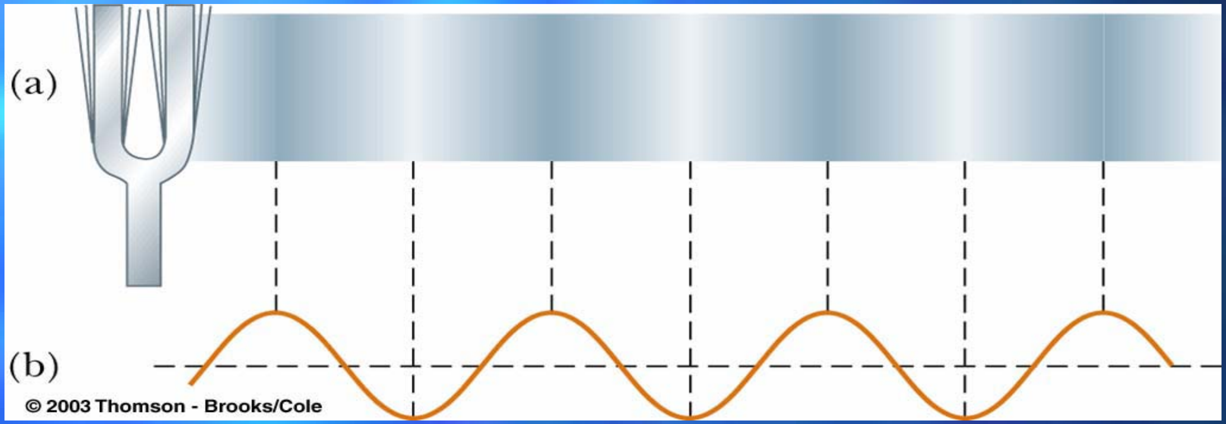


Using a Tuning Fork

- As the tine moves toward the left, the air molecules to the right of the tine spread out
- This produces an area of low density
  - This area is called a *rarefaction*



Using a Tuning Fork



- As the tuning fork continues to vibrate, a succession of compressions and rarefactions spread out from the fork
- A sinusoidal curve can be used to represent the longitudinal wave
  - Crests correspond to compressions and troughs to rarefactions

Categories of Sound Waves

- Audible waves
  - Lay within the normal range of hearing of the human ear
  - Normally between 20 Hz to 20,000 Hz
- Infrasonic waves
  - Frequencies are below the audible range
- Ultrasonic waves
  - Frequencies are above the audible range

Applications of Ultrasound

- Can be used to produce images of small objects
- Widely used as a diagnostic and treatment tool in medicine
  - Ultrasonic flow meter to measure blood flow
  - May use *piezoelectric* devices that transform electrical energy into mechanical energy
    - Reversible: mechanical to electrical
  - Ultrasounds to observe babies in the womb
  - Cavitron Ultrasonic Surgical Aspirator (CUSA) used to surgically remove brain tumors
  - Ultrasonic ranging unit for cameras

Speed of Sound

$$v = \sqrt{\frac{elastic\ property}{inertial\ property}}$$

- The speed of sound is higher in solids than in gases
  - The molecules in a solid interact more strongly
- The speed is slower in liquids than in solids
  - Liquids are more compressible

Speed of Sound in Air

$$v = (331\,\frac{m}{s})\sqrt{\frac{T}{273\ K}}$$

- 331 m/s is the speed of sound at 0° C
- T is the absolute temperature

Example: thunderstorm

Suppose that you hear a clap of thunder 16.2 s after seeing the associated lightning stroke. The speed of sound waves in air is 343 m/s and the speed of light in air is 3.00×10^8 m/s. How far are you from the lightning stroke?

Example:

Given:

v_{light}=343 m/s
v_{sound}=$3x10^8$ m/s
t=16.2 s

Find:

d=?

Example:

Given:

v_{light}=343 m/s
v_{sound}=$3x10^8$ m/s
t=16.2 s

Find:

d=?

Since $v_{light} >> v_{sound}$, we ignore the time required for the lightning flash to reach the observer in comparison to the transit time for the sound.

Then, $d \approx (343\ \text{m/s})(16.2\ \text{s}) = 5.56 \times 10^3\ \text{m} = \boxed{5.56\ \text{km}}$ ✓

Intensity of Sound Waves

- The *intensity* of a wave is the rate at which the energy flows through a unit area, A, oriented perpendicular to the direction of travel of the wave

$$I = \frac{\Delta E}{A\,\Delta t} = \frac{P}{A}$$

- P is the power, the rate of energy transfer
- Units are W/m^2

Various Intensities of Sound

- Threshold of hearing
  - Faintest sound most humans can hear
  - About 1×10^{-12} W/m^2
- Threshold of pain
  - Loudest sound most humans can tolerate
  - About 1 W/m^2
- The ear is a very sensitive detector of sound waves

Intensity Level of Sound Waves

- The sensation of loudness is logarithmic in the human hear
- β is the intensity level or the decibel level of the sound

$$\beta = 10 \log \frac{I}{I_o}$$

- I_o is the threshold of hearing
  - Threshold of hearing is 0 dB
  - Threshold of pain is 120 dB
  - Jet airplanes are about 150 dB

Example: rock concert

The sound intensity at a rock concert is known to be about 1 W/m^2. How many decibels is that?

