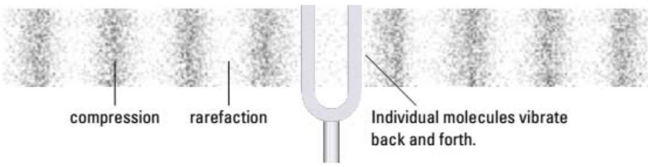
SPH3U	Sound
Unit 4	

Sound is a longitudinal wave. It is energy transmitted through a medium through collisions in the medium.
All sound is a result of vibrations. No sound would be made in a vacuum.

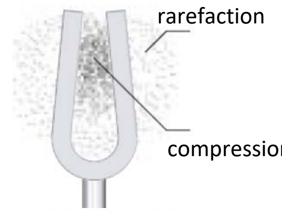
Pictorial representation of sound waves:

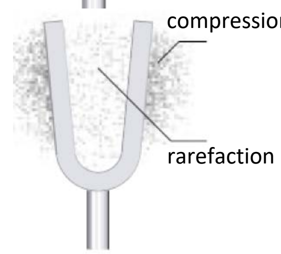


Examples of Sound Sources	Vibrating Object
Voice	Vocal cords
Violin	string
Tuning fork	Tines (prongs)

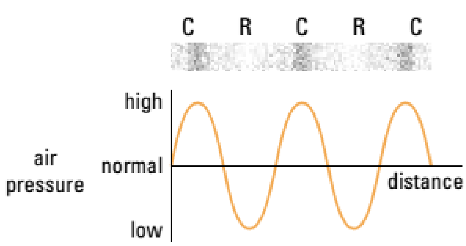
How a tuning fork makes a sound:

- As the tines moves, it pushes air molecules out until they bump into their neighbours. This creates an area of compressed molecules (**compressions** (C)).
- When the tines move back, it creates a region of low concentration of molecules (a **rarefaction** (R)). A series of compressions and rarefactions are produced**.**
- The molecules vibrate back and forth.





<u>Oscilloscope Trace (Visualizing Sound Waves)</u>
Since longitudinal waves are difficult to represent visually, they are graphed instead as air pressure or density over distance (or time). This produces a transverse waveform.



This graph makes it more helpful to measure frequency and amplitude.

Amplitude of a sound wave is the degree in which the air (or medium) particles are displaced from their rest position. The larger the amplitude, the louder the sound (more energy for compressions/rarefactions).

The **frequency** of a sound wave is the number of compressions (C) or rarefactions (R) of air particles experience per second. Pitch is the perceived frequency of sound (e.g. higher the frequency, the higher the pitch is perceived).

Humans can hear frequencies between 20 Hz and 20 000 Hz. Some animals can hear beyond this range. As humans get older, the range decreases (due to more exposure to sounds that damage the inner ear). Sounds with frequencies greater than 20 000 Hz is called **ultrasonic**, and those that are under 20 Hz is called **infrasonic**.

SPH3U	Speed of Sound
Unit 4	

Depends on the nature of the medium:
- its composition (air, water, steel, etc)
- temperature (density of medium changes)
- in general, $v_{solids} > v_{liquids} > v_{gases}$

To find the speed of sound, you can apply the same equations as before:

$$\boxed{v = \frac{\Delta d}{\Delta t}} \quad or \quad \boxed{v = \lambda f}$$

Uniform Motion Equation — Universal Wave Equation

Example: Calculate the speed of sound in sea water if a sound wave takes 0.068 s to travel 100.0 m.

$$v = \frac{\Delta d}{\Delta t}$$
$$v = \frac{100\ m}{0.068\ s}$$
$$v = 1470\ m/s$$

Table 1 The Speed of Sound in Common Materials

State	Material	Speed at 0°C (m/s)
solid	aluminum	5104
	glass	5050
	steel	5050
	maple wood	4110
	bone (human)	4040
	pine wood	3320
solid/liquid	brain	1530
liquid	fresh water	1493 (at 25°C)
	sea water	1470 (depends on salt content)
	alcohol	1241
gas (at atmospheric pressure)	hydrogen	1270
	helium	970
	nitrogen	350 (at 20°C)
	air	332
	oxygen	317
	carbon dioxide	258

There is a third equation that we may use to find the speed of sound, but it is only valid for the speed of sound in air. The previous equations may be used for all situations.

Experimentally, the speed of sound in **air** can be determined with the following equation:

$$\boxed{v = 332\ m/s + \left(0.59\ \frac{m/s}{℃}\right)T}$$

where T is the temperature of the air.

