9.1 Production and Propagation of Sound and Electromagnetic Waves

9.2 Factors Related to the Speed of Waves

9.3 Interference of Waves and Related Properties

CHAPTER 9 Review

CHAPTER 9 Sound Waves and Electromagnetic Radiation

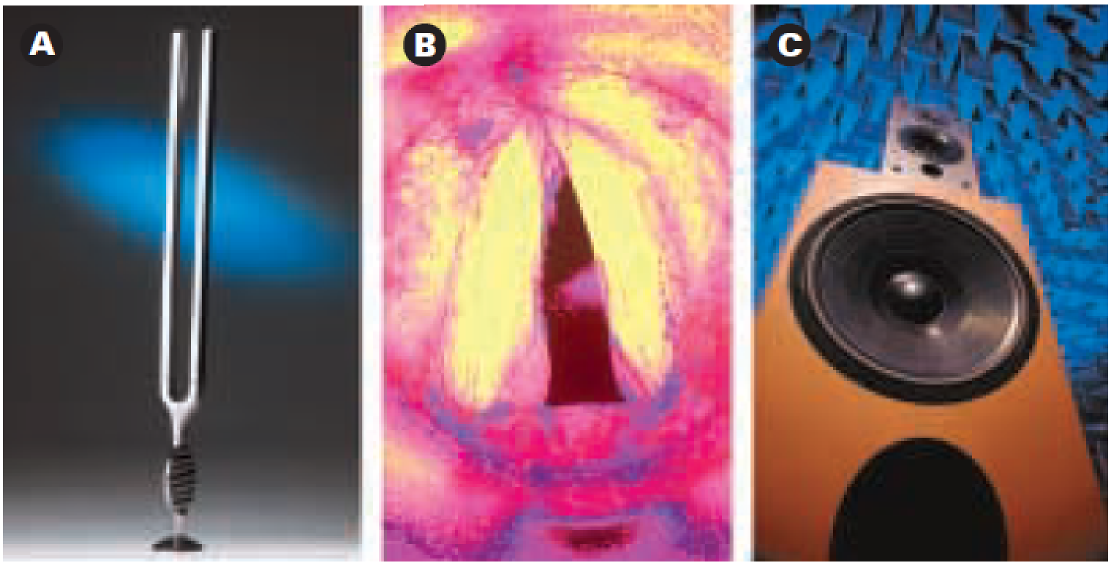
SECTION OUTCOMES

- Apply the law of reflection to predict wave behaviour.
- Describe how sound and electromagnetic radiation, as forms of energy transfer, are produced and transmitted.
- Compare and describe the properties of sound and electromagnetic radiation.

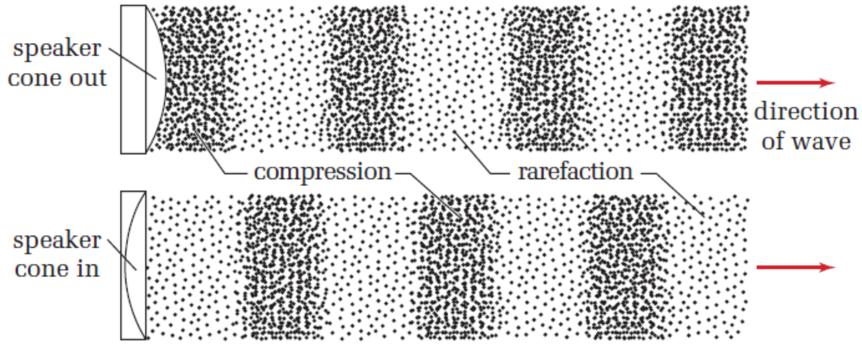
KEY TERMS

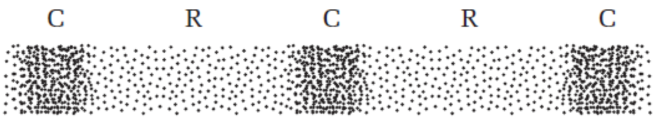
- compression
- rarefaction
- loudness
- pitch
- quality
- echolocation
- linear propagation of light
- ray model
- light ray
- law of reflection
- regular reflection
- diffuse reflection

Sound Waves

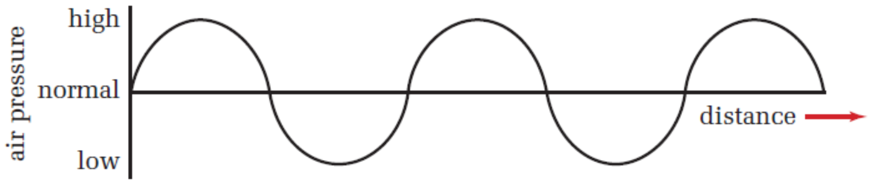


Sound Waves Are Longitudinal Waves



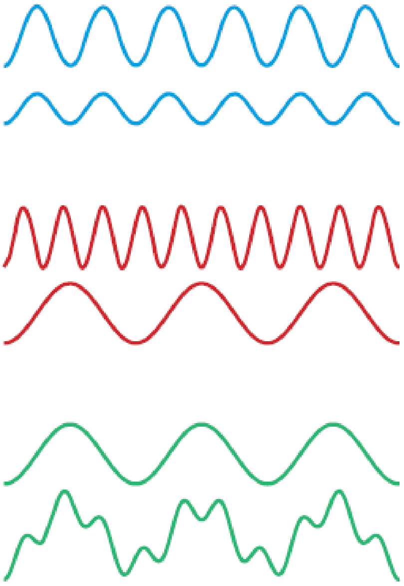


schematic representation of the density of air molecules

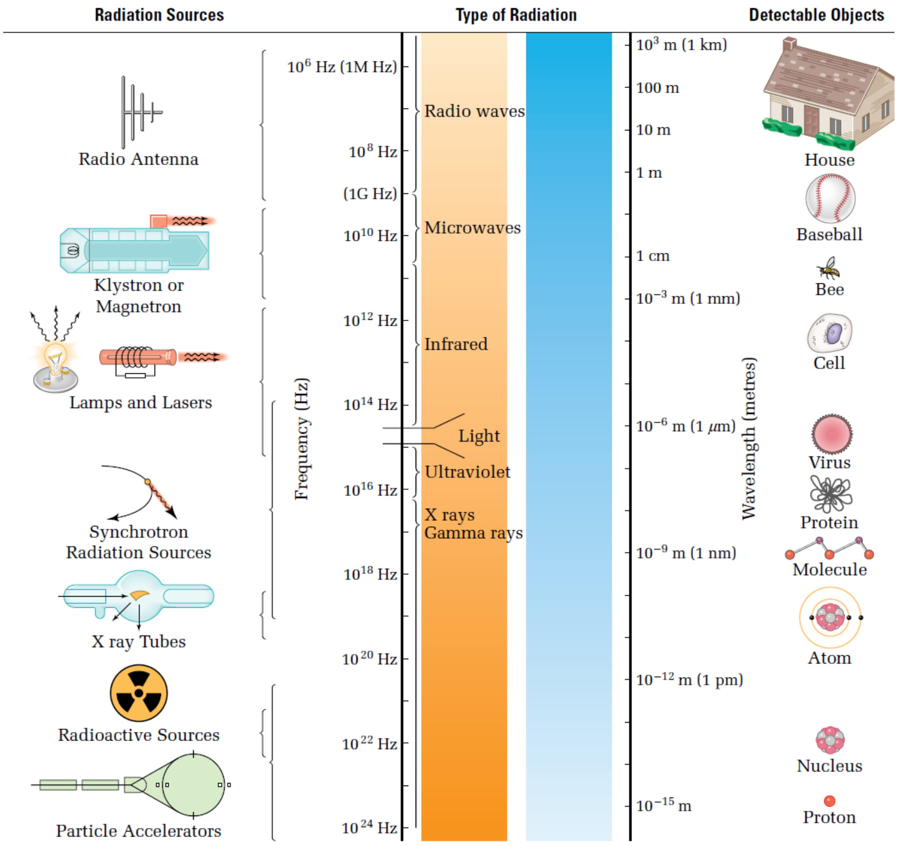


Properties of Sound

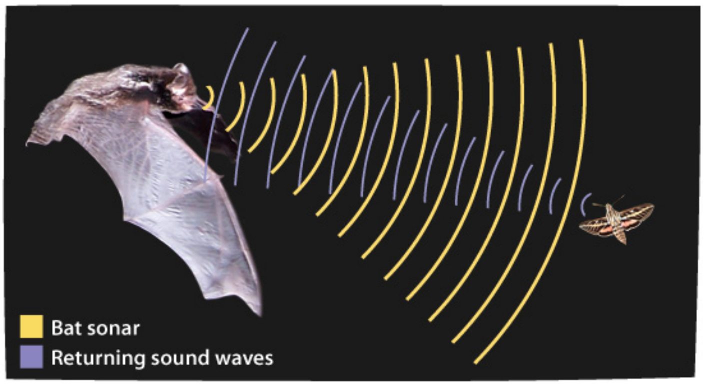
Sound perceptions	Sound wave characteristics
Loudness	**Amplitude**
loud	large
quiet	small
Pitch	**Frequency**
high	high
low	low
Quality	**Wave form**
pure	simple
rich	complex

