SOUND

Sound is a longitudinal (compression) wave. First, there must be a source for a sound and of course, it must be a vibrating object. Secondly, you must realize that the wave is transporting vibratory ENERGY and lastly, the sound is detected by an ear or an instrument.

12.1 CHARACTERISTICS OF SOUND

TABLE 12–1
Speed of Sound in Various Materials, at 20°C and 1 atm

Material	Speed (m/s)
Air	343
Air (0°C)	331
Helium	1005
Hydrogen	1300
Water	1440
Seawater	1560
Iron and steel	≈ 5000
Glass	≈ 4500
Aluminum	≈ 5100
Hardwood	≈ 4000

Sound CANNOT travel in the absence of matter!

- **speed of sound**--depends on the nature of the medium; temperature is a huge factor if the medium is a gas since temperature can radically change the density of the gas.
- $v_{sound} \approx (331 + 0.60\ T)$ m/s
- T is the temperature in degrees Celsius
- We'll assume 20^0 C most of the time so the speed of sound is **343 m/s**

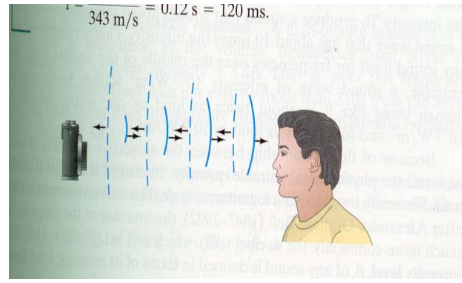
Example 12.1

A rule of thumb that tells how close lightning has hit is: "one mile for every five seconds before the thunder is heard". Justify, noting that the speed of light is so high that the time for light to travel is negligible compared to the time for sound.

Sensations in the consciousness of the listener:

- **loudness**--relates to the E of the sound wave
- **pitch**--relates to the frequency of the sound wave; first noted by Galileo; the higher the f, the higher the pitch
- **audible range**--the human ear can hear f's from 20 Hz to 20,000 Hz; age affects the ability to hear higher frequencies [spare me your comments!]
- **ultrasonic**--f above 20,000 Hz (do not confuse with supersonic--that's how we describe the speed of an object traveling faster than 343 m/s.)
    - dogs can hear f in the 50,000 Hz range
    - bats can hear f in the 100,000 Hz range

Example 12.2

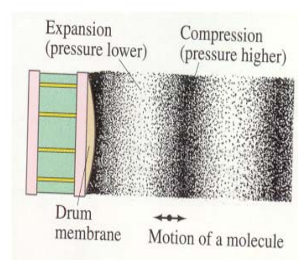


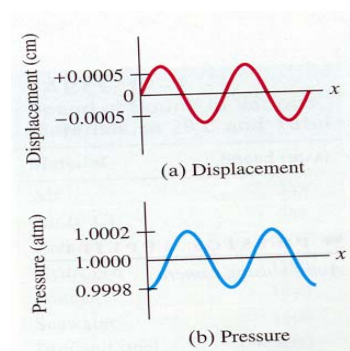
Auto focusing cameras emit a pulse of very high [ultrasonic] frequency sound that travels to the object being photographed, and include a sensor that detects the returning reflected sound, as shown in Fig. 12-1. To get an idea of the time sensitivity of the detector, calculate the travel time of the pulse for an object

a) 1.0 m away

b) 20.0 m away

- **infrasonic**--below 20,000 Hz; sources include earthquakes, thunder, volcanoes, and waves produced by vibrating heavy machinery. The latter causes resonant frequencies that can damage internal organs even though the sound cannot be detected!
- **pressure waves**--a.k.a. longitudinal waves; P is easier to measure than displacement
  - compression--P is higher since molecules are closer together
  - rarefaction--P is less than normal since molecules are farther apart than normal
  - compare the displacement vs. the pressure graphically
  - note that the displacement wave is 1/4 λ out of phase with the pressure wave
  - $\therefore$when P is a max. or min., disp. from equilibrium position is zero
  - when P variation is zero, displacement is at a max. or min.





