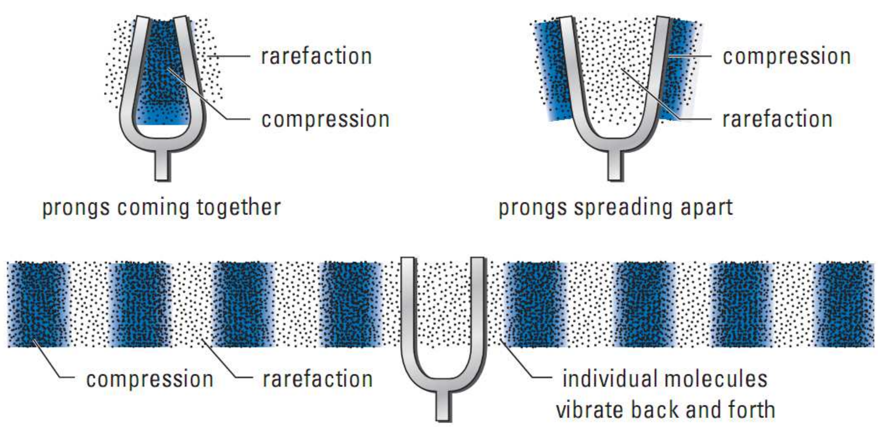
Sound

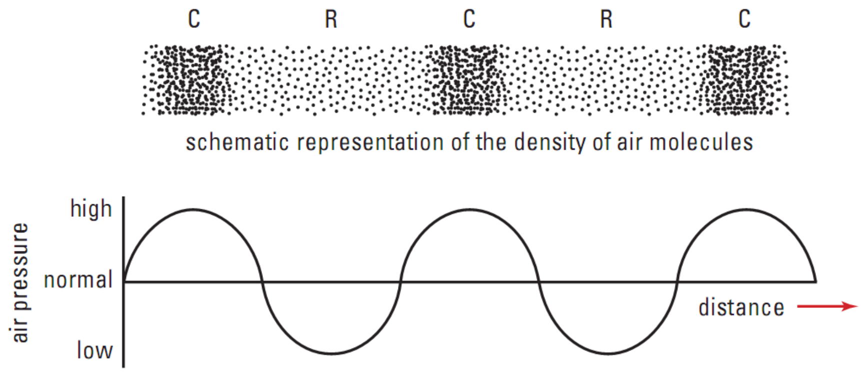
Grade 11 Physics

Transfer of Sound Wave in Air



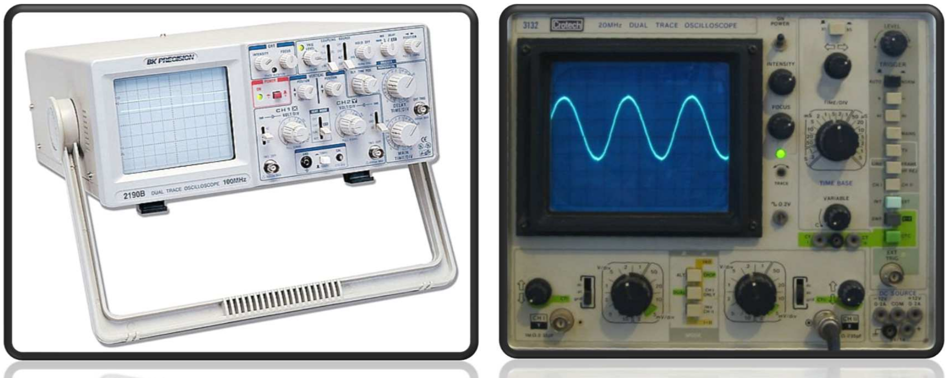
Transfer of Sound Wave

We can also express the amplitude of the sound wave by plotting the change in *air pressure*:



Visualizing Waves

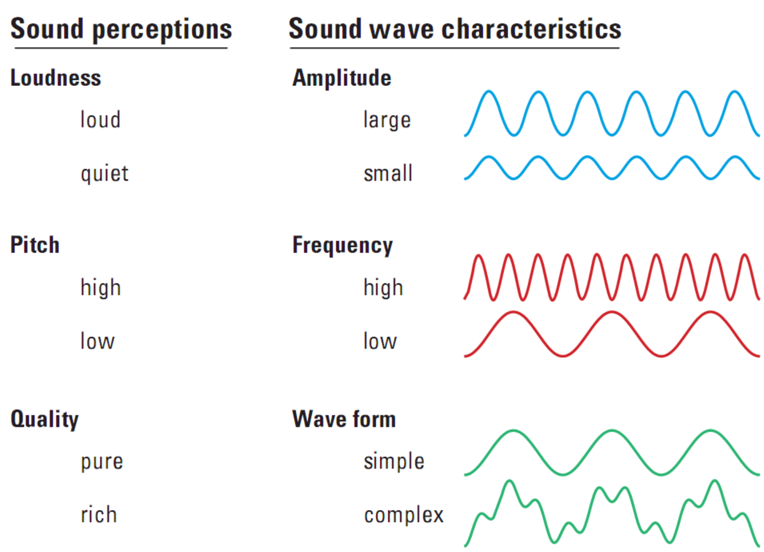
We use an oscilloscope to visual waves



Important Factor of Sound

- Loudness (perceived Intensity)
  - Amplitude (dB – decibel)
- Pitch
  - Frequency (Hz – hertz, or s^{-1})
- Quality
  - Complexity of the wave

Important Factor of Sound



FREQUENCY

Humans can hear sound between about 20 Hz and 20000 Hz, depending on age.