Example:

Given:

$I_0 = 10^{-12}$ W/m^2
$I_1 = 10^0$ W/m^2

Find:

1. $\beta = ?$

1. Use a definition of intensity level in decibels:

$$\beta = 10 \log_{10}\left(\frac{I}{I_0}\right) =$$

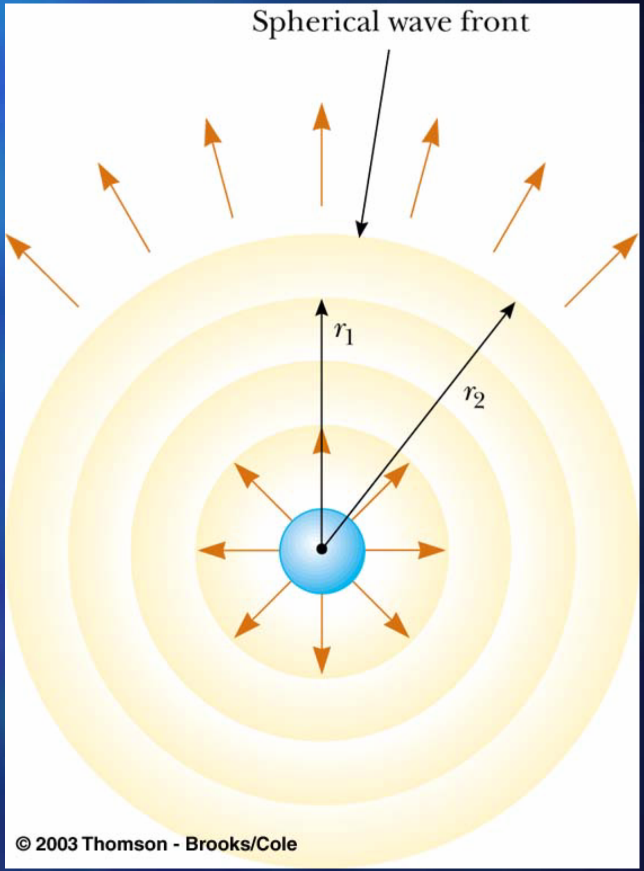
$$= 10 \log_{10}\left(\frac{10^0}{10^{-12}}\right) = 10 \log_{10}\left(10^{12}\right) = 120 dB$$ ✓

Note: same level of intensity level as pain threshold! Normal conversation's intensity level is about 50 dB.

Spherical Waves

- A spherical wave propagates radially outward from the oscillating sphere
- The energy propagates equally in all directions
- The intensity is

$$I = \frac{P}{4\pi r^2}$$



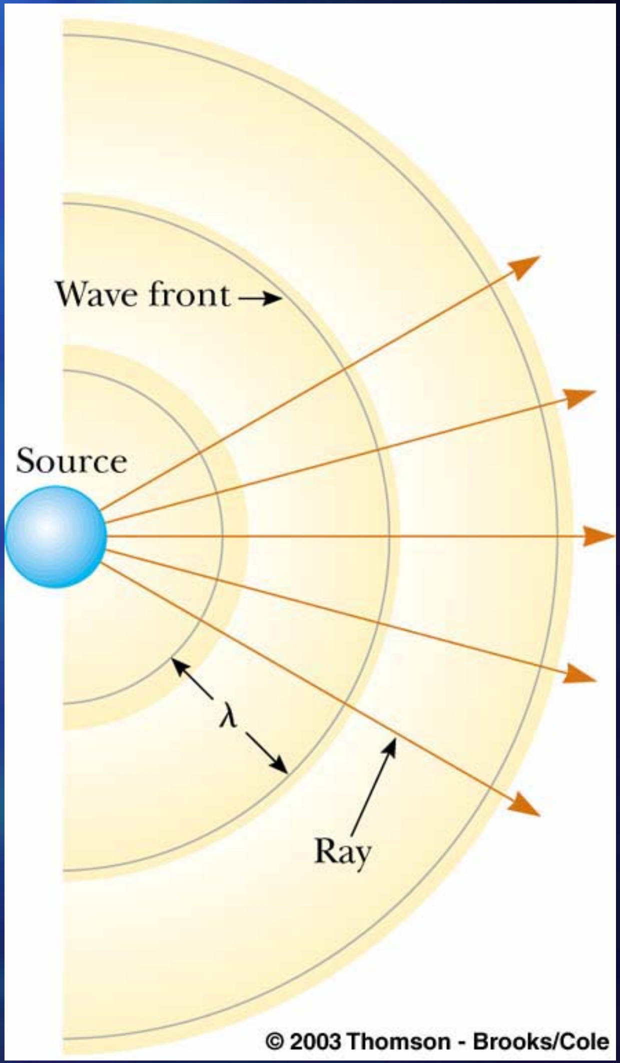
Intensity of a Point Source

- Since the intensity varies as $1/r^2$, this is an *inverse square relationship*
- The average power is the same through any spherical surface centered on the source
- To compare intensities at two locations, the inverse square relationship can be used