12.2 INTENSITY OF SOUND: DECIBELS

- **loudness**--relates to intensity or E transported per unit time across unit area. $I \propto A^2$ and E/t = Power $\therefore$ I is measured in W/m^2
  - **human ear**--10^{-12} W/m^2 to 1 W/m^2; more than the one W/m^2 and you feel pain!

- producing a sound twice as loud requires a sound wave with 10x the intensity
- 10^{-2} W/m^2 sounds twice as loud as 10^{-3} W/m^2 and four times as loud as 10^{-4} W/m^2
- ∴ a logarithmic scale is needed to compare loudness easily
  - **bel**--the unit of the logarithmic scale used to compare loudness [yes, it was named after Alexander Graham Bell!]
  - decibel--1/10 th of a bel (10 dB = 1 Bel)

TABLE 12–2 Intensity of Various Sounds

Source of the Sound	Intensity Level (dB)	Intensity (W/m^2)
Jet plane at 30 m	140	100
Threshold of pain	120	1
Loud indoor rock concert	120	1
Siren at 30 m	100	1×10^{-2}
Auto interior, moving at 90 km/h	75	3×10^{-5}
Busy street traffic	70	1×10^{-5}
Ordinary conversation, at 50 cm	65	3×10^{-6}
Quiet radio	40	1×10^{-8}
Whisper	20	1×10^{-10}
Rustle of leaves	10	1×10^{-11}
Threshold of hearing	0	1×10^{-12}

$$INTENSITY: \quad \beta(dB) = 10 \log \frac{I}{I_o}$$

- $I_o = 1 \times 10^{-12}$ W/m^2
  the threshold for human hearing

So, for a sound with an intensity = 1×10^{-10} W/m^2

$$\beta = 10 \log \frac{(1x10^{-10})}{(1x10^{-12})} = 10 \log 100 = 20 dB$$

- ∴ an increase in intensity by a factor of
  - 10 means a level increase of 10 dB
  - 100 means a level increase of 20 dB
  - a 50 dB sound is 100 times more intense than a 30 dB sound

Example 12.3

A high-quality loud speaker is advertised to reproduce, at full volume, frequencies from 30 Hz to 18,000 Hz with uniform intensity ± 3 dB. That is, over this frequency range, the intensity level does not vary by more than 3 dB from the average. By what factor does the intensity change for the maximum intensity level change of 3 dB?

- A sound level difference of 3 dB (twice the intensity) corresponds to a very small change in the subjective sensation of apparent loudness.
- loudness *decreases* as you get farther from the source

$$I \propto \frac{1}{r^2}$$

- Walls, ground, canyons, etc. complicate this by bouncing sound around!

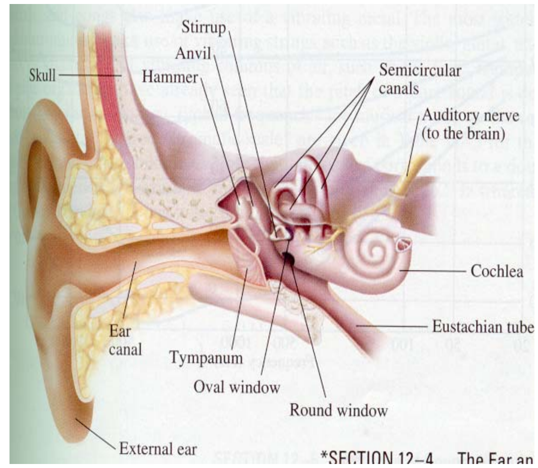
Example 12.4

The intensity level of the sound from a jet plane at a distance of 30 m is 140 dB. What is the intensity level at 300 m? (Ignore reflections from the ground.)

Example 12.5

Calculate the displacement of air moleucles for a sound having a frequency of 1000 Hz at the threshold of hearing.