Infrasound < 20Hz < **SOUND** < 20 kHz < *Ultrasound*

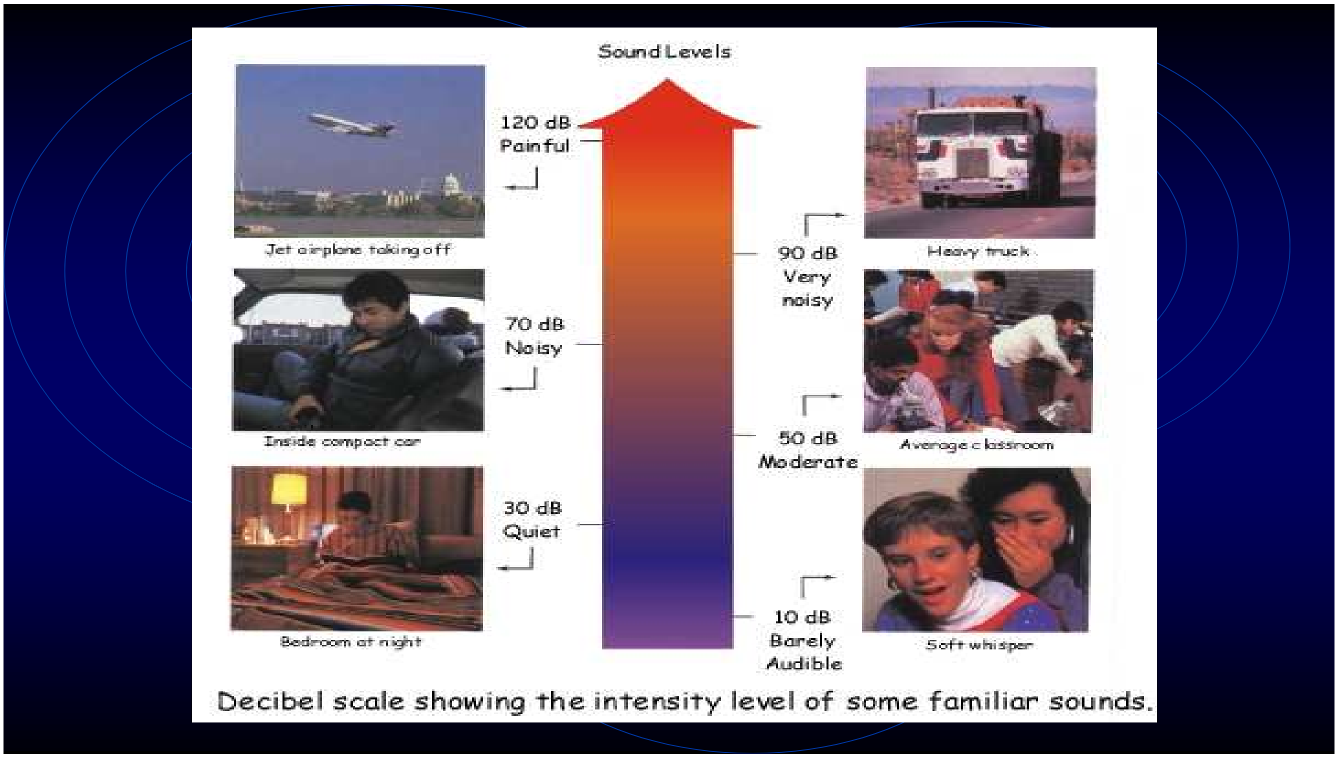
The Decibel

The decibel is defined as by the intensity of sound I compared to the threshold of hearing intensity I_0:

$$I(\mathrm{dB}) = 10\log_{10}\left[\frac{I}{I_0}\right] \quad \text{where} \quad I_0 = 10^{-12}\,\mathrm{W/m^2}$$

There is also a *threshold of pain*:

$$I_p = 10^{13} I_0 = 120\,\mathrm{dB}$$



Speed of Sound in Air

The speed of sound near room temperature (about 300 K) is approximately proportional to temperature:

$$v_s = 331 + 0.59T_C$$

Quantity	Symbol	SI Unit
Speed of sound	v_s	m/s (metres per second)
Temperature of air	T_C	Degree Celsius not an SI unit

Speed of Sound in Different Media

In general, sound travels fastest in solids, and slowest in gases.