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

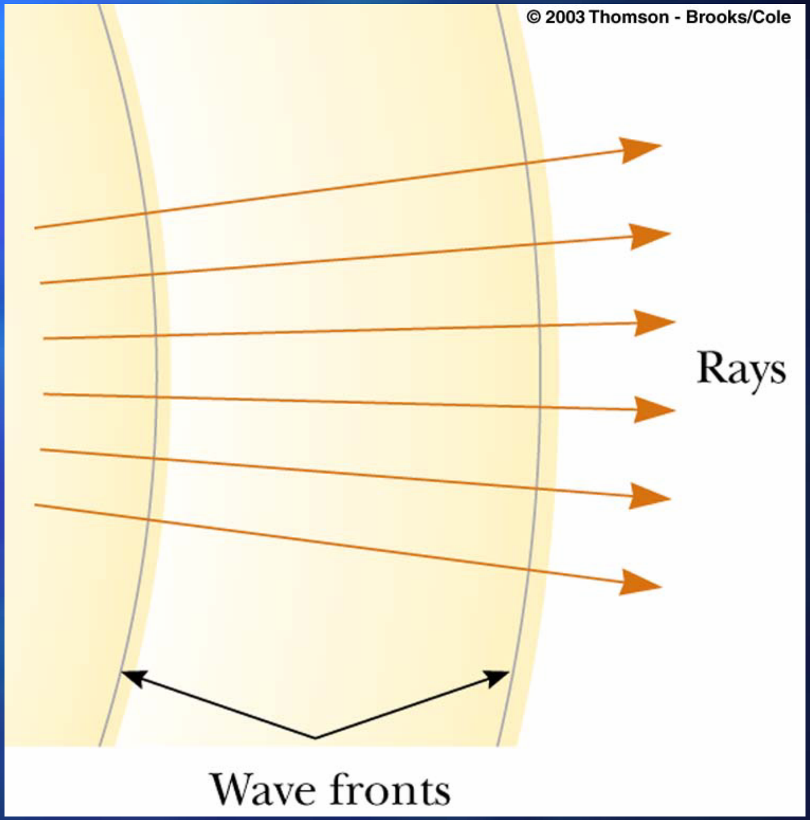
Representations of Waves

- *Wave fronts* are the concentric arcs
  - The distance between successive wave fronts is the wavelength
- *Rays* are the radial lines pointing out from the source and perpendicular to the wave fronts



Plane Wave

- Far away from the source, the wave fronts are nearly parallel planes
- The rays are nearly parallel lines
- A small segment of the wave front is approximately a plane wave



Doppler Effect

- A Doppler effect is experienced whenever there is relative motion between a source of waves and an observer.
  - When the source and the observer are moving toward each other, the observer hears a higher frequency
  - When the source and the observer are moving away from each other, the observer hears a lower frequency
- Although the Doppler Effect is commonly experienced with sound waves, it is a phenomena common to all waves

Doppler Effect, Case 1

- An observer is moving toward a stationary source
- Due to his movement, the observer detects an additional number of wave fronts
- The frequency heard is increased

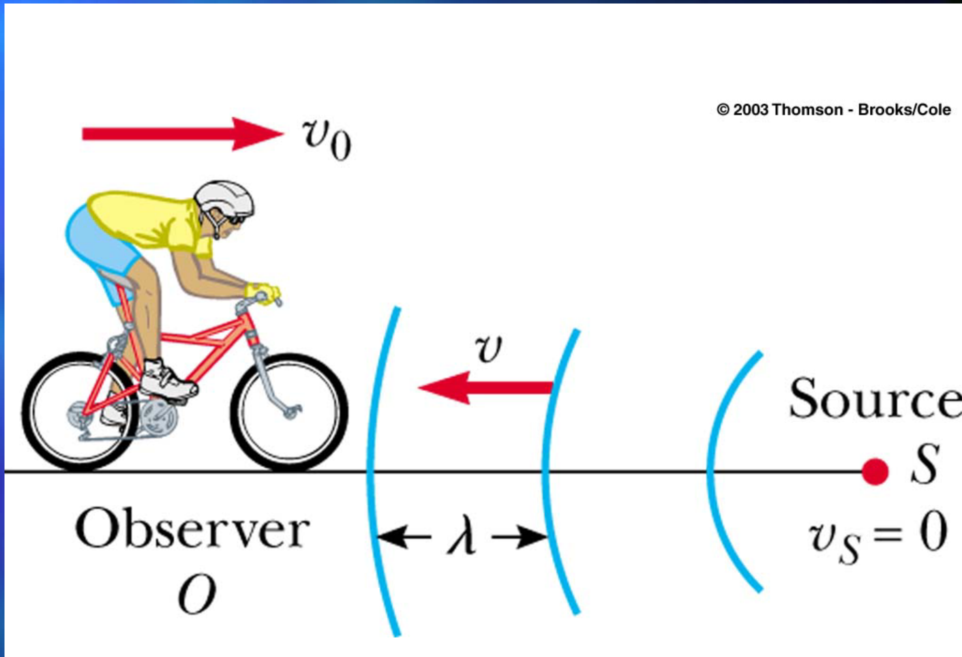


Fig 14.8, p. 435

Doppler Effect, Case 2

- An observer is moving away from a stationary source
- The observer detects fewer wave fronts per second
- The frequency appears lower