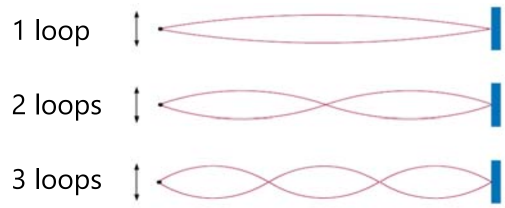
Example: at 25°C, the speed of sound in air is:

$$v = 332\ m/s + \left(0.59\ \frac{m/s}{℃}\right)T$$
$$v = 332\ m/s + \left(0.59\ \frac{m/s}{℃}\right)(25℃)$$
$$v = 347\ m/s$$

SPH3U
Unit 4

Modes of Vibration

If you attempt to create a standing wave with a string or a stretched Slinky, you can adjust the frequency of the vibrating source generating the waves. This will allow various **modes** or patterns of standing waves to be produced as you increase the frequency:



We can see how the first pattern – the simplest mode of vibration called the **fundamental frequency** - uses the entire length of the string to form one loop or one-half of a wavelength. We can also set up a standing wave pattern with two loops (antinodes) – the next mode of vibration – and the frequency of the waves that produce it is twice the fundamental. Each successive **mode** adds half a wave to the pattern with the same length of string, thus decreasing the wavelength.

We can use this to find a useful relationship between the frequencies of different modes of vibration of the same string. The frequency of each mode is an integer multiple of the fundamental frequency. So, if the fundamental frequency was 8 Hz, then the frequency required for the next mode (e.g. 2 loops) is 16 Hz, and so on.

SPH3U
Unit 4

Recall: Resonance

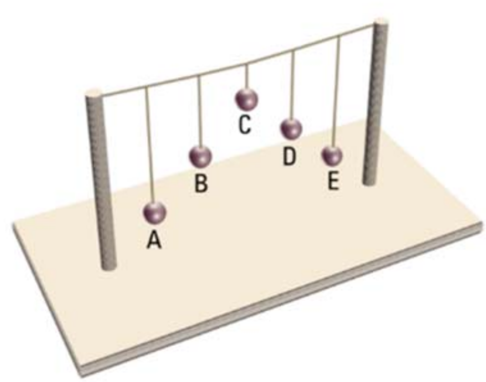
All objects have a natural frequency with which they would vibrate if allowed to move freely.

Resonance is the transfer of energy from one object to another having the same natural frequency.

A system (like a swing) that is driven at a frequency near its resonant frequency experiences very large amplitudes. If it is driven at a slightly higher or lower frequency than the resonant frequency, the amplitudes are smaller.

Demonstration:

Resonance can be demonstrated with a series of pendula suspended from a stretched string. When A is set in vibration, E begins to vibrate in time with it. Similarly, when B is set in vibration, D begins to vibrate. The pairs A and E, and B and D each have the same lengths and, thus, have the same natural frequencies. They are connected to the same support, so the energy from one pendulum is transferred along the supporting string to the other, causing it to vibrate in resonance.



Resonance in Air Columns

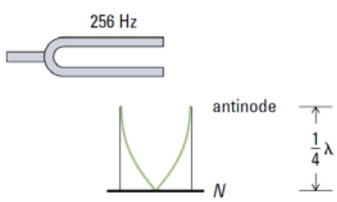
If you have ever blown across the opening of an empty bottle to make a loud sound, then you would have experienced resonance in air columns!

An “air column” is simply a volume of air inside a container. When air passes over the opening of an empty bottle or pipe, the air inside will vibrate due to **resonance**. If the frequency of vibration is just right, a **standing wave pattern** of sound will be set up within the container and a large-amplitude sound will result.

We have just studied resonance and modes of vibration and we will apply those concepts to air columns except that the patterns will no longer be shown as vibrations of a single string but the pressure fluctuations of the air in the air column. There are two types of air columns: **closed air** and **open air columns.**

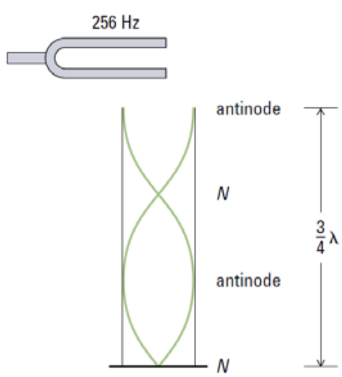
<u>**Closed Air Columns:**</u> Closed air columns are air columns that are **closed at one end and open at the other**. The closed end of the air column <u>must</u> be a node and the open end of the air column <u>must</u> be an anti-node.

If we use a tuning fork, we can create resonance in air columns. The length of the air column that produces a loud sound (resonance) is called the **resonant length**.