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

Sample Problem #1

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

$$v_s = 331 + 0.59T_C$$

$v_s\,(\frac{m}{s}) = 331 + (0.59)(21)$

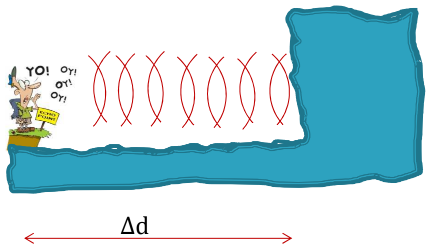
$v_s(\frac{m}{s}) = 331 + 12.39$ *(s.f.!)*

$v_s(\frac{m}{s}) = 331 + 12$

$v_s = 343$ m/s

Sample Problem #2

- The temperature was 4.0 °C one morning as Martita 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?



$\Delta d_{sound} = 2\Delta d$

$\Delta d_{sound} = v_s\,\Delta t$

$v_s\ (@\ 4.0\ ^{o}C) = 333\ m/s$ *(see Sample Problem #1)*

$$\Delta d = \frac{v_s \times \Delta t}{2} = \frac{(333\,\frac{m}{s})\times(2.8\ s)}{2} = 460\ m$$

$\Delta d = 460\ m$

Mach Number

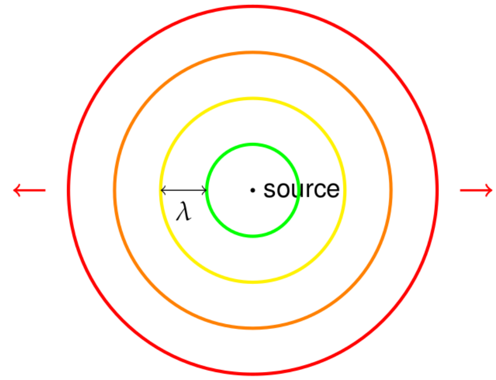
When working with sound, it is useful to express speed in terms of its ratio to the speed of sound. This is called the **Mach number**:

$$M = \frac{v}{v_s}$$

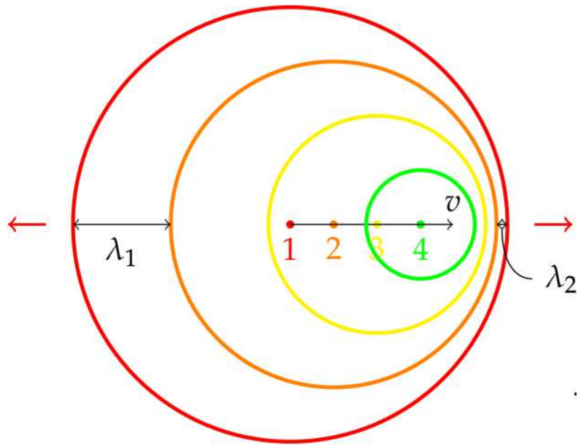
When an object is travelling at M < 1, it is travelling at a subsonic speed
When an object is travelling at M > 1, it is travelling at a supersonic speed

Sound from a Stationary Source

When a sound is emitted from a stationary point source, the sound wave moves radially outward from the point of origin:



Sound from a Moving Source



When sound is emitted from a moving source, the diagram looks different. In this case, the sound source is moving to the right, from 1 to 4.

- When the sound source is moving towards you, the wavelength λ_2 decreases, and the frequency increases.
- When the sound source is moving away from you, the wavelength λ_1 increases, and the frequency decreases.

This is called the **Doppler effect**.

Doppler Effect

We all experience Doppler effect every time an ambulance speeds by us with its sirens on.

When it is moving towards us, the pitch (frequency) of the siren is high, but the moment it passes us, the pitch decreases.

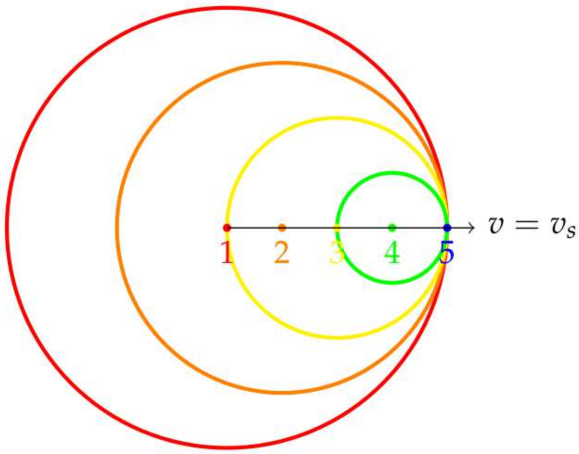
Doppler Effect

When a wave source is moving at a speed v_{src}, or if the observer is moving at v_{ob} the frequency is shifted:

$$f' = \frac{v_s + v_{\text{ob}}}{v_s - v_{\text{src}}} f$$

Quantity	Symbol	SI Unit
Apparent frequency	f'	Hz (hertz)
Actual frequency	f	Hz (hertz)
Speed of sound	v_s	m/s (metres per second)
Speed of the observer	v_{ob}	m/s (metres per second)
Speed of source	v_{src}	m/s (metres per second)