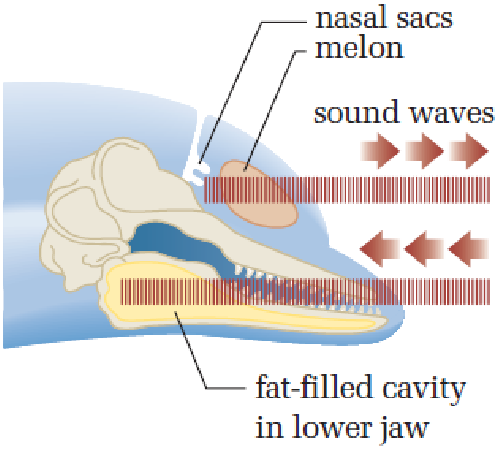


Electromagnetic Waves



Reflection of Sound Waves

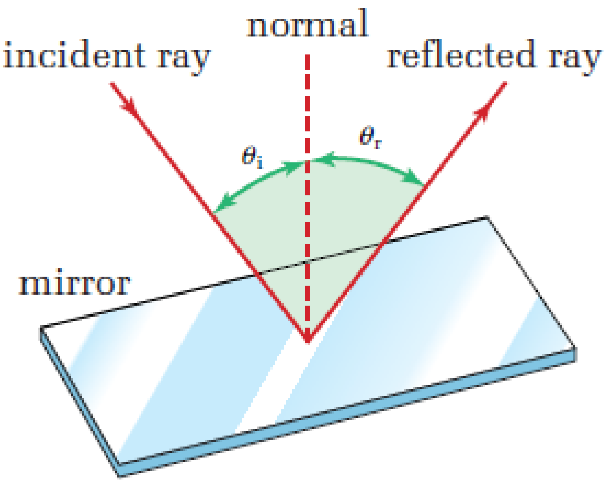




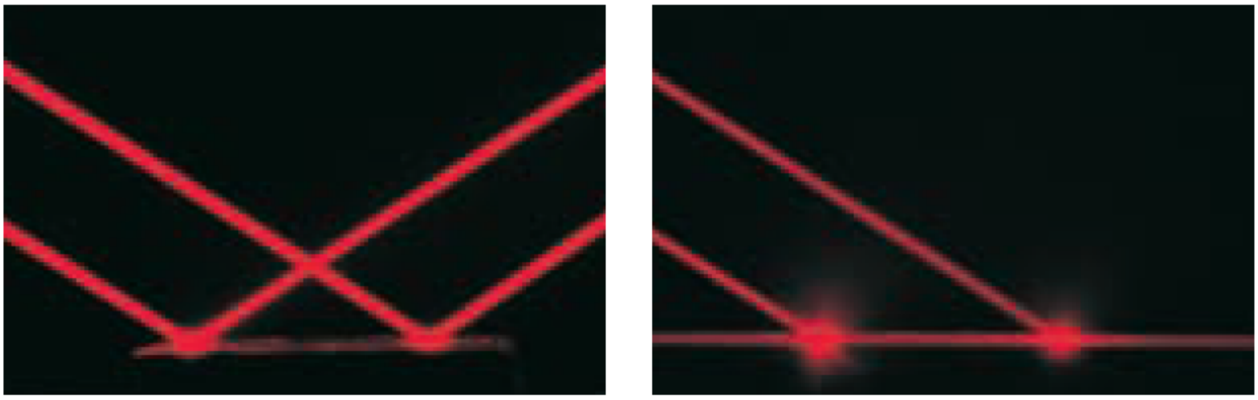
Reflection of Light

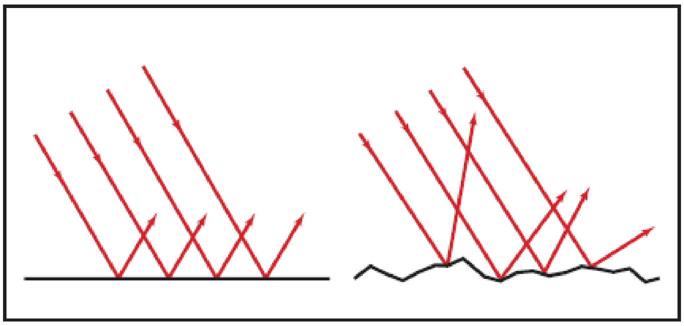
THE LAW OF REFLECTION

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



Regular and Diffuse Reflection





9.2

Factors Related to the Speed of Waves

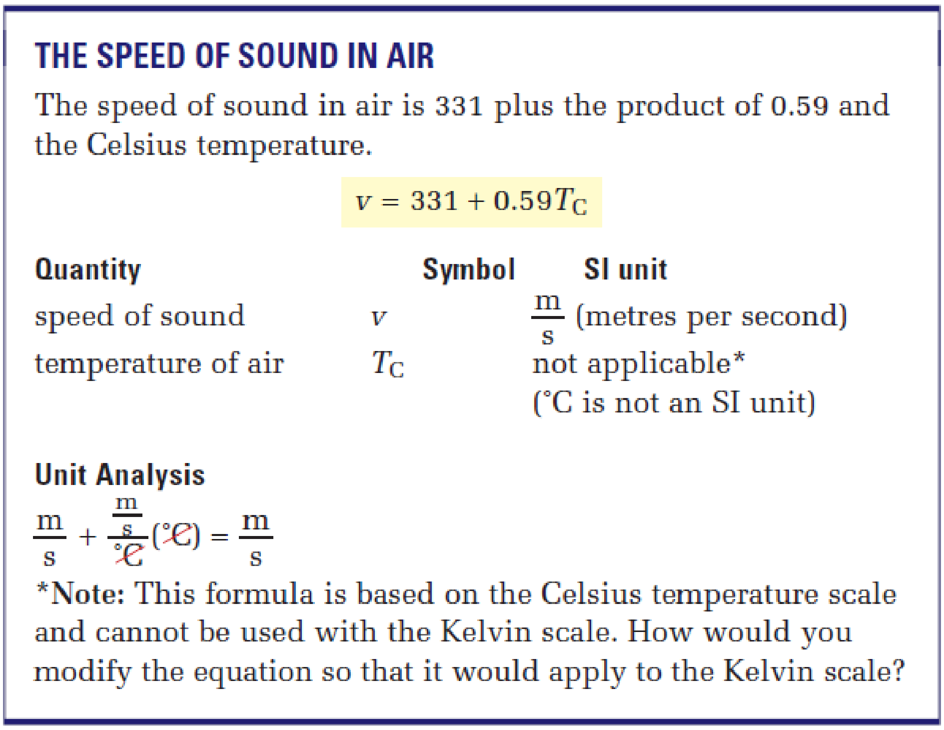
SECTION OUTCOMES

- Apply the law of refraction to predict wave behaviour.
- Explain the phenomena of refraction and the Doppler-Fizeau effect.
- Compare and describe the properties of sound and electromagnetic radiation.