12.4 THE EAR AND ITS RESPONSE; LOUDNESS



Microphones can barely match the human ear in detecting low intensity sounds!

- **<u>ear</u>**--efficiently transforms vibrational energy into electrical energy carried to the brain by nerves [microphones work the same way!]
  - outer--sound waves travel to tympanum which vibrates
  - middle--3 small bones, the anvil, hammer and stirrup. These transfer vibrational energy of the tympanum to inner ear at the oval window. The pressure is amplified by a factor of 40 due to the huge change in the surface area of the tympanum compared to the oval window.
  - inner--semicircular canals; these control balance and fluid-filled cochlea where vibrational E is converted into electrical energy and sent to the brain via the auditory nerves

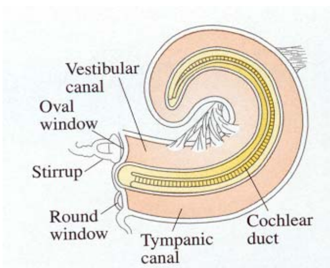
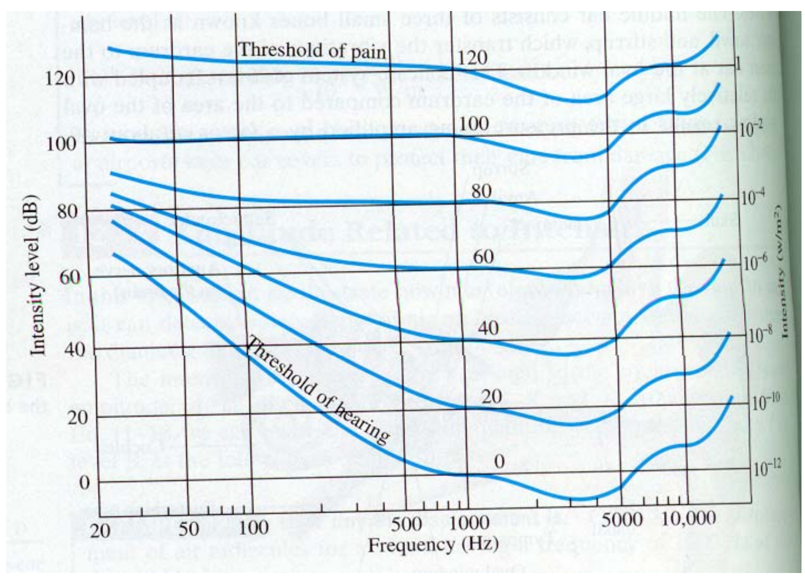


FIGURE 12–6 Diagram of the cochlea.

  - inside the cochlea, vibrations travel down the vestibular canal and back up the tympanic canal. Damping occurs in the fluid [viscosity], but any remaining E is dissipated at the round window @ the end of the tympanic canal
  - Between the 2 canals is a 3rd canal, a.k.a. the cochlear duct--here the basilar membrane is the organ of Corti (a mere 30,000 nerve endings)
  - As a P wave passes along the canal, ripples form in basilar membrane and the attached organ of Corti. Variations in the thickness of the basilar membrane help us determine pitch. [Mine is obviously mutated.]



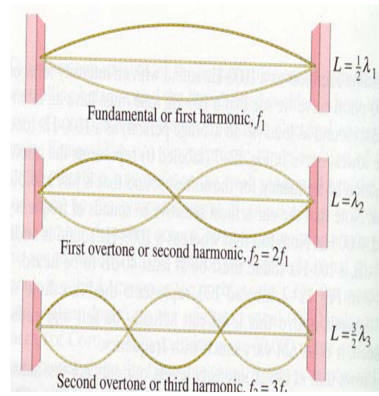
12.5 SOURCES OF SOUND; VIBRATING STRINGS AND AIR COLUMNS

TABLE 12–3 Equally Tempered Chromatic Scale†

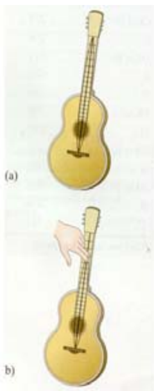
Note	Frequency (Hz)
C	262
C# or D♭	277
D	294
D# or E♭	311
E	330
F	349
F# or G♭	370
G	392
G# or A♭	415
A	440
A# or B♭	466
B	494
C′	524

†Only one octave is included.