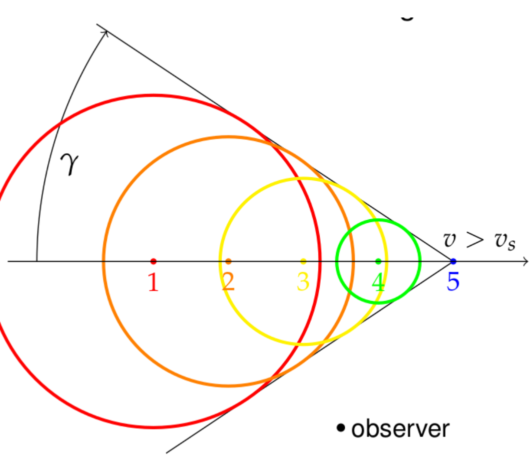
Source Moving at Sonic Speed



Doppler effect is more interesting is when sound source is moving at the speed of sound (*M*=1):

- The wave fronts (crests) from all the waves are bunched up just in front of the source
- Since sound wave is a pressure wave, right in front of the sound source, there is a large change in pressure (called a shock wave)
- When the shock passes an observer, an loud bang can be heard (aka **sonic boom**)

Sound from a Supersonic Source

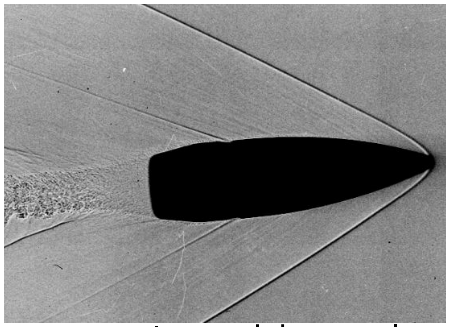


When sound source is moving at *M*>1:

- A stationary observer does not hear the sound source coming until it has gone past!

Bullet in Supersonic Flight

Generating a shock wave does not require an actual sound source; any object moving through air creates a pressure disturbance. This is a bullet in supersonic flight.



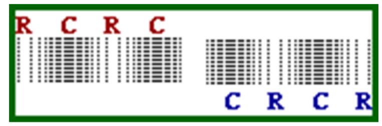
This bullet was not fired from a gun. Instead, it was placed in a shock tube that generates a short burst of supersonic flow, and a high-speed camera is then used to take the photo.

Duck in Water

No sonic booms here (just a duck swimming), but a similar shock behaviour is observed. The duck swims faster than the speed of the water wave, and it also creates a cone shape.

Sound Wave Interference

- Principle of superposition: waves add together
- Destructive Interference:
  - Amplitude is smaller than original
  - e.g. when two waves are out of phase
- Constructive Interference:
  - Amplitude is higher than original
  - e.g. when two waves are in phase
- “Beats” happen when
  - Waves of two different frequencies are added together
  - There is both constructive and destructive interference



Beat Frequency

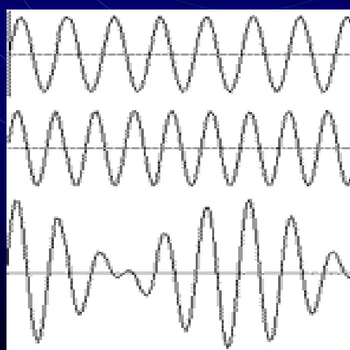
The absolute value of the difference of the frequencies of the two component waves:

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

Quantity	Symbol	SI Unit
Beat frequency	f_{beat}	Hz (hertz)
Frequency of 1st component wave	f_1	Hz (hertz)
Frequency of 2nd component wave	f_2	Hz (hertz)

Interference of Sound Waves

The result of the interference of two waves with similar frequencies, $f_1 \sim f_2$, is called **beats**:



f_1

f_2

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

Sample Problem #3

A tuning fork of unknown frequency is sounded at the same time as one of the 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 of unknown tuning fork?

Solution

f_1 = 440 Hz
n = 45
Δt = 15 s

f_2 = ?