KEY TERMS

- Mach number
- Doppler effect
- sonic boom
- Cerenkov radiation
- refraction
- index of refraction
- angle of refraction
- critical angle
- total internal reflection

The Speed of Sound in Air: A Wave Property



THE SPEED OF SOUND IN AIR

The speed of sound in air is 331 plus the product of 0.59 and the Celsius temperature.

$$v = 331 + 0.59T_C$$

Quantity	Symbol	SI unit
speed of sound	v	$\frac{m}{s}$ (metres per second)
temperature of air	T_C	not applicable* (°C is not an SI unit)

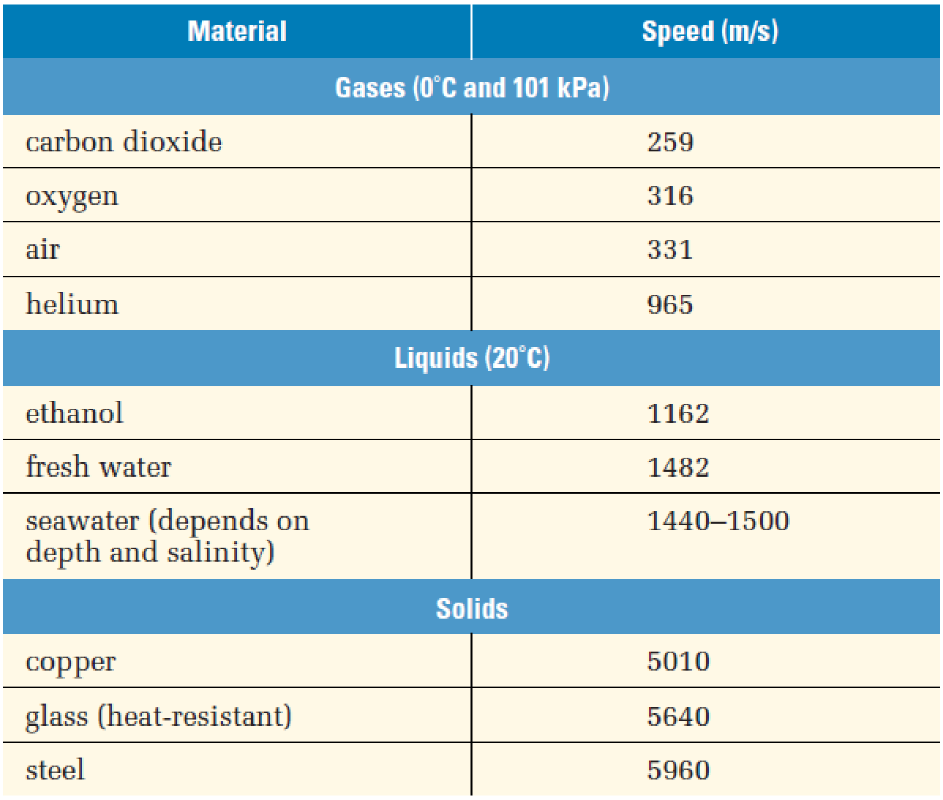
Unit Analysis

$$\frac{m}{s} + \frac{\frac{m}{s}}{\cancel{°C}}(\cancel{°C}) = \frac{m}{s}$$

***Note:** This formula is based on the Celsius temperature scale and cannot be used with the Kelvin scale. How would you modify the equation so that it would apply to the Kelvin scale?

Table 9.1 The Speed of Sound in Some Common Materials

Shale Gas Thumper Trucks



Material	Speed (m/s)
Gases (0°C and 101 kPa)	
carbon dioxide	259
oxygen	316
air	331
helium	965
Liquids (20°C)	
ethanol	1162
fresh water	1482
seawater (depends on depth and salinity)	1440–1500
Solids	
copper	5010
glass (heat-resistant)	5640
steel	5960

Applying the Speed of Sound Equation

1. Suppose the room temperature of a classroom is 21°C. Calculate the speed of sound in the classroom.

$$v = 331 + 0.59T_C$$

$V = 331 + (0.59)(21)$

$= 342.34 \text{ m/s}$

2. The temperature was 4.0°C one morning as Marita hiked through a canyon. She shouted at the canyon wall and 2.8 s later heard an echo. How far away was the canyon wall?

$V = 331 + 0.59T_c$

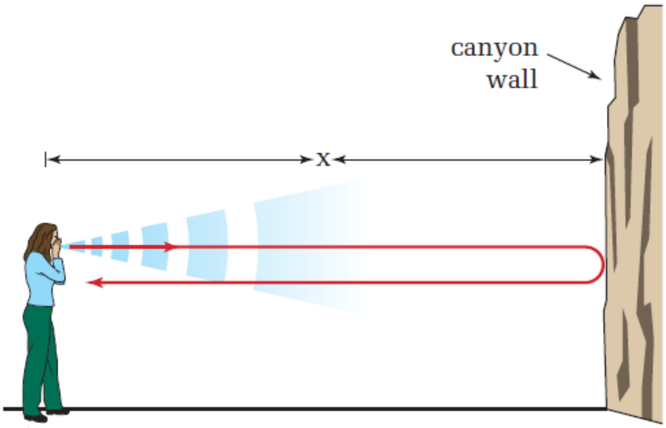
$= 331 + (0.59)(4)$

$V = 333.36 \text{ m/s}$

$V = \frac{d}{t}$

$d = v \cdot t = (333.36)(1.4)$

$\underline{= 466.7 \text{ m}}$



Mach Number

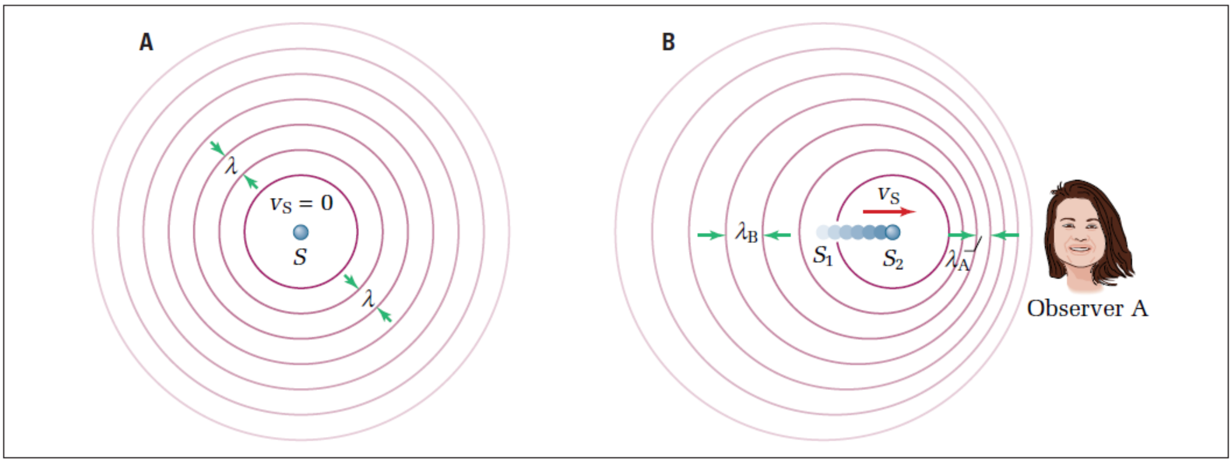
- developed by a Austrian physicist, Ernst Mach
- ratios of the actual speed of sound at the conditions of temperature and pressure in which the object is flying.

- therefore, Mach 1 describes an object travelling at the speed of sound for the conditions indicated
    - > ex: a plane flying at 331m/s at 0℃
- Mach 2 would be an object flying at 2X the speed of sound for those conditions

The Doppler Effect

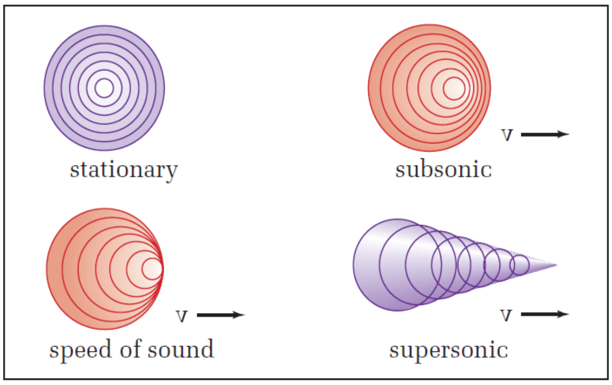
https://www.youtube.com/watch?v=imoxDcn2Sgo