Typical f for musical notes on the so-called "equally tempered chromatic scale" are given below for the octave beginning with middle C. One octave corresponds to a doubling of f. Middle C is 262 Hz.



- **<u>pitch</u>**--determined by the lowest fundamental frequency
- $f = v/\lambda = v/2L$



- Put your finger on the fret of a guitar and you shorten the string so the pitch increases since the λ of the fundamental frequency is now shorter.
- Thicker, heavier more dense strings have a lower frequency

Example 12.6

The highest key on a piano corresponds to a f about 150 times that of the lowest key. If the string for the highest note is 5.0 cm long, how long would the string for the lowest note have to be if it had the same mass per unit length and was under the same tension?

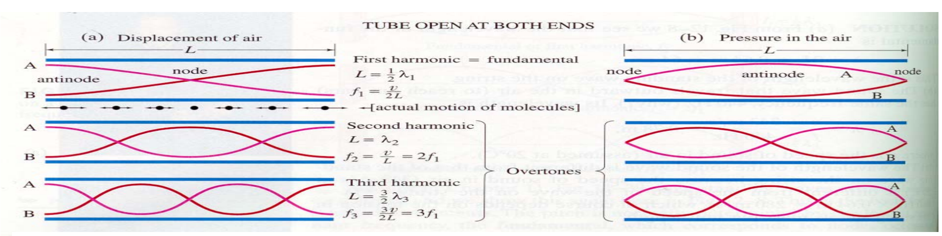
Example 12.7

a 0.32 m long violin string is tuned to play A above middle C at 440 Hz.
a) What is the λ of the fundamental string vibration

b) what are the f and λ of the sound wave produced?

c) Why is there a difference?

- The string alone would be pitiful--needs sounding board/box for a decent musical instrument
  - amplifies the sound by putting more surface area in contact with the air
- Woodwinds, brasses & pipe organs produce sound from vibration of standing waves in a column of air within a tube or pipe.
  - We talk either in terms of displacement or P of air
  - air oscillates itself horizontally, parallel to tube length
- open pipes are open at BOTH ends & closed are closed at one end
- we'll deal with open on one end first [called an open pipe]
  - the open end has an antinode for displacement
  - exact position of antinode near open end depends on

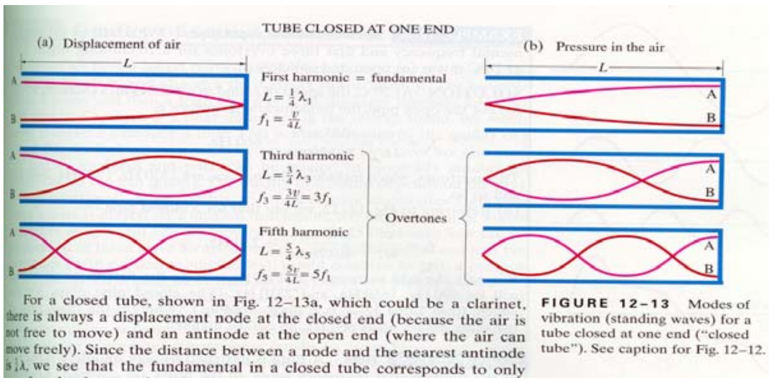


- diameter of tube
  -if d is small compared to length, antinode is close to end [usual for musical instruments]