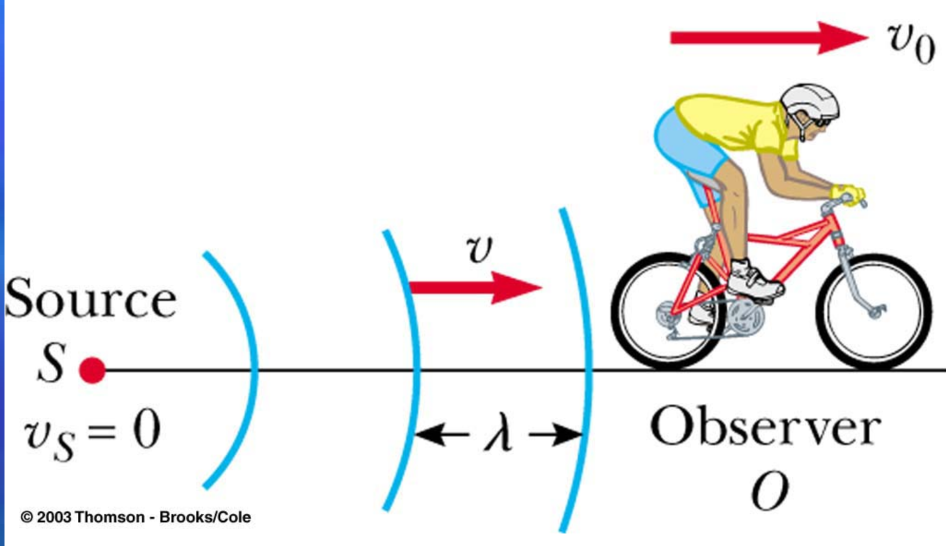


Fig 14.9, p. 436

Doppler Effect, Summary of Observer Moving

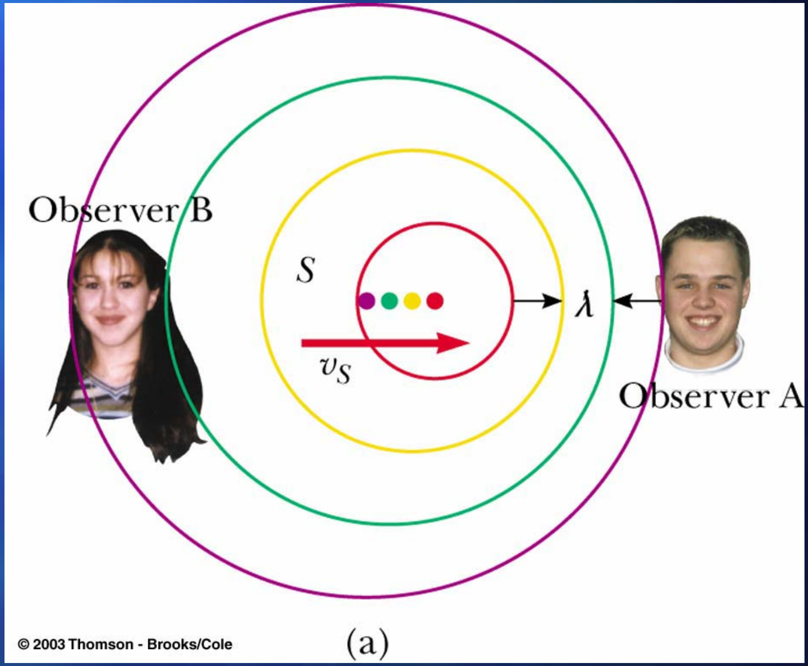
- The apparent frequency, f', depends on the actual frequency of the sound and the speeds

$$f' = f\left(\frac{v + v_o}{v}\right)$$

- v_o is positive if the observer is moving toward the source and negative if the observer is moving away from the source

Doppler Effect, Source in Motion

- As the source moves toward the observer (A), the wavelength appears shorter and the frequency increases
- As the source moves away from the observer (B), the wavelength appears longer and the frequency appears to be lower



Doppler Effect, Source Moving

$$f' = f\left(\frac{v}{v - v_s}\right)$$

- Use the $-v_s$ when the source is moving toward the observer and $+v_s$ when the source is moving away from the observer

Example: taking a train

An alert phys 2130 student stands beside the tracks as a train rolls slowly past. He notes that the frequency of the train whistle is 442 Hz when the train is *approaching* him and 441 Hz when the train is *receding* from him. From this he can find the speed of the train. What value does he find?

Example:

<u>Given:</u>

frequencies:

f_1=442 Hz

f_2=441 Hz

sound speed: *v=345 m/s*

<u>Find</u>:

v=?

With the train *approaching* at speed , the observed frequency is

$$442 \text{ Hz} = f\left(\frac{345 \text{ m/s} + 0}{345 \text{ m/s} - v_t}\right) = f\left(\frac{345 \text{ m/s}}{345 \text{ m/s} - v_t}\right) \quad (1)$$

As the train *recedes*, the observed frequency is

$$441 \text{ Hz} = f\left[\frac{345 \text{ m/s} + 0}{345 \text{ m/s} - (-v_t)}\right] = f\left(\frac{345 \text{ m/s}}{345 \text{ m/s} + v_t}\right) \quad (2)$$

Dividing equation (1) by (2) gives ,

$$\frac{442}{441} = \frac{345 \text{ m/s} + v_t}{345 \text{ m/s} - v_t}$$

and solving for the speed of the train yields

$$v_t = 0.391 \text{ m/s}$$ ✓

Doppler Effect, both moving

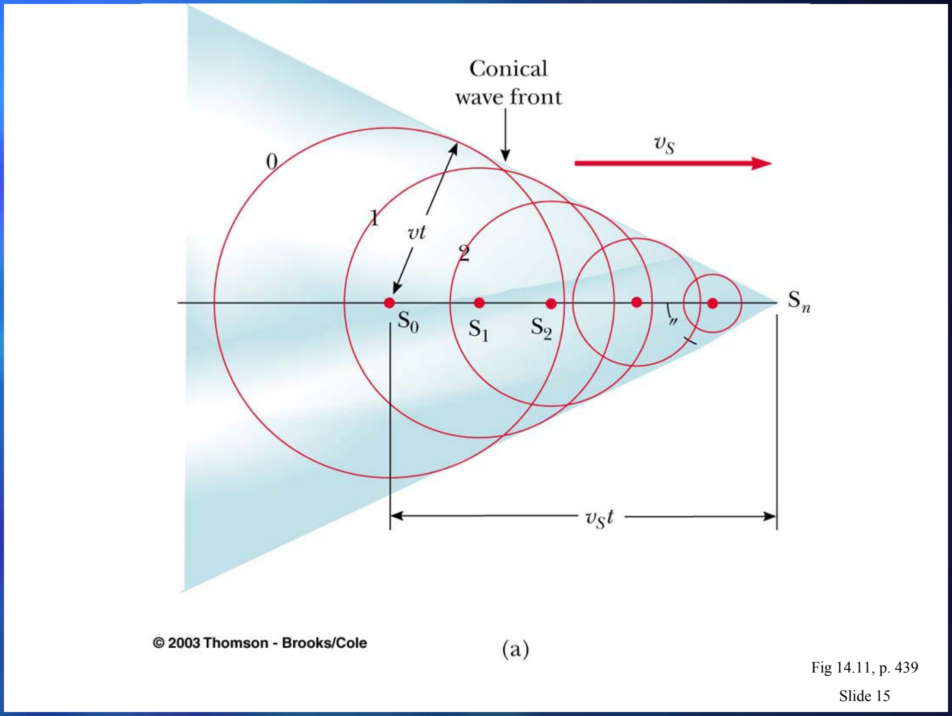
- Both the source and the observer could be moving

$$f' = f\left(\frac{v + v_o}{v - v_s}\right)$$

- Use positive values of v_o and v_s if the motion is toward
  - Frequency appears higher
- Use negative values of v_o and v_s if the motion is away
  - Frequency appears lower