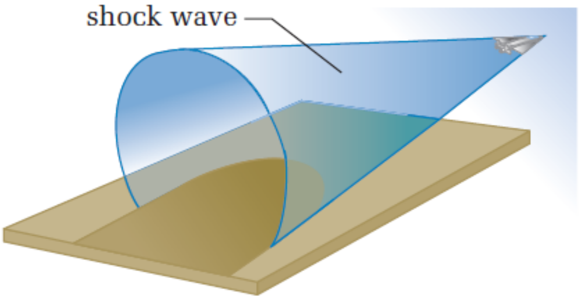
Figure 9.17 The Doppler effect



Sonic Booms

https://www.youtube.com/watch?v=gWGLAAYdbbc

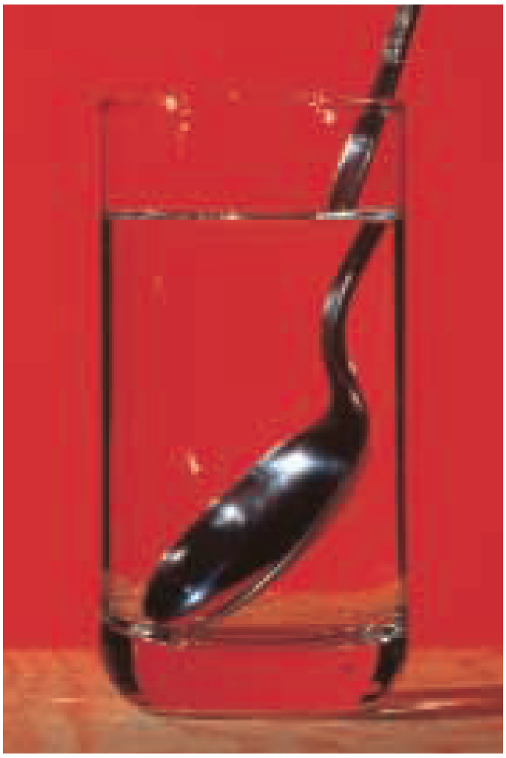




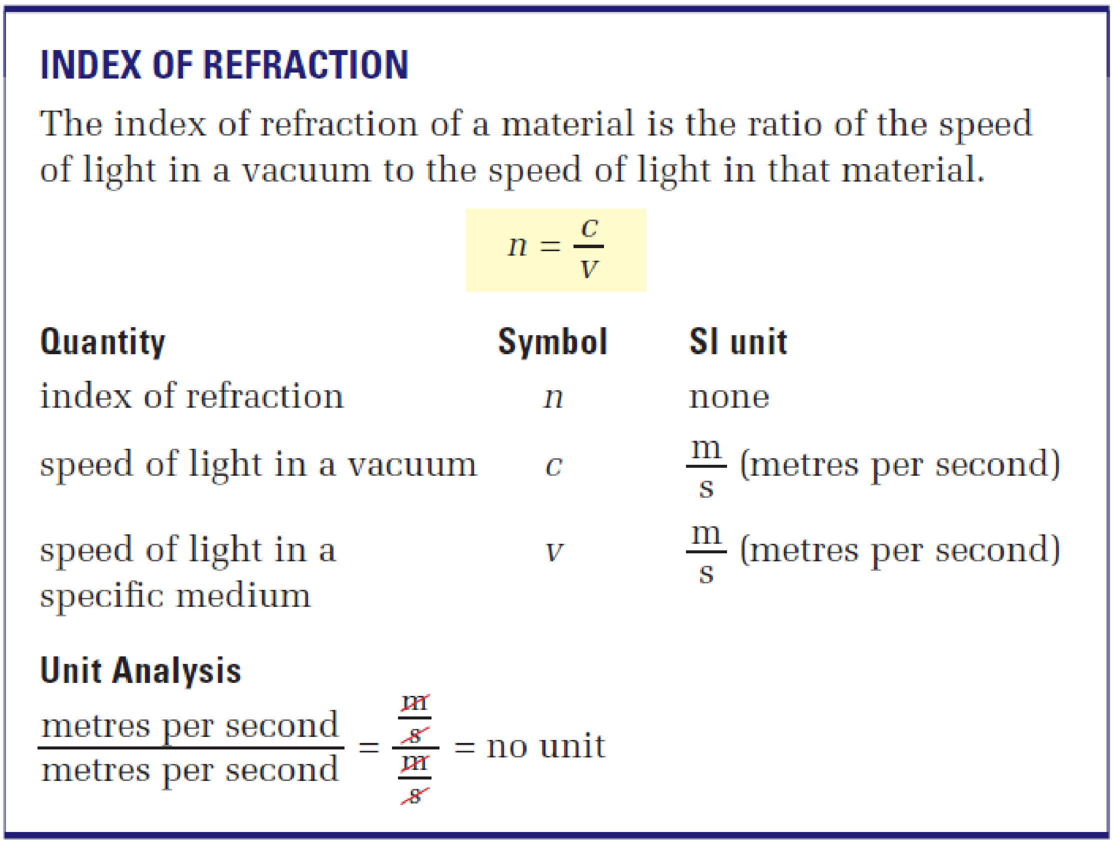
Refraction and Light Waves

- light rays appear 'bent' when the beam passes from one medium into another
- ex: From water into air

- called 'refraction'
  > heat waves, rainbows



Index of Refraction



INDEX OF REFRACTION

The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in that material.

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

Quantity	**Symbol**	**SI unit**
index of refraction	n	none
speed of light in a vacuum	c	$\frac{\text{m}}{\text{s}}$ (metres per second)
speed of light in a specific medium	v	$\frac{\text{m}}{\text{s}}$ (metres per second)

Unit Analysis

$$\frac{\text{metres per second}}{\text{metres per second}} = \frac{\frac{\cancel{\text{m}}}{\cancel{\text{s}}}}{\frac{\cancel{\text{m}}}{\cancel{\text{s}}}} = \text{no unit}$$

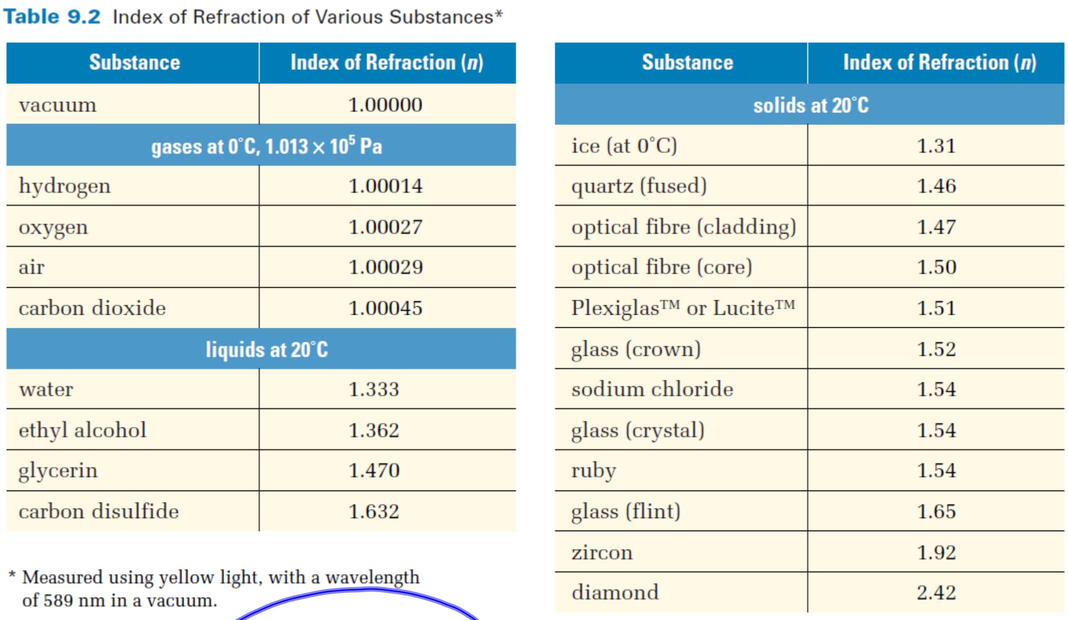


Table 9.2 Index of Refraction of Various Substances*

Substance	Index of Refraction (n)
vacuum	1.00000
gases at 0°C, 1.013×10^5 Pa	
hydrogen	1.00014
oxygen	1.00027
air	1.00029
carbon dioxide	1.00045
liquids at 20°C	
water	1.333
ethyl alcohol	1.362
glycerin	1.470
carbon disulfide	1.632
solids at 20°C	
ice (at 0°C)	1.31
quartz (fused)	1.46
optical fibre (cladding)	1.47
optical fibre (core)	1.50
Plexiglas™ or Lucite™	1.51
glass (crown)	1.52
sodium chloride	1.54
glass (crystal)	1.54
ruby	1.54
glass (flint)	1.65
zircon	1.92
diamond	2.42

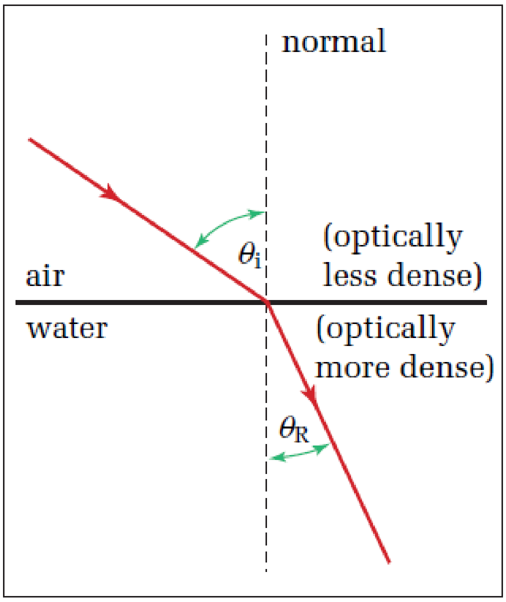
* Measured using yellow light, with a wavelength of 589 nm in a vacuum.