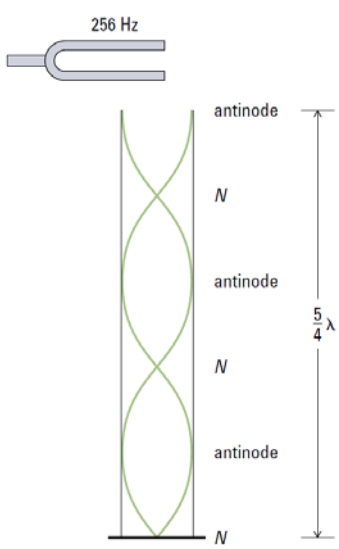


The first resonant length is $L_1 = \frac{\lambda}{4}$

If we had the ability to change the lengthen the air column, we can find other lengths in which a loud sound is heard.



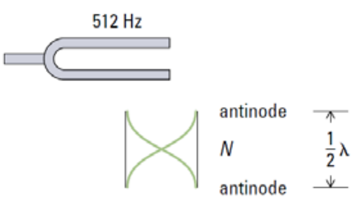
The second resonant length is $L_2 = \frac{3\lambda}{4}$



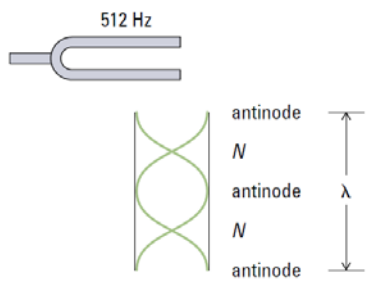
The third resonant length is $L_3 = \frac{5\lambda}{4}$

<u>Open Air Columns</u>: Open air columns are air columns that are open at **both** ends.

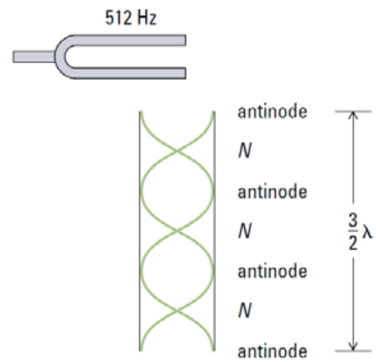
To determine a general formula for open air columns, we perform a similar analysis as we did for closed air columns. However, this time each end of the air column <u>must</u> be an anti-node.



First resonant length is $L_1 = \frac{\lambda}{2}$



Second resonant length is $L_2 = \frac{2\lambda}{2} = \lambda$



Third resonant length is $L_3 = \frac{3\lambda}{2}$

Example:
A tuning fork with frequency 1024 Hz is struck near the open end of an adjustable length pipe in 24°C air. Determine the first two resonant lengths of the pipe if the other end is:
a) closed
b) open

Solution: First, we need to find the speed of sound in air and the wavelength of the sound waves.

$$v_{air} = 332\frac{m}{s} + \left(0.59\,\frac{m/s}{°C}\right)T$$

$$v_{air} = 332\frac{m}{s} + \left(0.59\,\frac{m/s}{°C}\right)(24\,°C)$$

$$v_{air} = 346\,m/s$$

$$v = f\lambda$$

$$\lambda = \frac{v}{f} = \frac{346\,m/s}{1024\,Hz} = 0.338\,m$$

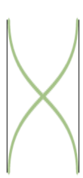
Closed air column:

$$L_1 = \frac{\lambda}{4} = \frac{0.338\,m}{4}$$
$$L_1 = 0.084\,m\ \ (or\ 8.4\,cm)$$

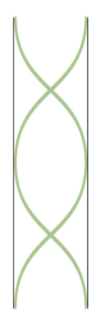
$$L_2 = \frac{3\lambda}{4} = \frac{3(0.338\,m)}{4}$$
$$L_2 = 0.25\,m\ \ (or\ 25\,cm)$$

Open air column:

$$L_1 = \frac{\lambda}{2} = \frac{0.338\,m}{2}$$
$$L_1 = 0.17\,m\ \ (or\ 17\,cm)$$



$$L_2 = \lambda$$
$$L_2 = 0.34\,m\ \ (or\ 34\,cm)$$



SPH3U	Doppler Effect
Unit 4	

Have you ever heard a siren or horn from a fast-moving vehicle as it is passes you? You might have noticed that the siren/horn sounds more high-pitched as the vehicle approaches you and more low-pitched as it is moving away. From the listener's perspective, the apparent frequency of the siren changes when the source of sound is approaching, compared to when it is moving away. This change in frequency from your perspective due to the motion of the source is called the **Doppler effect**.