- depends slightly on λ and other factors

air at the closed end is a displacement node since air is NOT free to move there

- displacement antinodes at both ends
- must be one node within the pipe to get a wave at all!
- single node corresponds to f_1
- $L = \frac{1}{2}\lambda$ or $\lambda = 2L$
- $f_1 = v/\lambda = v/2L$ where v = speed of sound of air
- standing wave with 2 nodes is first overtone or 2nd harmonic ($l = \lambda$) and the frequency is doubled–works the same as the string in the last chapter



- closed means closed on only one end
  - displacement node always at the closed end
  - antinode at the open end
  - $L = \lambda/4$ (½ that of an open pipe)
  - only odd harmonics are present
  - overtones have f = 3,5,7...times the f_1
- change L or diameter and you get a different sound
- flute–open pipe
- clarinet–closed pipe
- trumpets–change L when valves are depressed
- in general–the longer L, the lower the f_1

Example 12.8

What will be the fundamental frequency and first three overtones for a 26 cm long organ pipe at 20°C if it is

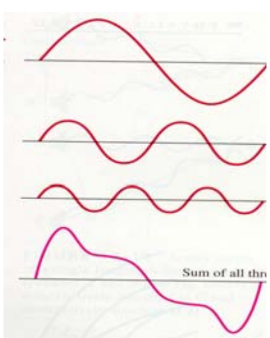
a) open?

b) closed?

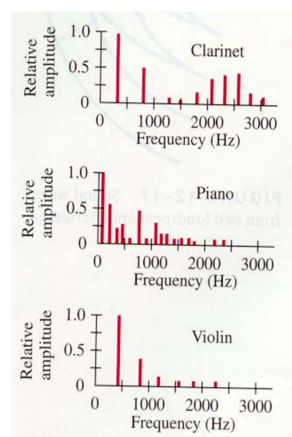
Example 12.9
A flute is designed to play middle C (262 Hz) as the fundamental frequency when all the holes are covered. Approximately how long should the distance be from the mouthpiece to the far end of the flute? Assume 20^0 C.

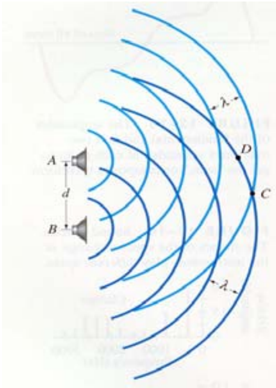
Example 12.10
If the temperature is only 10^0C, what will be the frequency of the note played when all the openings are covered in the flute?

12.6 QUALITY OF SOUND AND NOISE



- **quality**--3rd aspect of sound; timbre, tone color, if a piano and a flute both play middle C, their "quality" is different
  - depends on presence of overtones, their # and relative A's
  - play a note and fundamental as well as overtones are present
- Relative A of the various overtones are different for different instruments and are responsible for timbre
- sound spectrum--graph showing relative A of the harmonics produced
- fundamental f has the greatest A and its f = pitch

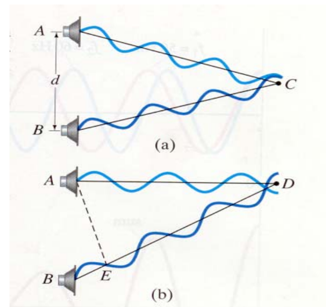




12.7 INTERFERENCE OF SOUND WAVES; BEATS

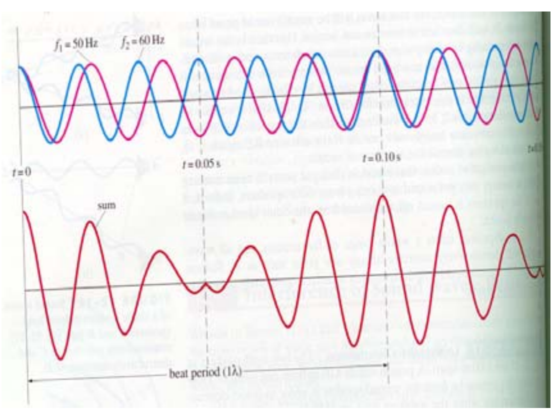
Consider 2 large loud speakers A & B a distance, d, apart on the stage of an auditorium.