Shock Waves

- A shock wave results when the source velocity exceeds the speed of the wave itself
- The circles represent the wave fronts emitted by the source



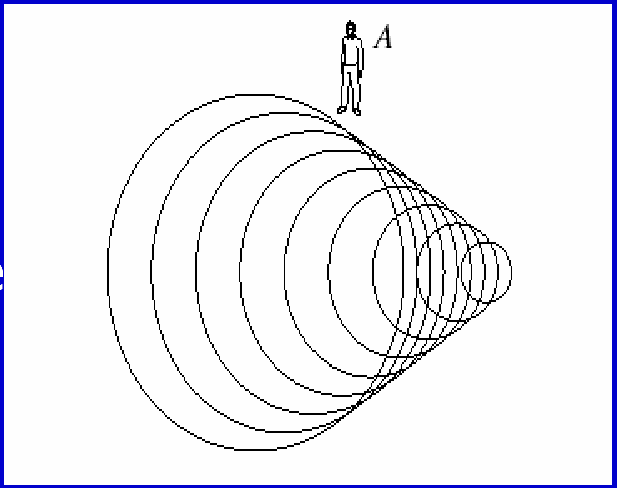
Shock Waves

- Tangent lines are drawn from S_n to the wave front centered on S_o
- The angle between one of these tangent lines and the direction of travel is given by $\sin \theta = v / v_s$
- The ratio v/v_s is called the *Mach Number*
- The conical wave front is the *shock wave*
- Shock waves carry energy concentrated on the surface of the cone, with correspondingly great pressure variations

ConcepTest

The following figure shows the wave fronts generated by an airplane flying past an observer *A* at a speed greater than that of sound. After the airplane has passed, the observer reports hearing

1. a sonic boom only when the airplane breaks the sound barrier, then nothi
2. a succession of sonic booms.
3. a sonic boom, then silence.
4. first nothing, then a sonic boom, the the sound of engines.
5. no sonic boom because the airplane flew faster than sound all along.



Interference of Sound Waves

- Sound waves interfere
  - Constructive interference occurs when the path difference between two waves' motion is zero or some integer multiple of wavelengths
    - path difference = $n\lambda$
  - Destructive interference occurs when the path difference between two waves' motion is an odd half wavelength
    - path difference = $(n + \frac{1}{2})\lambda$

Standing Waves

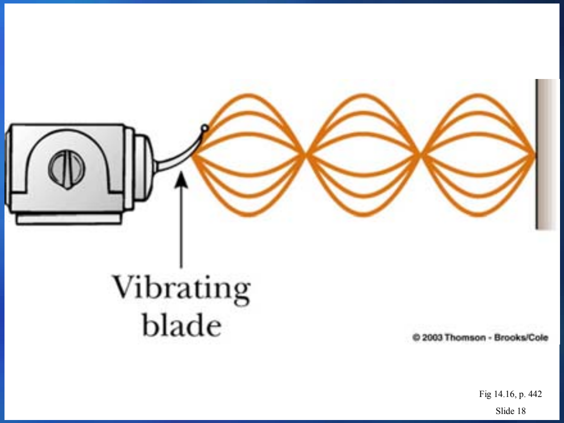
- When a traveling wave reflects back on itself, it creates traveling waves in both directions
- The wave and its reflection interfere according to the superposition principle
- With exactly the right frequency, the wave will appear to stand still
  - This is called a *standing wave*

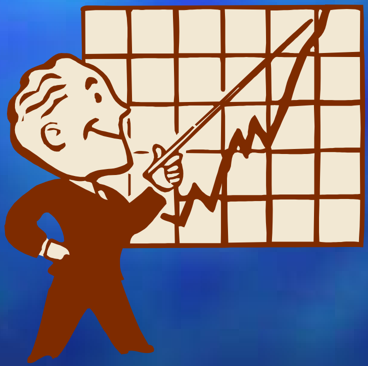
Standing Waves

- A *node* occurs where the two traveling waves have the same magnitude of displacement, but the displacements are in opposite directions
  - Net displacement is zero at that point
  - The distance between two nodes is $\frac{1}{2}\lambda$
- An *antinode* occurs where the standing wave vibrates at maximum amplitude