$$f_{beat} = \frac{n}{\Delta t}$$

$$f_{beat} = \frac{45}{15\ s}$$

$$f_{beat} = 3\ Hz$$

$$f_2 = f_1 \pm f_{beat}$$

$$f_2 = 440\ \ Hz + 3\ Hz$$

or

$$f_2 = 440\ \ Hz - 3\ Hz$$

$$\boldsymbol{f_2 = 443\ Hz\ or\ 397\ Hz}$$

SOUND

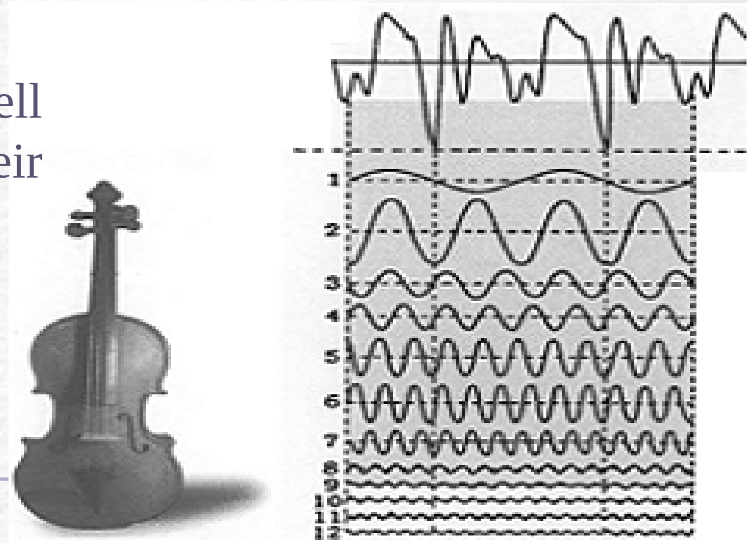
Talking

Music

Noise

MUSIC

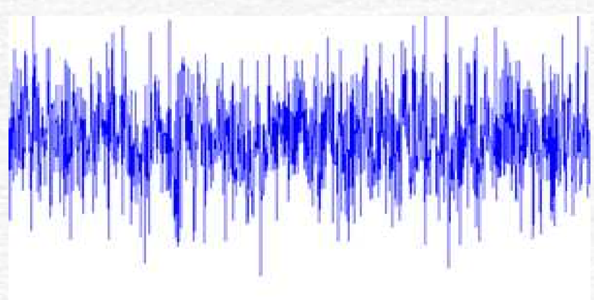
Music – Sound made of well defined frequencies and their multiples



NOISE

Noise – Sound made of random frequencies.

Music is sound with a discrete structure. Noise is sound with a continuous structure



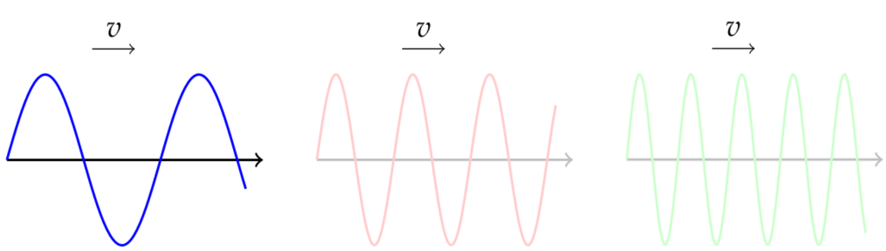
Musical Instruments

When a musical instrument produces a sound at a certain frequency, it also produces higher frequency sounds

- The higher frequency sounds are not random; but whole number multiples of the lowest frequency
- e.g. a violin playing at 440 Hz actually produces sound waves at

  440 Hz, 880 Hz, 1320 Hz, 1760 Hz, 2200 Hz, 2640 Hz…
- Generally, the higher the frequency, the smaller the amplitude
- The overall quality of the sound is the sum of all the waves (principle of superposition)
- This is why a violin and a trumpet can both be playing a 440 Hz (concert A) note, but sound different

Harmonic Frequencies

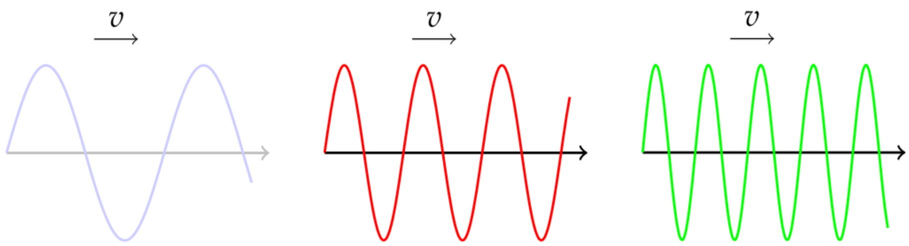


The sound wave with the longest wavelength and lowest frequency is called:

- **fundamental frequency**
- first harmonic
- first partial

When a musical instrument produces a sound, the fundamental frequency is the one that is "heard"

Harmonic Frequencies



A second wave has half the wavelength and twice the frequency. It's called:

- second harmonic
- second partial
- first overtone

From there we have the third, fourth, fifth… harmonics

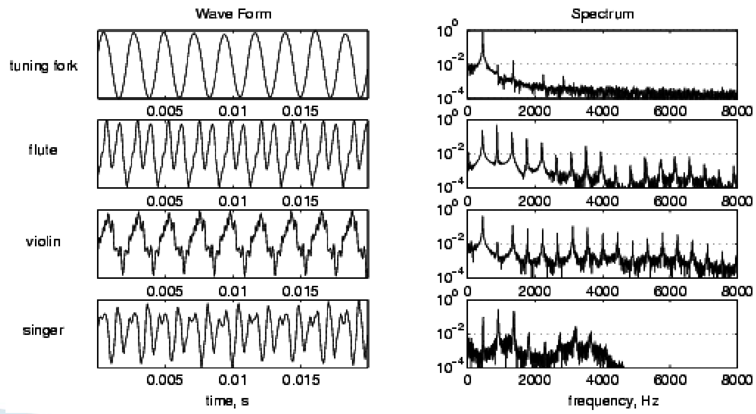
Harmonic Frequencies

Every whole-number multiples of the fundamental frequency f_1 is its harmonic frequency, i.e. the n-th harmonic is:

$$f_{\text{harm},n} = nf_1$$

Different Musical Instruments

This is how wave forms of different "musical instruments" look like at 440Hz.
The graph on the right correspond to the amplitudes at different frequencies.
Note the peaks at regular intervals. Those are the harmonic frequencies