- the term 'optically dense' refers to any material where the speed of light in that material is low in comparison to the speed of light in another material
- the more optically dense a material is, the greater the change from the speed of light in a vaccuum

Snell's Observations

$$\frac{\sin\theta_i}{\sin\theta_R} = \text{a constant}$$

- it turns out that the constant above is actually the index of refraction for that medium



Light travels from air into an unknown liquid at an angle of incidence of 65.0°. The angle of refraction is 42.0°. Determine the index of refraction of the unknown liquid.

$$\frac{\sin\theta_i}{\sin\theta_R} = n = 1.35$$

$$\frac{\sin 65^\circ}{\sin 42^\circ} = \frac{0.9063}{0.6691} =$$

SNELL'S LAW

The product of the index of refraction of the incident medium and the sine of the angle of incidence is the same as the product of the index of refraction of the refracting medium and the sine of the angle of refraction.

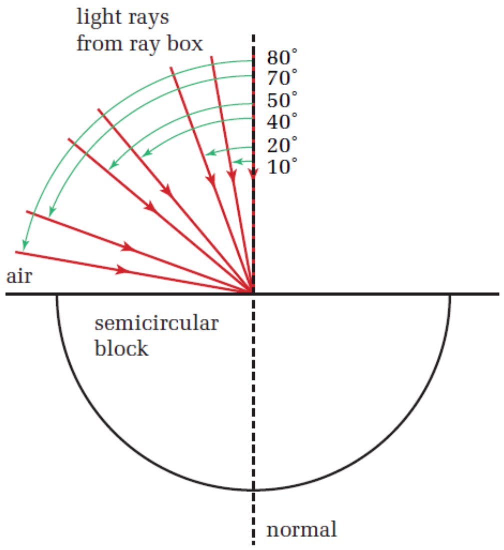
$$n_i \sin \theta_i = n_R \sin \theta_R$$

Quantity	**Symbol**	**SI unit**
index of refraction of the incident medium	n_i	unitless
angle of incidence	θ_i	none (degree is not a unit)
index of refraction of the refracting medium	n_R	unitless
angle of refraction	θ_R	none (degree is not a unit)

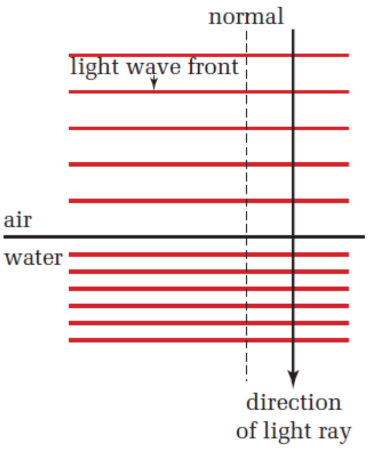
INVESTIGATION 9-A

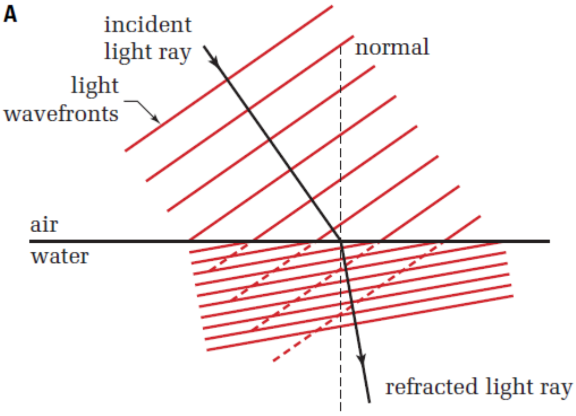
Verifying Snell's Law

- Cause a beam from a laser to be incident on the refractive material at various angles.
- Measure and record the angle of incidence and angle of refraction
- Using Snell's Law, calculate the index of refraction for the material used.
- Compare your value with that of other students using the same material.

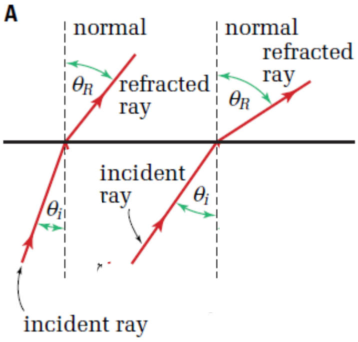


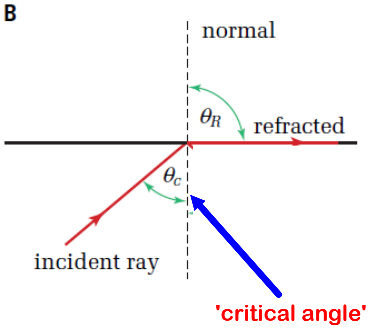
Refraction and the Wave Model for Light

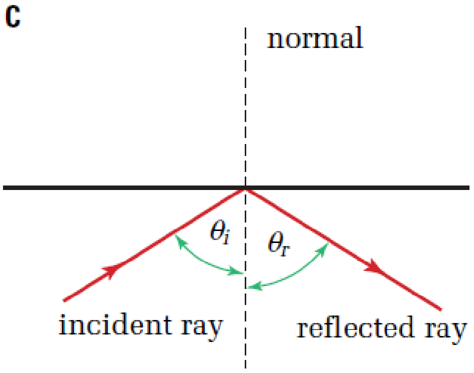




Total Internal Reflection







TOTAL INTERNAL REFLECTION

The two conditions required for total internal reflection to occur are as follows.

- The light must travel from an optically more dense medium into an optically less dense medium.
- The angle of incidence must exceed the critical angle, θ_c, associated with the material.

Finding θ_c

Determine the critical angle for diamond.

$$n_i \sin \theta_i = n_R \sin \theta_R$$

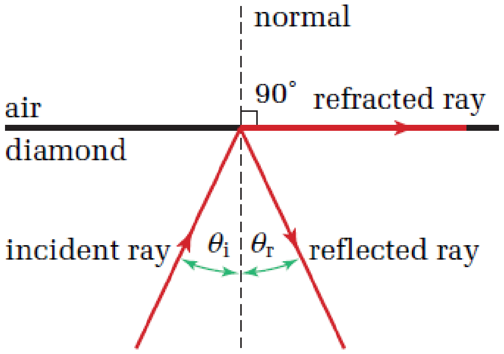
$$2.42 \sin \theta_{c/\text{diamond}} = 1.0003 \sin 90^\circ$$

$$\sin \theta_{c/\text{diamond}} = \frac{1.0003 \times 1.000}{2.42}$$

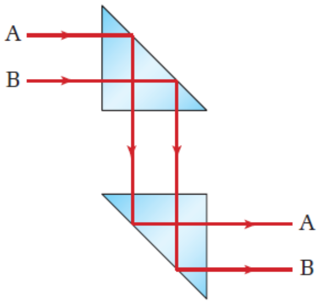
$$\sin \theta_{c/\text{diamond}} = 0.4133$$

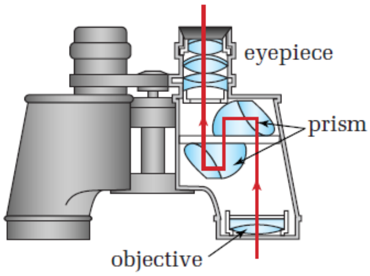
$$\theta_{c/\text{diamond}} = \sin^{-1} 0.4133$$