- Both emit a sound of the same single f in phase
- @ C, loud sound due to constructive interference
- @ D, little sound due to destructive interference
- These figures at the left represent the wave fronts graphically



- @ D wave from B must travel a greater distance than from A, therefore wave from B lags behind that from A
- E is chosen so that ED = AD so if BE = ½ λ of sound, the 2 waves are exactly out of phase at D
- Destructive interference occurs when d from one speaker is greater than d from the other speaker by EXACTLY ½ λ (or 1 ½ λ or 2 ½ λ). D hears nothing--turn off one speaker!
- IF BE is greater by a whole λ (or 2 λ or 3 λ), then the two waves will be in phase and constructive interference occurs.

Example 12.11
The two loudspeakers in figure 12.17 are 1.00 m apart. A person stands 4.00 m from one speaker. How far must this person be from the second speaker in order to detect destructive interference when the speakers emit an 1150-Hz sound? Assume 20^0C.



- **beats**--if 2 sources of sound are close in f but not EXACTLY the same--sound waves from the 2 sources interfere with each other and sound level @ a given position alternately rises and falls; regularly spaced I changes are called beats
- f_1 = 50 Hz and f_2 = 60 Hz
- In 1.00 second 50 vibrations vs. 60 vibrations
- Examine the waves at one point equidistant from the two sources
- lower graph shows the sum of the 2 waves
  - @ t = 0; in phase constructive, int.
  - @ t = 0.05 s; out of phase, destructive int.
  - @ t = 0.10 s; in phase again

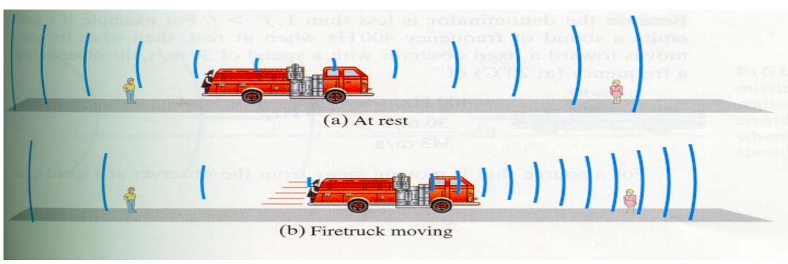
- Resultant A is large every 0.10 seconds and drops drastically in between--those surges are the beats
- the beat frequency is 10 per second or 10 Hz (just the difference between the original 2 frequencies)

Example 12.12
A tuning fork produces a steady 400 Hz tone. When this tuning fork is struck and held near a vibrating guitar string, twenty beats are counted in five seconds. What are the possible frequencies produced by the guitar string?

12.8 DOPPLER EFFECT

Pitch of the siren on a speeding fire truck drops abruptly as it passes you.

- When the source of a sound is moving toward an observer, the pitch is higher than when the source is at rest; and when the source is moving away from the observer, the pitch is lower
- A moving object catches up with emitting wave fronts, therefore the observer detects more wave fronts per second, so the f is higher
- behind--farther apart wave fronts since source is speeding away from them
- assume the air is at rest