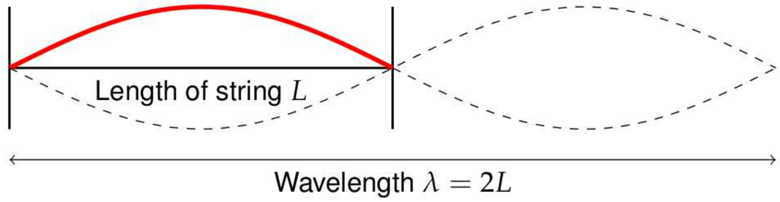


Standing Waves on a String

- A "vibrating" string is actually a standing wave on a string
- Both ends of the string are nodes
- As the string vibrates, the air around it vibrates at the same frequency
- The vibration travels as a sound wave towards your ears
- Examples:
  - Plucking a guitar or violin string

Standing Waves on a String of Length *L*

A **resonance frequency** is a frequency that allows a standing wave to be created on the string. The first resonance (fundamental) frequency at occurs when λ=2*L*:

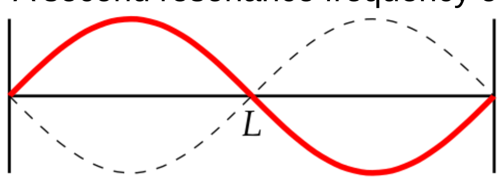


The fundamental frequency is based on the speed of the travelling wave along the string v_{str} which we studied in the last unit:

$$f_1 = \frac{v_{\mathrm{str}}}{\lambda} = \frac{v_{\mathrm{str}}}{2L}$$

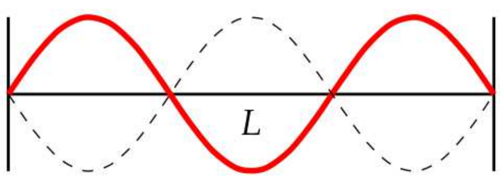
Standing Waves on a String of Length *L*

A second resonance frequency occurs when *L*=λ:



$$f_{\mathrm{res},2} = \frac{v_{\mathrm{str}}}{\lambda} = \frac{v_{\mathrm{str}}}{L} = 2f_1$$

And a third resonance frequency occurs at *L*=3/2 λ:



$$f_{\mathrm{res},3} = \frac{3v_{\mathrm{str}}}{2L} = 3f_1$$

Standing Waves on a String of Length *L*

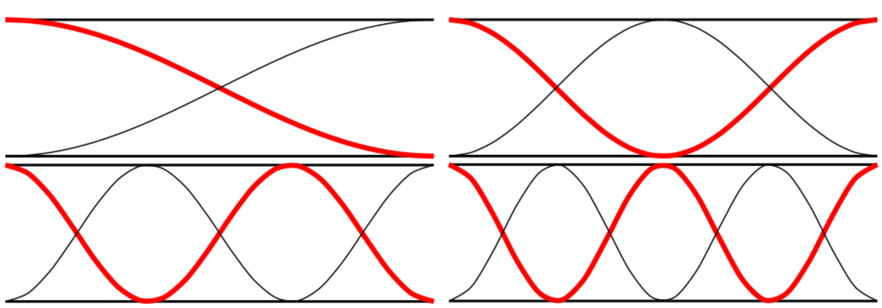
In fact, the *n*-th resonance frequency of a wave on string is just:

$$f_{\mathrm{res,n}} = n f_1$$

- f_1 is the fundamental frequency, and *n* is a whole-number multiple
- This equation is *identical* to the equation for harmonic frequencies, meaning that every harmonic is a resonance frequency
- It has a "full set of harmonics"

Standing Waves in Open Pipes

- Example: Some organ pipes, flute
- Both ends of the pipes are anti-nodes



$$f_1 = \frac{v_s}{\lambda} = \frac{v_s}{2L} \qquad f_2 = \frac{v_s}{\lambda} = \frac{v_s}{L} = 2f_1$$

Standing Waves in Open Pipes

Like strings and closed pipes, open pipes also have a "full set of harmonics". The *n*-th resonance frequency is given by:

$$f_{\mathrm{res,n}} = n f_1$$

where n is a whole-number multiple of fundamental frequency f1:

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

This is not the case for every configuration. Some common configurations do not have a full set of harmonics

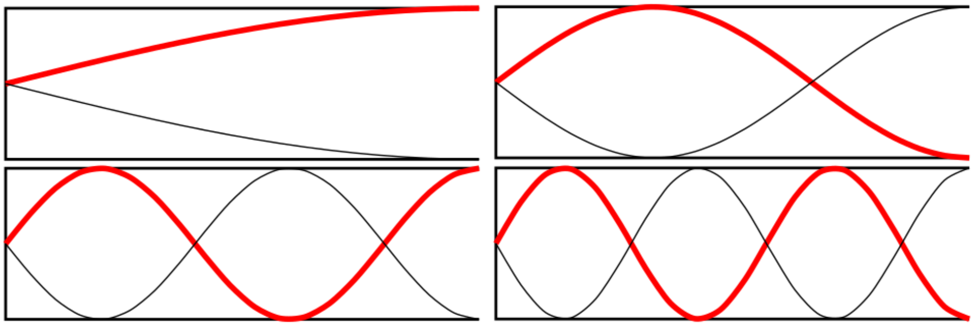
Sample Problem#4

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

1. What are the frequencies of the second and third harmonics?
2. If the speed of sound in air is 344 m/s, what is the length of the air column?

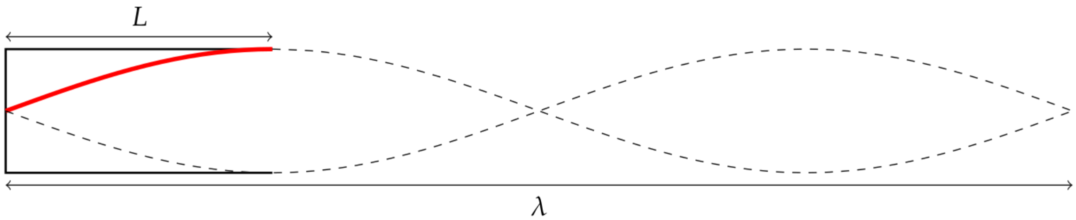
Standing Waves in Semi-Open Pipes

- Examples: Most organ pipes, clarinet, oboes, brass instruments
- Closed end: node (like in the closed pipes)
- Open end: anti-node (like in the open pipes)



Standing Waves in Semi-Open Pipes

Again starting with the fundamental frequency (lowest frequency where a standing wave can form inside the pipe). This occurs at λ=4L:

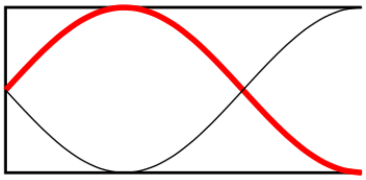


This time, the fundamental frequency f_1 differs from the open-pipe and closed-pipe configurations by a factor of 2:

$$f_1 = \frac{v_s}{\lambda} = \frac{v_s}{4L}$$

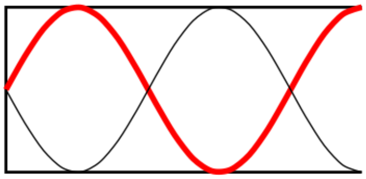
Standing Waves in Semi-Open Pipes

Likewise, second resonance occurs at *λ*=4/3 *L*:



$$f_{\text{res},2} = \frac{v_s}{\lambda} = \frac{3v_s}{4L} = 3f_1$$

And a third resonance occurs at *λ*=4/5 *L*:



$$f_{\text{res},3} = \frac{v_s}{\lambda} = \frac{5v_s}{4L} = 5f_1$$

We can repeat that for 4^{th}, 5^{th}… resonances.

Standing Waves in Semi-Open Pipes

Only **odd-number multiples** of the fundamental frequency are resonance frequencies in a semi-open pipe. We say that semi-open pipes have an *odd set of harmonics*.

$$f_{\text{res,n}} = (2n-1)f_1$$

Because fundamental frequency f_1 is lower than open-pipe and closed-pipe configurations by a factor of 2 for the same length *L*, it has many advantages when designing an organ pipe that produces low frequencies.

$$f_1 = \frac{v_s}{\lambda} = \frac{v_s}{4L}$$

Standing Waves in Semi-Open Pipes

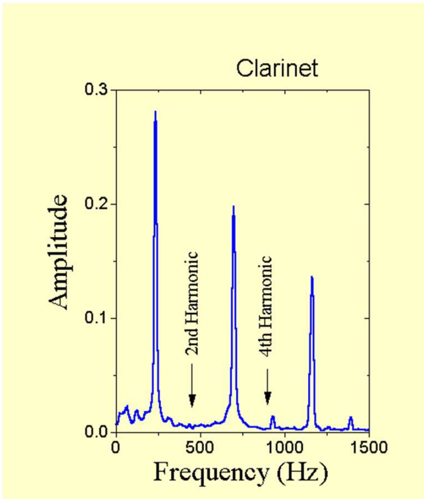
Remember: harmonic frequencies are multiples of the fundamental frequency. This means that:

- 2nd resonance frequency = 3rd harmonic frequency
- 3rd resonance frequency = 5th harmonic frequency
- 4rd resonance frequency = 7th harmonic frequency

The clarinet has a wave pattern of this type…

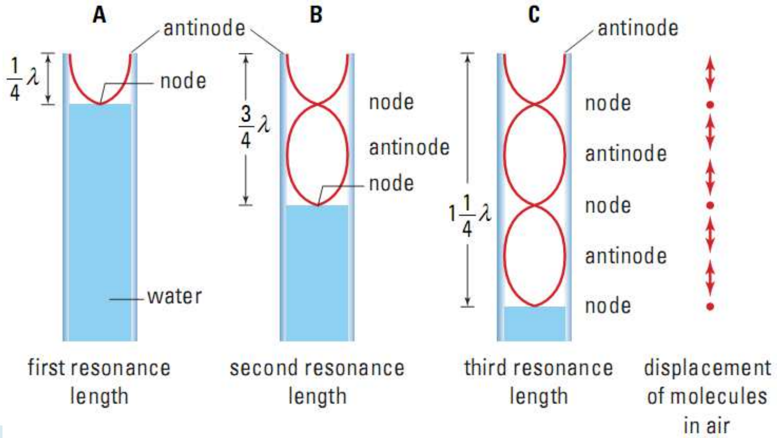
Standing Waves in Semi-Open Pipes

We can see that indeed the even number harmonics are missing. This is what gives the clarinet a very distinct sound.