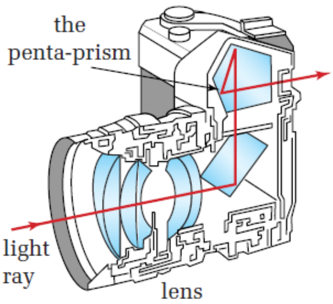
$$\theta_{c/\text{diamond}} = 24.415^\circ$$



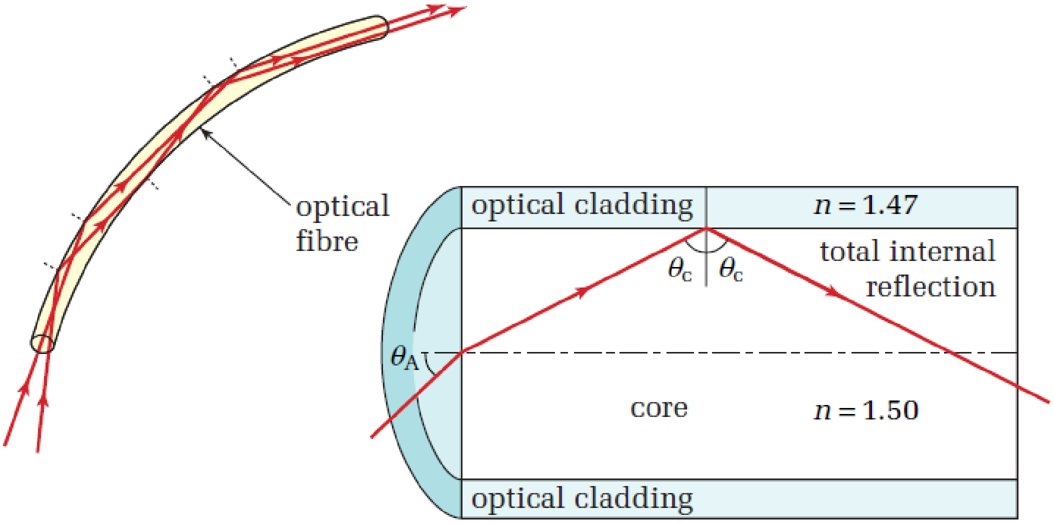
Applications of Total Internal Reflection







Optical Fibres



9.3 Interference of Waves and Related Properties

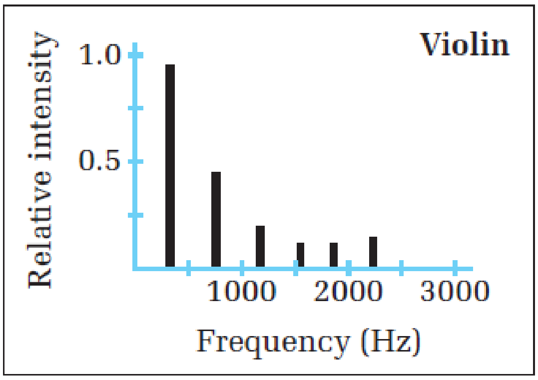
SECTION OUTCOMES

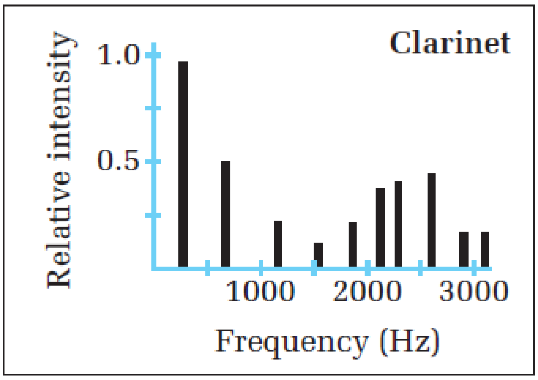
- Explain the phenomena of wave interference and diffraction.
- Conduct investigations on wave interference including Young's double-slit experiment.
- Compare and describe the properties of sound and electromagnetic radiation.

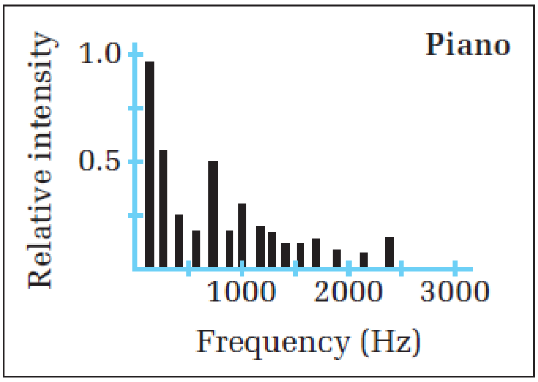
KEY TERMS

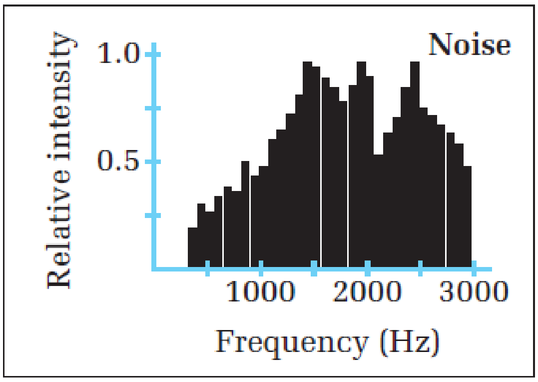
- noise
- music
- harmonics
- fundamental frequency
- sound spectrum
- closed air column
- resonance lengths
- open air column
- beat
- beat frequency
- coherent
- fringe

Music, Noise, and Resonance in Air Columns







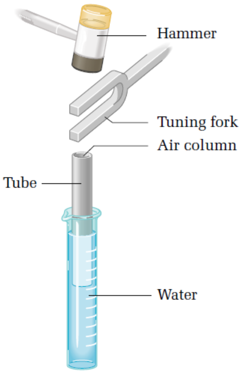


QUICK LAB

Resonance Lengths of a Closed Air Column

- Place a 50 cm long piece of plastic pipe inside a large graduated cylinder almost completely filled with water that is at room temperature.

- Sound a tuning fork and hold it over the open end of the plastic pipe. Raise the pipe slowly out of the water while keeping the tuning fork positioned over the open end. Measure the lengths of the air column for which resonance occurs. Repeat the procedure using a different frequency tuning fork.



Analyze and Conclude

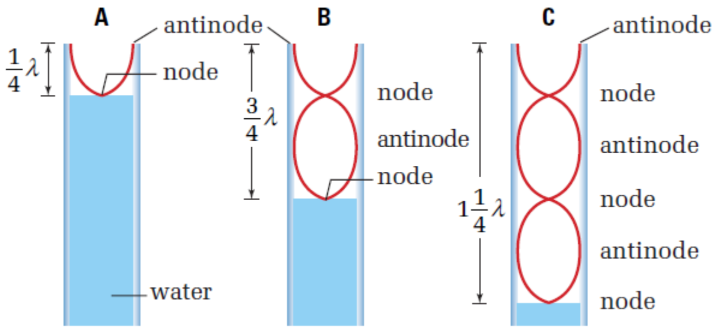
1. Use a thermometer to measure the room temperature. Calculate the speed of sound in air, and from that, the wavelength of the sound produced by the first tuning fork.

2. By how much is one resonance length longer than the previous one? (If you were able to determine three or more resonance lengths, was this increase in length constant?) What fraction of a wavelength is this increase in resonance length?

3. Repeat questions 1 and 2 for the second tuning fork.

Resonance in a Closed Air Column

which lengths will resonate for a specific frequency



first resonance length

second resonance length

third resonance length

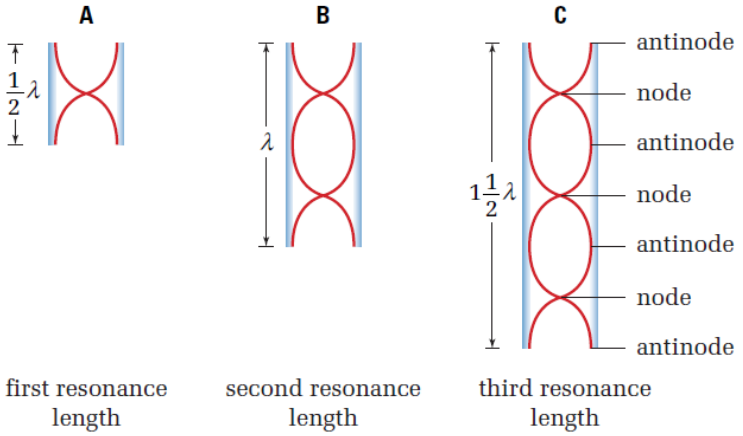
RESONANCE LENGTHS OF A CLOSED AIR COLUMN

The resonance lengths of a closed air column are odd integer multiples of the first resonance length, $\frac{1}{4}\lambda$.

$$L_n = (2n - 1)\frac{\lambda}{4}$$

where n is a positive integer.