$$f' = \frac{f}{(1 + \frac{v_s}{v})}$$

Source movingTOWARD observer

f' is new f and v_s= velocity of the source
V=velocity of sound wave in air

$$f' = \frac{f}{(1 + \frac{v_s}{v})}$$

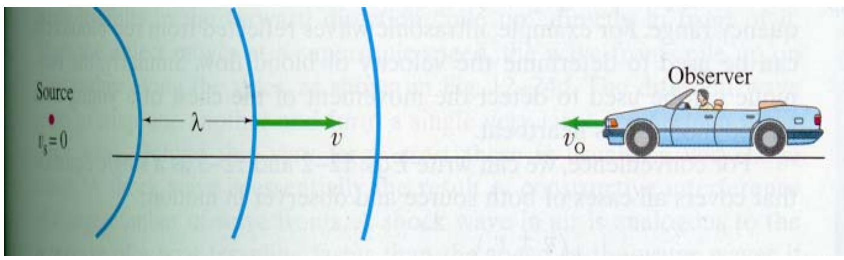
Source moving AWAY from observer

$$f' = f(1 + \frac{v_o}{v})$$

Observer moving TOWARD stationary source

$$f' = f(1 - \frac{v_o}{v})$$

Observer moving AWAY from stationary source
v_o = velocity of observer
v_s = velocity of source



Say we have a source that emits a sound of 400 Hz @ rest, the source then moves at 30 m/s toward the stationary observer at 20˚ C.

$$f' = \frac{400\ Hz}{(1 - \frac{30\ m/s}{343\ m/s})} = 438\ Hz$$

If both move toward each other: + in numerator and - in denominator
If both move apart: - in numerator and + in denominator

Example 12.13
The siren of a police car at rest emits at a predominant frequency of 1600 Hz. What frequency will you hear if you are at rest and the police car moves at 25.0 m/s

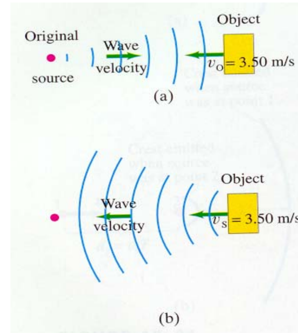


FIGURE 12–23 Example 12–14.

a) toward you?

b) away from you?

Example 12.14
A 5000 Hz sound wave is directed toward an object moving 3.50 m/s toward the stationary source. What is the frequency of the reflected wave?

Doppler applies to light and EM waves but the equations are a bit different.

12.9 SHOCK WAVES AND SONIC BOOM

- **supersonic speed**--object is faster than the speed of sound
- **Mach**--ratio of objects speed to speed of sound in that medium
  - 900 m/s vs. speed of sound at 300 m/s @ a high altitude = Mach 3

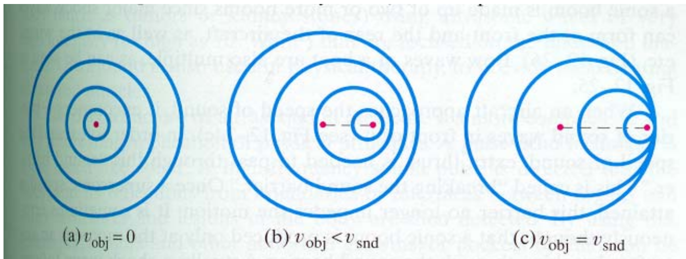
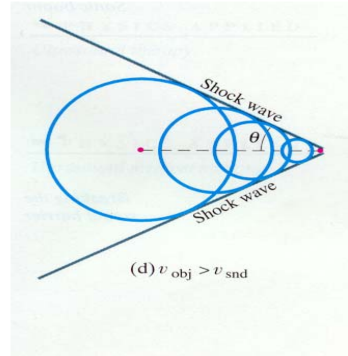


FIGURE 12–24 Sound waves emitted by an object at rest (a) or moving (b, c, and d). If the object's velocity is less than the velocity of sound, the Doppler effect occurs (b); if its velocity is greater than the velocity of sound, a shock wave is produced (d).



shockwave--source outruns the waves it produces. Waves pile up directly in front of it

- waves pile up along the sides (d) overlap and create a very large crest--followed by a very large trough
- result of constructive interference
- **sonic boom**--shock wave passes a listener, huge E--actually 2 or more booms since major shock waves can form at front and rear of aircraft as well as the wings

- When an aircraft approaches the speed of sound, it encounters a barrier of sound waves
- An extra thrust from the engines is needed to “break” the sound barrier