Resonance Lengths of Semi-Open Pipes

Let's submerge a part of this pipe in water. We can change the effective length of the pipe by lowering/raising it. If we place a sound source at the mouth of the pipe (e.g. tuning fork) at certain lengths, we hear a loud sound coming from the pipe



Resonance Lengths of Semi-Open Pipes

The resonance lengths are odd whole-number multiples of the first resonance length L_1:

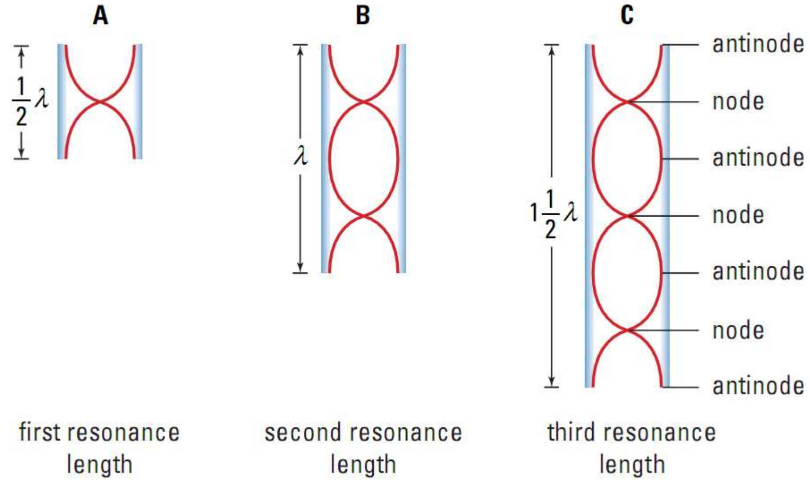
$$L_{\text{res,n}} = (2n-1)L_1$$

Where

$$L_1 = \frac{\lambda}{4}$$

Resonance Lengths of Open Pipes

We can also repeat this with pipes that are open on both ends.



Resonance Lengths of Open Pipes

Resonance lengths of an open pipe are whole-number multiples of the first resonance length L_1:

$$L_{\mathrm{res,n}} = nL_1$$

where first resonance length is given by:

$$L_1 = \frac{\lambda}{2}$$

This equation looks a lot like the resonance frequency equation. When you read your homework/test questions to make sure you know what the question is asking for.

Sample Problem #5

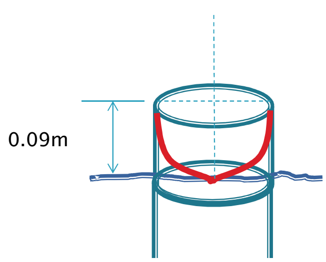
A vibrating tuning fork is held near the mouth of a narrow plastic pipe partially submerged in water. The pipe is raised, and the first loud sound is heard when the air column is 9.0 cm long. The temperature in the room is 20°C.

1. Calculate the wavelength of the sound produced by the tuning fork.
2. Calculate the length of the air column for the second and third resonances.
3. Estimate the frequency of the tune

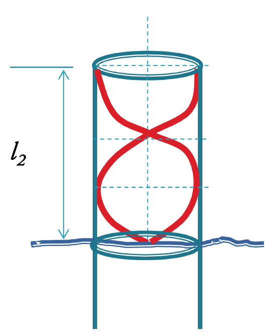
Solution

l_1 = 9 cm = 0.09 m
T_C = 20°C

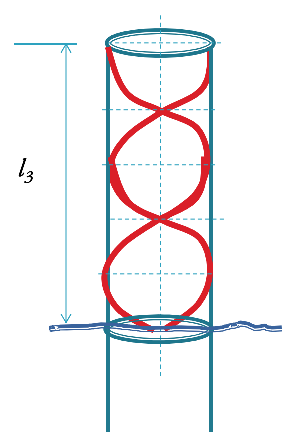
λ = ?
l_2, l_3 =?
f = ?



$l_1 = \lambda/4$
$\lambda = 4l_1$
λ =4 x 0.09 m
λ =0.36 m



l_2 = ¾ λ
l_2 = ¾ x 0.36 m
l_2 = 0.27m



l_3 = 5/4 λ
l_2 = 5/4 x 0.36 m
l_2 = 0.45 m

v=fλ ;   v = 343m/s @ 20°C

f =v/λ;   f=343m/s/0.36m; f =953 Hz