Resonance Lengths of an Open Air Column



RESONANCE LENGTHS OF AN OPEN AIR COLUMN

The resonance lengths of an open air column are integral multiples of the first resonance length, $\frac{1}{2}\lambda$.

$$L_n = \frac{n\lambda}{2}$$

Resonance Lengths of a Closed Air Column

A vibrating tuning fork is held near the mouth of a narrow plastic pipe partially submerged in water. The pipe is raised, and the first loud sound is heard when the air column is 9.0 cm long. The temperature in the room is 20°C.

(a) Calculate the wavelength of the sound produced by the tuning fork.

(b) Calculate the length of the air column for the second and third resonances.

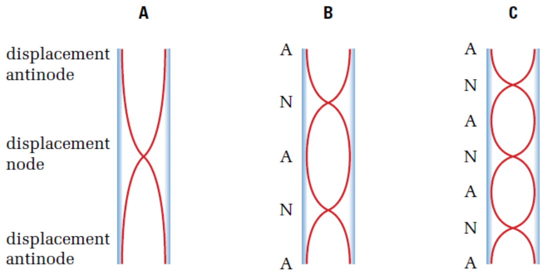
(c) Estimate the frequency of the tuning fork.

Resonance Frequencies for Fixed-Length Air Columns

which frequencies resonate
at a specific length

p422

Open Air Columns



$\lambda_1 = 2L$

$f_1 = \frac{v}{\lambda_1} = \frac{v}{2L}$

$\lambda_2 = L$

$f_2 = \frac{v}{\lambda_2} = \frac{v}{L} = 2f_1$

$\lambda_3 = \frac{2L}{3}$

$f_3 = \frac{v}{\lambda_3} = \frac{v}{\frac{2L}{3}} = \frac{3v}{2L} = 3f_1$

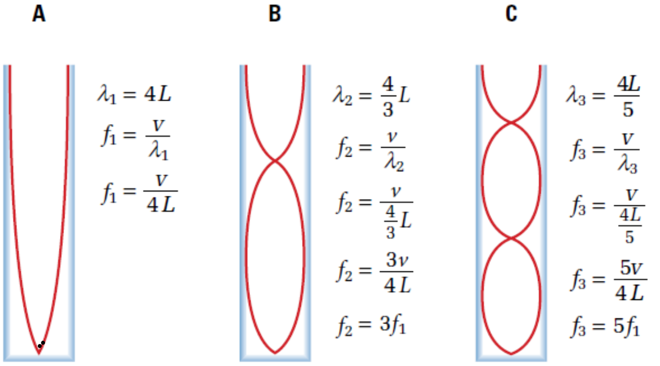
RESONANCE FREQUENCIES OF A FIXED-LENGTH OPEN AIR COLUMN

The resonance frequencies of a fixed-length open air column are integral multiples of the first resonance frequency, f_1.

$$f_n = nf_1$$

where $f_1 = \frac{v}{2L}$

Closed Air Columns



$\lambda_1 = 4L$

$f_1 = \frac{v}{\lambda_1}$

$f_1 = \frac{v}{4L}$

$\lambda_2 = \frac{4}{3}L$

$f_2 = \frac{v}{\lambda_2}$

$f_2 = \frac{v}{\frac{4}{3}L}$

$f_2 = \frac{3v}{4L}$

$f_2 = 3f_1$

$\lambda_3 = \frac{4L}{5}$

$f_3 = \frac{v}{\lambda_3}$

$f_3 = \frac{v}{\frac{4L}{5}}$

$f_3 = \frac{5v}{4L}$

$f_3 = 5f_1$

RESONANCE FREQUENCIES OF A FIXED-LENGTH CLOSED AIR COLUMN

The resonance frequencies of a fixed-length closed air column are odd integer multiples of the first resonance frequency, f_1.

$$f_n = (2n - 1)f_1$$

where $f_1 = \frac{v}{4L}$

Harmonics in a Fixed-Length Air Column

1. An air column, open at both ends, has a first harmonic of 330 Hz.

(a) What are the frequencies of the second and third harmonics?

The air column is *open at both ends*, so the *harmonics* are integral multiples of f_1.

$$f_n = nf_1$$

$$f_2 = 2f_1 = 660\ \text{Hz}$$

$$f_3 = 3f_1 = 990\ \text{Hz}$$

(b) If the speed of sound in air is 344 m/s, what is the length of the air column?

$$f_1 = \frac{V}{2L}$$

$$330\ \text{Hz} = \frac{344\ \text{m/s}}{2(L)}$$

$$660\,L = 344$$

$$L = \frac{344}{600} = 0.52\ \text{m} \qquad 52\ \text{cm}$$

An air column, closed at one end, has a first harmonic of 330 Hz. If the speed of sound in air is 344 m/s, what is the length of the air column?

$$f_1 = \frac{V}{4L}$$

$$330\ \text{Hz} = \frac{344}{4L}$$

$$1320\,L = 344$$

$$L = \frac{344}{1320} = 0.26\ \text{m} \qquad 26\ \text{cm}$$

You must determine:

Are you looking for the length of column that will resonate for a specific frequency?

-or-

The frequency that will resonate at a specific length of column?

AND

Is the column 'open' or 'closed'

Summary of Equations-Open vs Closed Columns, Frequency vs Length

RESONANCE LENGTHS OF A CLOSED AIR COLUMN

$$L_{\mathrm{n}} = (2n - 1)\frac{\lambda}{4}$$

RESONANCE LENGTHS OF AN OPEN AIR COLUMN

$$L_{\mathrm{n}} = \frac{n\lambda}{2}$$

RESONANCE FREQUENCIES OF A FIXED-LENGTH OPEN AIR COLUMN

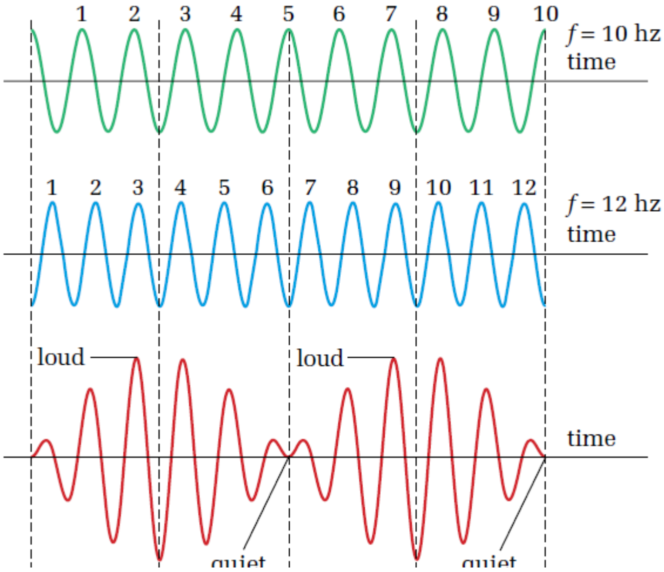
$$f_{\mathrm{n}} = nf_1 \quad \text{where } f_1 = \frac{v}{2L}$$