Standing Waves on a String

- Nodes must occur at the ends of the string because these points are fixed



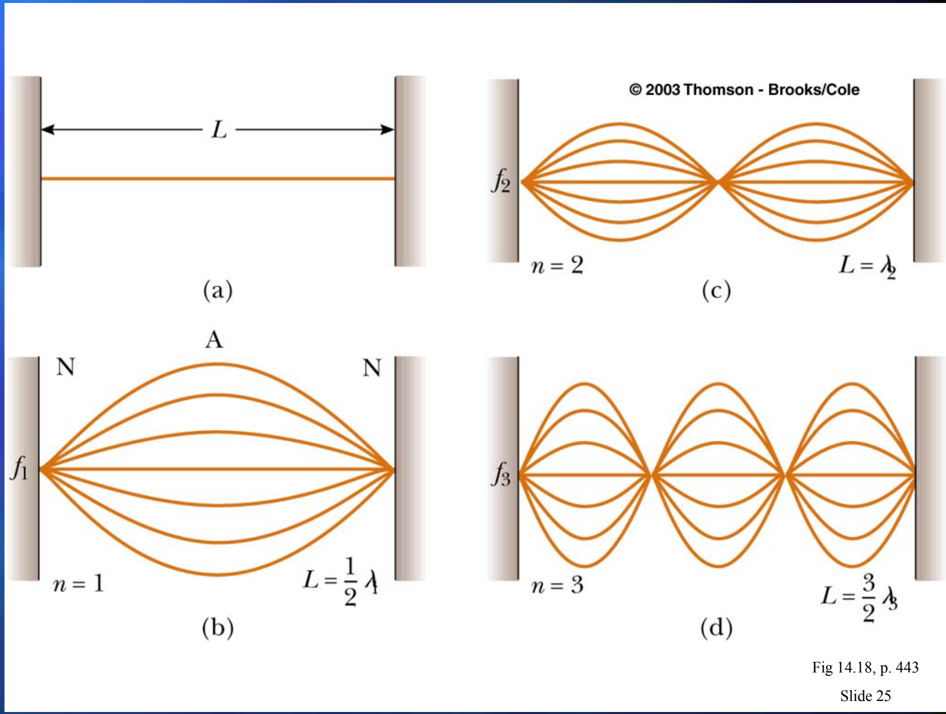


Let’s watch the movie!

Standing Waves on a String

- The lowest frequency of vibration (b) is called the *fundamental frequency*

$$f_n = n f_1 = \frac{n}{2L}\sqrt{\frac{F}{\mu}}$$



Standing Waves on a String

- f_1, f_2, f_3 form a harmonic series
  - f_1 is the fundamental and also the first harmonic
  - f_2 is the second harmonic
- Waves in the string that are not in the harmonic series are quickly damped out
  - In effect, when the string is disturbed, it "selects" the standing wave frequencies

Forced Vibrations

- A system with a driving force will force a vibration at its frequency
- When the frequency of the driving force equals the natural frequency of the system, the system is said to be in *resonance*

An Example of Resonance

- Pendulum A is set in motion
- The others begin to vibrate due to the vibrations in the flexible beam
- Pendulum C oscillates at the greatest amplitude since its length, and therefore frequency, matches that of A

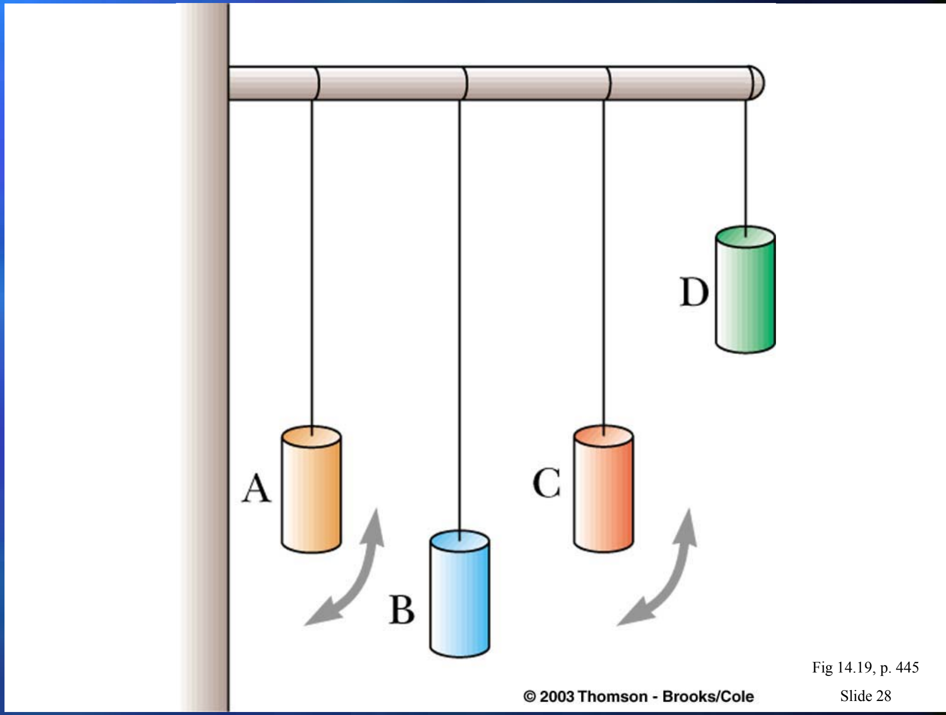
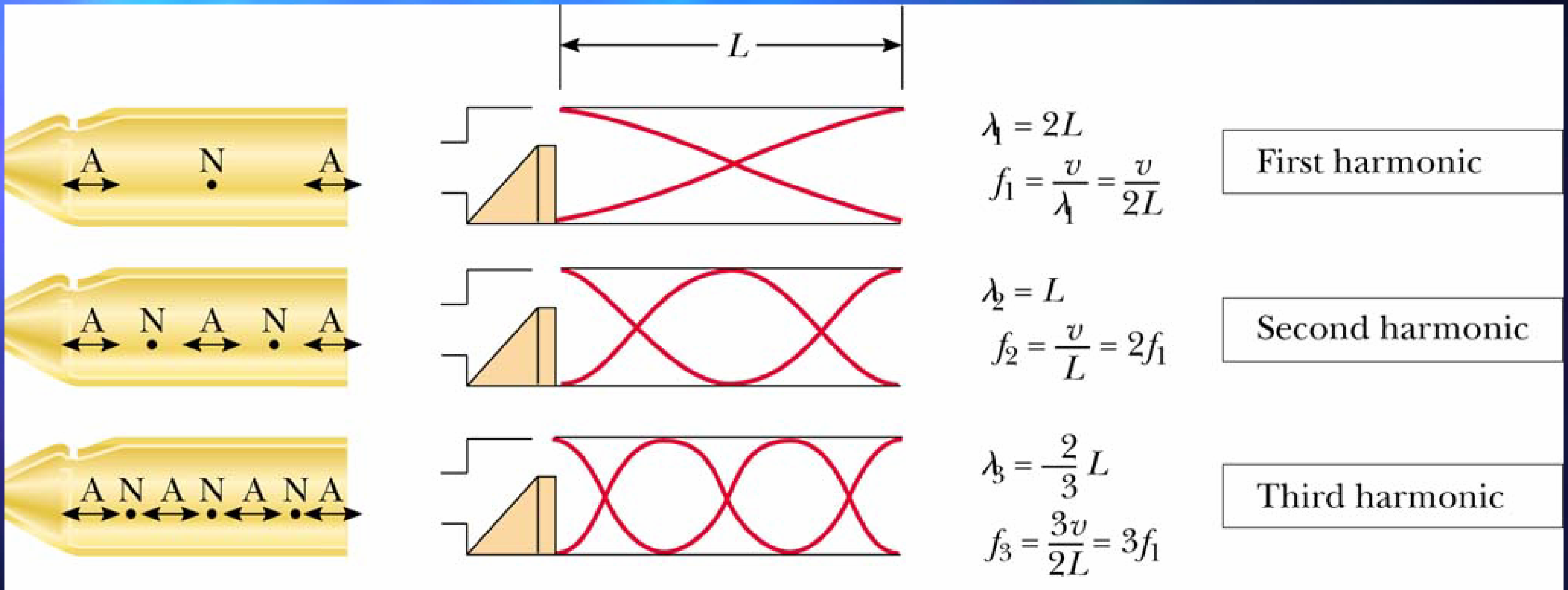