Consider a moving sound source:

When the sound source is moving towards an observer, the observed (perceived) frequency is greater than the actual (true) frequency of the sound.

When the sound source is moving away from an observer, the observed (perceived) frequency is lower than the actual (true) frequency of the sound.

Figure 1 As the moving siren passes an observer, the observer hears a change in the siren's sound. The sound waves are compressed as the siren approaches the observer and more spread out as the siren passes the observer.

We can calculate the observed (perceived) frequency by using the following equation:

$$f_2 = f_1 \left(\frac{v_{sound}}{v_{sound} \pm v_{source}} \right)$$

Where f_1 is the true frequency, f_2 is the perceived frequency, v_{sound} is the speed of the sound in air, v_{source} is the speed of the moving source.

Use the "+" version when the source is moving away, use the "−" version when the source is moving towards.

Example: Suppose a fire truck is moving toward a stationary observer at 25.0 m/s. The frequency of the siren on the fire truck is 800.0 Hz. Calculate the frequency detected by the observer as the fire truck approaches. The speed of sound in this case is 342 m/s.

Solution:

$$f_2 = f_1\left(\frac{v_{sound}}{v_{sound} \pm v_{source}}\right)$$

$$f_2 = (800\ Hz)\left(\frac{342\ m/s}{342\ m/s - 25\ m/s}\right)$$

$$f_2 = 863\ Hz$$

Notice that the observed (apparent) frequency is higher than the actual frequency of the siren.

SPH3U	Supersonic Travel
Unit 4	

Rockets and fighter aircrafts can travel faster than the speed of sound in air – they can achieve speeds that are **supersonic**. Objects travelling at speeds less than the speed of sound in air have **subsonic** speeds. When the speed of an object equals the speed of sound in air at that location, the speed is called Mach 1. The **Mach number** of a source of sound is the ratio of the speed of the source to the speed of sound in air at that location.

Mach Number

It is named after Austrian physicist Ernst Mach, and since it is a ratio of two speeds it has no units. Formula:

$$\boxed{Mach\ number = \frac{v_{object}}{v_{sound}}}$$

Example: What is the speed of an aircraft travelling at Mach 2 at a location with a temperature of 0°C?

$v = 332\ m/s$ at 0°C

$$Mach\ number = \frac{v_{object}}{v_{sound}}$$

$$v_{object} = Mach\ number\ \times v_{sound}$$

$$v_{object} = 2 \times 332\ m/s$$

$$v_{object} = 664\ m/s$$

Breaking the Sound Barrier (Enrichment)

When an aircraft is flying at the speed of sound, the wavefronts in front of the airplane pile up, producing an area of very dense air, or intense compression, called the **sound barrier**. Aircrafts are designed to be able to break the sound barrier.

When objects travel faster than the speed of sound, they create a region of high-pressure air in front of them (as the air molecules get pushed together.) This region of high-pressure air gets pushed along at supersonic speeds as the object travels. The boundary between the moving high-pressure air and the normal air in front of it is called a **shock wave**, though it is not really a wave. The **shock wave** takes the shape of a cone with its point at the leading edge of the object (see figure c below). When the shock wave passes an observer, they experience an extremely rapid change in pressure that is perceived as a very loud noise; this is known as a **sonic boom**.

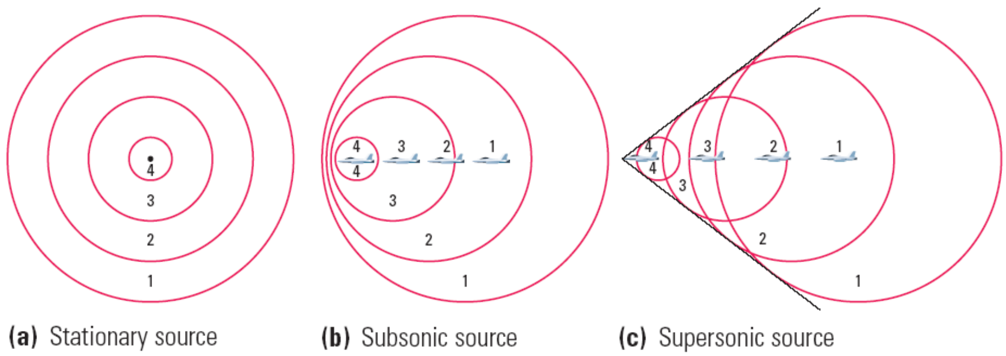


Figure 4 from page 271 of the textbook. The image shows successive positions of a stationary, subsonic and supersonic object. The circles show the boundaries of the sound waves generated at each location.