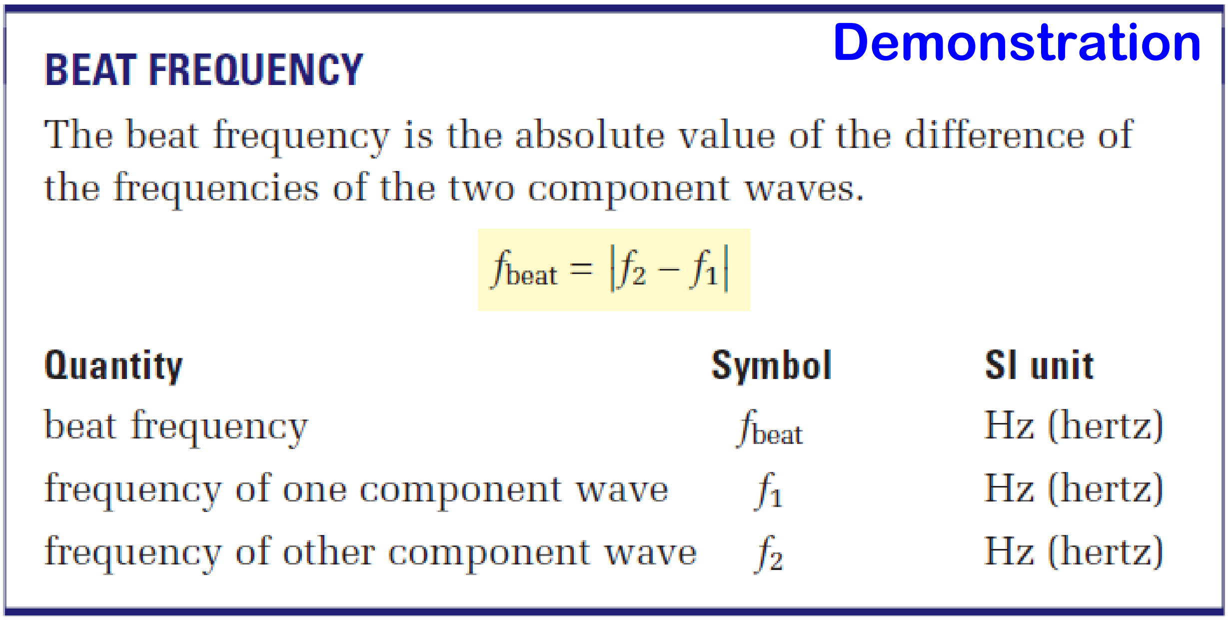
RESONANCE FREQUENCIES OF A FIXED-LENGTH CLOSED AIR COLUMN

$$f_{\mathrm{n}} = (2n - 1)f_1 \quad \text{where } f_1 = \frac{v}{4L}$$

Hearing Interference

One "**beat**" is a complete cycle from loud to quiet to loud, and the "**beat frequency"** is the number of cycles of loud-quiet-loud produced per second.





Demonstration

BEAT FREQUENCY

The beat frequency is the absolute value of the difference of the frequencies of the two component waves.

$$f_{\text{beat}} = |f_2 - f_1|$$

Quantity	Symbol	SI unit
beat frequency	f_{beat}	Hz (hertz)
frequency of one component wave	f_1	Hz (hertz)
frequency of other component wave	f_2	Hz (hertz)

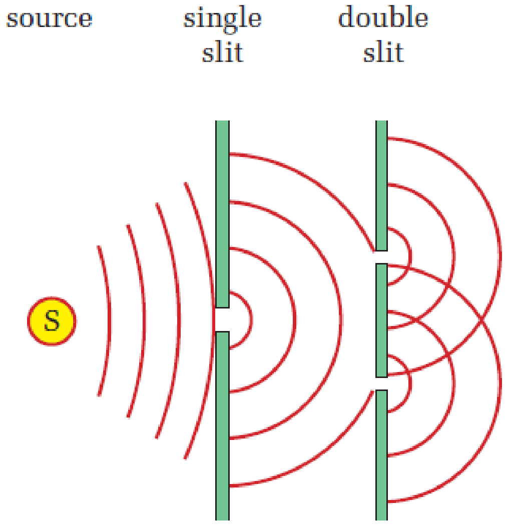
Finding the Unknown Frequency

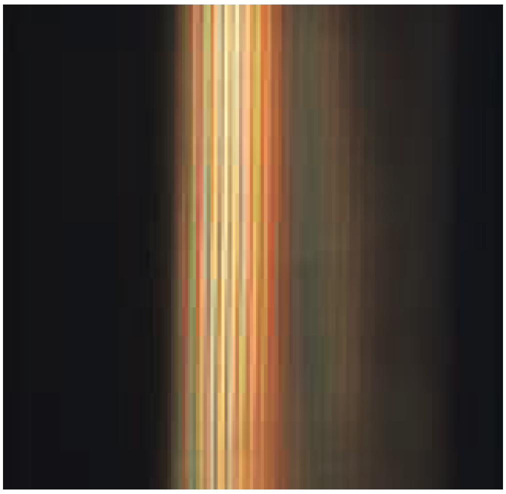
A tuning fork of unknown frequency is sounded at the same time as one of frequency 440 Hz, resulting in the production of beats. Over 15 s, 46 beats are produced. What are the possible frequencies of the unknown-frequency tuning fork?

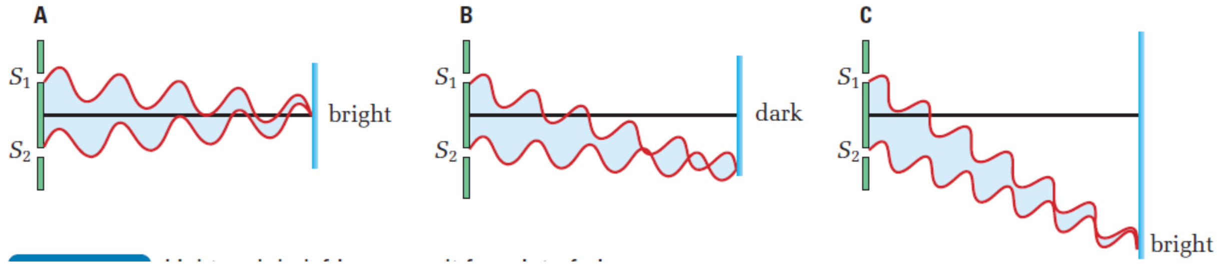
- late 1700's
- tried to see if light could be bent (diffracted)
- if mechanical waves diffract, would light waves as well?

Young's Double-Slit Experiment

Demonstration







Waves Unit Review Questions

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CHAPTER 9 Review

- Regular reflection occurs when light reflects from a smooth surface, such as a mirror. Diffuse reflection occurs when light reflects from a rough surface.
- The Doppler effect is the apparent change in the frequency of a sound due to relative motion of the source of sound and the observer.
- When an object is moving faster than the speed of sound in the air through which it is travelling, each new compressional wavefront is ahead of the previous one. The overlapping of wavefronts along a cone creates extremely large compressions that are heard as a "sonic boom."
- Mach number $= \frac{\text{speed of object}}{\text{speed of sound}}$

- Refraction of light, as of other waves, is the change in velocity when light passes from one medium into another.
- The index of refraction of a medium is the ratio of the speed of light in a vacuum to the speed of light in the medium: $n = \frac{c}{v}$. A medium with a high index of refraction is optically dense.
- The angle of refraction is the angle of a light ray exiting from a refractive boundary. For any given media, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant: $\frac{\sin \theta_i}{\sin \theta_R} = \text{constant}$.
- Snell's law relates angles of incidence and refraction to indices of refraction: $n_i \sin \theta_i = n_R \sin \theta_R$. The incident ray, the refracted ray, and the normal all lie in the same plane.

- The principle of reversibility of light states that, if a new ray of light is directed backwards along the path of a refracted ray, it will follow the same path after crossing the boundary between the media.
- Total internal reflection occurs when light in an optically more dense medium strikes the boundary with an optically less dense medium at an angle of incidence greater than the critical angle for the medium.

- Sound does not travel through a vacuum.
- Sound waves are longitudinal waves.
- The speed of sound in air at standard atmospheric pressure (101 kPa) is constant for a given temperature, and given by the equation $v = 331 + 0.59T_C$.
- In general, the speed of sound is slowest in gases, faster in liquids, and fastest in solids.
- When two sounds of similar frequency are sounded at the same time, alternately loud and quiet sounds are produced. This wavering effect is called beats.

  The beat frequency is given by the equation

$$f_{\text{beat}} = |f_2 - f_1|$$

- Music is a sound made up of whole number multiples of a lowest or fundamental frequency. Noise is a sound made up of a multitude of sound frequencies with no recognizable relationship to each other.
- A closed air column (closed at one end) has resonance lengths
$$L_n = \frac{(2n - 1)\lambda}{4}$$
- An open air column (open at both ends) has resonance lengths
$$L_n = \frac{n\lambda}{2}$$
- A closed air column of fixed length has resonance frequencies
$$f_n = (2n - 1)f_1$$
where $f_1 = \frac{v}{4L}$.
- An open air column of fixed length has resonance frequencies
$$f_n = nf_1$$
where $f_1 = \frac{v}{2L}$.