Fig 14.19, p. 445

Standing Waves in Air Columns

- If one end of the air column is closed, a node must exist at this end since the movement of the air is restricted
- If the end is open, the elements of the air have complete freedom of movement and an antinode exists

Tube Open at Both Ends



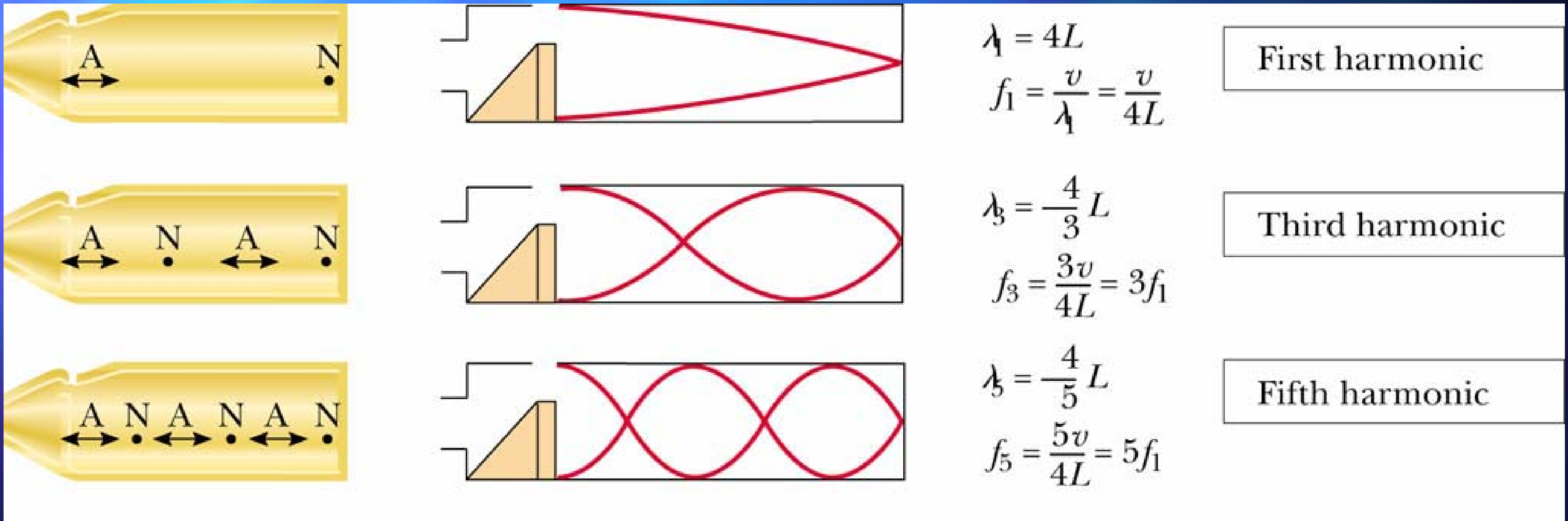
(a) Open at both ends

Resonance in Air Column Open at Both Ends

- In a pipe open at both ends, the natural frequency of vibration forms a series whose harmonics are equal to integral multiples of the fundamental frequency

$$f_n = n\frac{v}{2L} \quad n = 1, 2, 3, \ldots$$

Tube Closed at One End



(b) Closed at one end, open at the other

Resonance in an Air Column Closed at One End

- The closed end must be a node
- The open end is an antinode

$$f_n = n\frac{v}{4L} \quad n = 1, 3, 5, \ldots$$

The Ear

- The outer ear consists of the ear canal that terminates at the eardrum
- Just behind the eardrum is the middle ear
- The bones in the middle ear transmit sounds to the inner ear

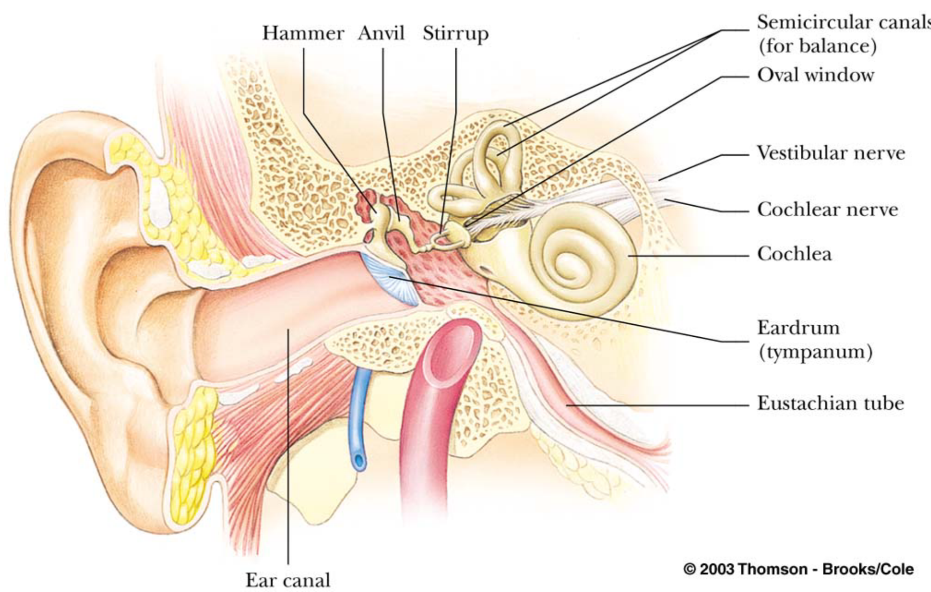


Fig 14.27, p. 452

Reflection and Refraction of Light

Dual nature of light

- In some cases light behaves like a *wave* (classical E & M – light propagation)
- In some cases light behaves like a *particle* (photoelectric effect)
- Einstein formulated theory of light:

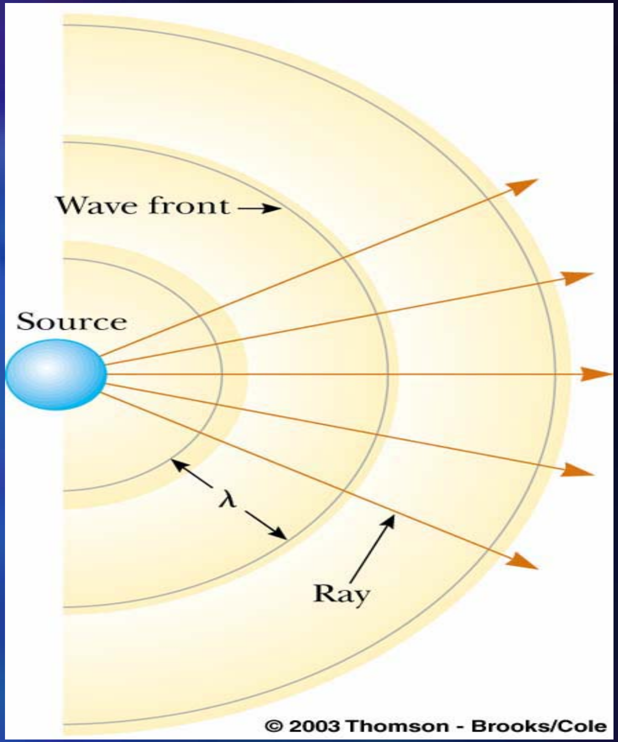
$$E = hf$$

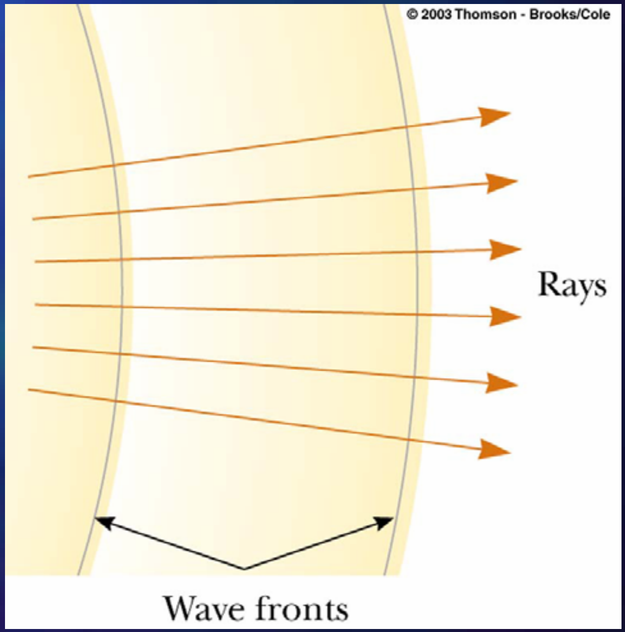
$$h = 6.63 \times 10^{-34} J \cdot s$$

Plank's constant

Optics

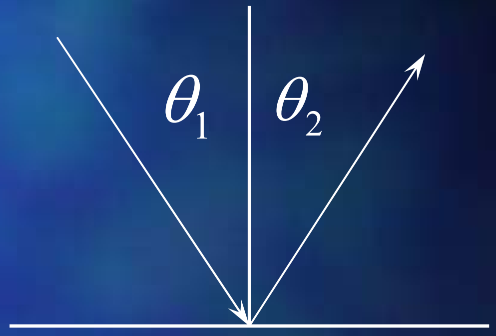
- Light travels at
  3.00×10^8 m/s in vaccum
  - travels slower in liquids and solids (in accord with predictions of particle theory)
- In order to describe propagation: Huygens method
  - All points on given wave front taken as point sources for propagation of spherical waves
- Assume wave moves through medium in straight line in direction of rays





Reflection of Light

- When light encounters boundary leading into second medium, part of incident ray reflects back



$$\theta_1 = \theta_2$$

Angle of incidence = angle of reflection

- Smooth surface:

- Rough surface: