Lecture 18: Sound Levels, The Doppler Effect, Heat, & Temperature

Physics for Engineers & Scientists (Giancoli): Chapters 16, 17, & 19
University Physics V1 & V2 (Openstax): Chapters 17 (*V1*) & 1 (*V2*)

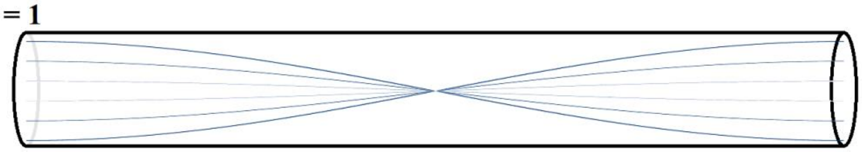
Longitudinal Waves in a Pipe

- A closed end of a pipe creates a node while an open end creates an anti-node.
- Each mode of vibration (n) occurs at a specific wavelength (and frequency) related to the pipe's length (L), depending upon whether one end or both ends are open.
- Harmonics in pipe with two open ends:

$$\lambda_n = \frac{2L}{n} \qquad f_n = \frac{v_{sound}}{\lambda_n} = \frac{nv_{sound}}{2L} \qquad \#Nodes = n \qquad \#Anti\text{-}Nodes = n+1$$

  - The first harmonic or fundamental mode (n = 1) is the simplest and usually the loudest tone heard (largest amplitude). It has an anti-node at each end, and one node in between.

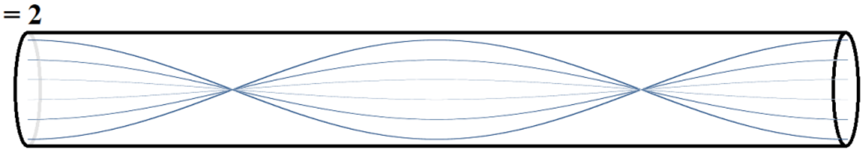
n = 1



$$L = \frac{1}{2}\lambda_1 \qquad \lambda_1 = 2L \qquad f_1 = \frac{v_{sound}}{\lambda_1} = \frac{v_{sound}}{2L}$$

  - The second harmonic (n = 2) has an anti-node at each end, another anti-node in the middle, and two nodes (halfway between each adjacent pair of anti-nodes).

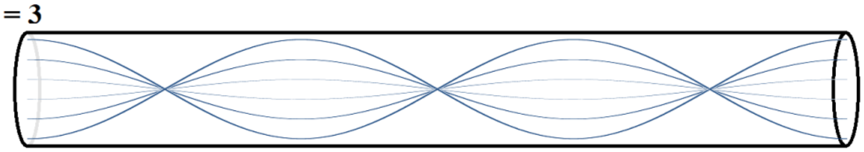
n = 2



$$\lambda_2 = L \qquad f_2 = \frac{v_{sound}}{\lambda_2} = \frac{v_{sound}}{L}$$

  - The third harmonic (n = 3) has an anti-node at each end, two more anti-nodes evenly spaced in between, and three nodes (halfway between each adjacent pair of anti-nodes).

n = 3



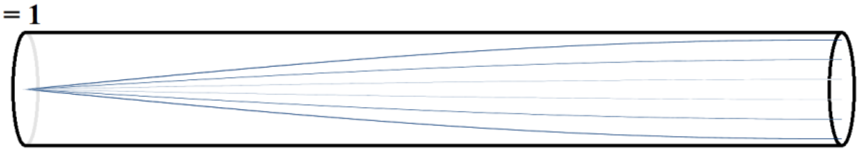
$$L = \frac{3}{2}\lambda_3 \qquad \lambda_3 = \frac{2L}{3} \qquad f_3 = \frac{v_{sound}}{\lambda_3} = \frac{3v_{sound}}{2L}$$

- Harmonics in pipe with one end open and one end closed:

$$\lambda_n = \frac{4L}{2n-1} \qquad f_n = \frac{v_{sound}}{\lambda_n} = \frac{(2n-1)v_{sound}}{4L} \qquad \#Nodes = n \qquad \#Anti\text{-}Nodes = n$$

- The first harmonic or fundamental mode (n = 1) is the simplest and usually the loudest tone heard (largest amplitude). It has a node at one end and an anti-node at the other.

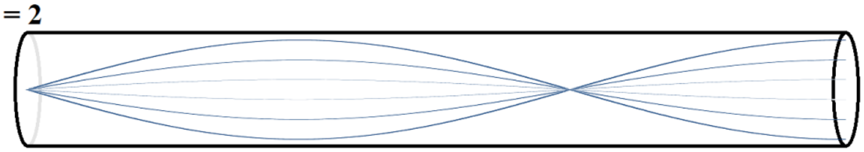
n = 1



$$L = \frac{1}{4}\lambda_1 \qquad \lambda_1 = 4L \qquad f_1 = \frac{v_{sound}}{\lambda_1} = \frac{v_{sound}}{4L}$$

- The second harmonic (n = 2) has a node and an anti-nodes at either end, with another node and anti-node in the middle.

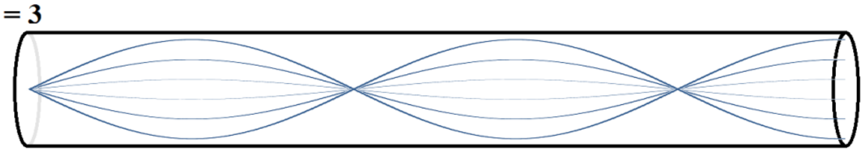
n = 2



$$L = \frac{3}{4}\lambda_2 \qquad \lambda_2 = \frac{4}{3}L \qquad f_2 = \frac{v_{sound}}{\lambda_2} = \frac{3v_{sound}}{4L}$$

- The third harmonic (n = 3) has three nodes and three anti-nodes.

n = 3



$$L = \frac{5}{4}\lambda_3 \qquad \lambda_3 = \frac{4L}{5} \qquad f_3 = \frac{v_{sound}}{\lambda_3} = \frac{5v_{sound}}{4L}$$

Sometimes musicians playing horns will cover the opening, providing a drop in frequency (one octave) and a change in the harmonic frequencies.

<u>Example</u>: Two pipes are the same length. The first pipe has both ends open, and the second has one closed end. If the both pipes have their 4th harmonic excited, which pipe produces the higher pitch?

1st Pipe: $f_n = \frac{nv_{sound}}{2L} = \frac{4v_{sound}}{2L} = 2\frac{v_{sound}}{L}$

2nd Pipe: $f_n = \frac{(2n-1)v_{sound}}{4L} = \frac{[2(4)-1]v_{sound}}{4L} = \frac{7}{4}\frac{v_{sound}}{L}$

As $2 > \frac{7}{4}$, the 1st pipe produces the higher pitch.

<u>Intensity</u> (I): $I = \frac{P}{A}$

- The **<u>Intensity</u> (I)** of a wave is the power per unit area carried by the wave. Units: $\frac{W}{m^2}$
- Typically a time averaged value is used for power.
- As sound tends to radiate spherically, the intensity will drop with the square of the radius.

Sound Levels (β) $\quad \beta(dB) = 10log\left(\frac{I}{I_0}\right)$

- Normal human hearing is sensitive to frequencies from 20 Hz to 20 kHz, but is most sensitive to sounds between 1 kHz and 4 kHz.
- The minimum intensity that we can hear is $I_0 = 10^{-12}\,\frac{W}{m^2}$
- As human hearing is sensitive to a wide range of intensity, a log scale is used for sound levels.

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

- Sound below 75 dB typically does no damage to hearing.
    - Breathing (10 dB) is barely audible.
    - Whispering or a Quiet Rural Area (30 dB) is very quiet.
    - Conversation in restaurant, office background music, or an air conditioner at 100 ft. (60 dB) is fairly quiet.
    - Vacuum Cleaner (70 dB)
- Intense sounds (85 dB and above) can damage a person's ability to hear depending upon the duration of exposure.
    - 8 hours of exposure to sounds over 90 dB can possibly cause damage. This includes the sound of a power mower (96 dB), being 25 ft. from a motorcycle (90 dB), or being 1 nautical mile (6080 ft.) from a landing commercial aircraft (97 dB)
    - Sounds at the average human pain threshold of 110 dB such as a car horn at 1m (110 dB) or live music at a rock concert (108 to 114 dB) can cause damage in minutes.
    - Sounds at 120dB (such as a chainsaw) are painful and can damage an ear after only seconds.
    - Sounds at 150 dB (such a jet taking off at 25 meters) can rupture eardrums.

Example: The sound technician in a recording studio sets the sound level of the backing vocals to be 3.00 dB lower than the lead vocals. Determine the ratio of the intensity of the background vocals to that of the lead vocals.

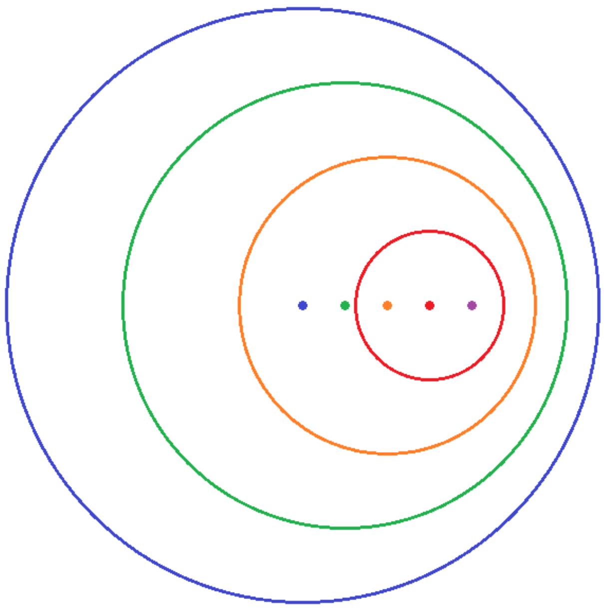
$$\beta_B = \beta_L - 3.00 \qquad 10log\left(\frac{I_B}{I_0}\right) = 10log\left(\frac{I_L}{I_0}\right) - 3.00 \qquad log\left(\frac{I_B}{I_0}\right) = log\left(\frac{I_L}{I_0}\right) - 0.300$$

$$10^{log\left(\frac{I_B}{I_0}\right)} = 10^{log\left(\frac{I_L}{I_0}\right) - 0.300} = 10^{log\left(\frac{I_L}{I_0}\right)}10^{-0.300} = \frac{I_L}{I_0}\,(0.501)$$

$$\frac{I_B}{I_0} = 0.501\frac{I_L}{I_0} \qquad \frac{I_B}{I_L} = 0.501$$

The Doppler Effect

- Moving sources of sound compress the wavelengths in front of them and stretch the wavelengths behind them. A stationary observer will hear a different frequency than that emitted by the source.
- A similar effect occurs when the observer is moving.



$$f' = f\left(\frac{v_{sound} \pm v_{observer}}{v_{sound} \mp v_{source}}\right)$$

f' is the frequency heard by the observer.

f is the frequency emitted by the source.

v_{sound} is the speed of sound in air (343 m/s).

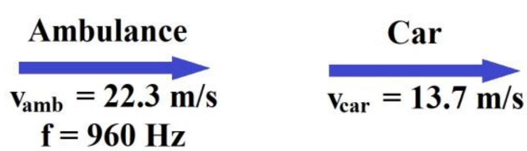
$v_{observer}$ is the velocity of the observer.

v_{source} is the velocity of the source.

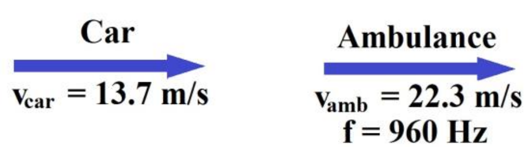
The top sign is used when the velocity of the observer (source) is directed towards the source (observer).

Or, if you prefer, if you always place the source on the right and the observer on the left, then us a positive sign when moving right and a negative sign when moving left.

Example: A car is moving down a street at 13.7 m/s when the driver hears the siren of an ambulance approaching from behind at 22.3 m/s. The frequency of the horn on the ambulance is 960 Hz. (A) What frequency does the driver of the car hear as the ambulance approaches? And (B) What frequency does the driver of the car hear after being passed by the ambulance?



$$f' = f\left(\frac{v_{sound} \pm v_{observer}}{v_{sound} \mp v_{source}}\right) = (960\ Hz)\left(\frac{343\frac{m}{s} - 13.7\frac{m}{s}}{343\frac{m}{s} - 22.3\frac{m}{s}}\right) = 986\ Hz$$



$$f' = f\left(\frac{v_{sound} \pm v_{observer}}{v_{sound} \mp v_{source}}\right) = (960\ Hz)\left(\frac{343\frac{m}{s} + 13.7\frac{m}{s}}{343\frac{m}{s} + 22.3\frac{m}{s}}\right) = 937\ Hz$$

Example: A bat is flying at 4.50 m/s towards an insect the bat intends to feed upon. The insect is moving towards the bat at 3.00 m/s. The bat chirps at a frequency of 100 kHz. Determine the frequency of the reflected sound heard by the bat.

Let f' be the frequency observed by the insect. As this is what reflects, it becomes the source for the return trip. We shall call f'' the frequency heard by the bat.

$$f' = f\left(\frac{v_{sound} \pm v_{observer}}{v_{sound} \mp v_{source}}\right) = f\left(\frac{v_{sound} + v_{insect}}{v_{sound} - v_{bat}}\right)$$

$$f'' = f'\left(\frac{v_{sound} \pm v_{observer}}{v_{sound} \mp v_{source}}\right) = f'\left(\frac{v_{sound} + v_{bat}}{v_{sound} - v_{insect}}\right) = f\left(\frac{v_{sound} + v_{insect}}{v_{sound} - v_{bat}}\right)\left(\frac{v_{sound} + v_{bat}}{v_{sound} - v_{insect}}\right)$$

$$f'' = (100\ kHz)\left(\frac{343\frac{m}{s} + 3.00\frac{m}{s}}{343\frac{m}{s} - 4.50\frac{m}{s}}\right)\left(\frac{343\frac{m}{s} + 4.50\frac{m}{s}}{343\frac{m}{s} - 3.00\frac{m}{s}}\right) = 104\ kHz$$

Temperature Scales

- The **Fahrenheit Scale**, proposed by Daniel Fahrenheit in 1724 and still used in the United States, placed the freezing point of water at 32°F and the boiling point of water at 212°F.
- The **Celsius Scale**, previously known as the centigrade scale, is the SI unit for temperature. It is named after Anders Celsius and places the freezing point of water at 0°C and the boiling point of water at 100°C. This scale is used almost everywhere else in the world.

$$T(°\text{C}) = \tfrac{5}{9}[T(°\text{F}) - 32] \qquad T(°\text{F}) = \tfrac{9}{5}T(°\text{C}) + 32 \qquad \Delta T(°\text{F}) = \tfrac{9}{5}\Delta T(°\text{C})$$

- The temperature of an object is directly related to the kinetic energy of the random motions of its constituent particles. The minimum possible temperature would be the temperature associated with no motion at all, zero kinetic energy. This temperature is called **Absolute Zero**.
- The **Kelvin Scale** is the same scale as the Celsius Scale with zero moved from the freezing point of water to absolute zero, where motion stops.

$$0\ K = -273.15°C \qquad T(°\text{C}) = T(K) - 273.15$$

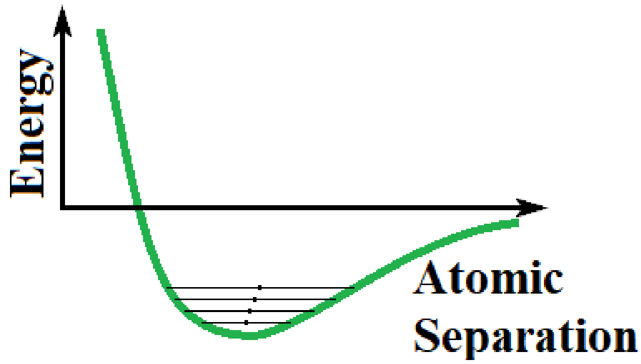
Example: The high one day this summer was 104°F. What temperature is this in A) Celsius and B) Kelvin?

$$T(°\text{C}) = \frac{5}{9}[T(°\text{F}) - 32] = \frac{5}{9}[104 - 32] = \frac{5}{9}[72] = 40°\text{C}$$

$$T(K) = T(°\text{C}) + 273.15 = 40 + 273.15 = 313\ K$$

Thermal Expansion

- In most cases, the atomic separation increases in solids as the temperature (internal energy) increases. This causes solids to expand (**Thermal Expansion**).



Each atom vibrates in a potential well created by its neighbors. Notice that the average separation (the center of the vibration) increases with energy due to the shape of the well.

$$L = L_0[1 + \alpha\Delta T] \qquad \Delta L = \alpha L_0 \Delta T$$

- The Coefficient of Thermal Expansion (α) is a constant, but its value differs from material to material. The units of α are $(°C)^{-1}$ (one over a degree Celsius).

Example: An overpass is to being constructed from 20.0 m long slabs of concrete. The coefficient of thermal expansion for concrete is $1.10 \times 10^{-5}\ (°C)^{-1}$. Determine the width of the gap needed between slabs at 78.0°F such that the concrete slabs won't touch the next slab until it reaches the maximum expected temperature of 132.0°F.

$$\Delta T\ (°F) = 132.0°F - 78.0°F = 54.0°F \qquad \Delta T(°C) = \frac{5}{9}\Delta T(°F) = \frac{5}{9}(54.0) = 30.0°C$$

$$\Delta L = \alpha L_0 \Delta T = [1.10 \times 10^{-5}(°C)^{-1}](20.0\ m)(30.0°C) = 6.60\ mm$$

Heat and Temperature Change $Q = cm\Delta T$

- All objects have **Internal Energy** (U) consisting of the random atomic and molecular motions.
- This energy can be transferred from one object to another, and the movement of this energy is called **Heat** (Q).
- Heat (Q) flows from higher temperature to lower temperature.

$$Q = cm\Delta T$$

  - Q is the heat added (in J).
  - c is the specific heat capacity of that substance (units $\frac{J}{kg \cdot °C}$)
  - m is the mass of the object (in kg)
  - ΔT is the change in temperature (in °C or K)

- In gases the volume (V), the pressure (P), and the temperature (T) are dependent. Changing the temperature must change either the volume of the pressure.
- The specific heat capacity of a gas is different depending upon whether the volume or pressure is held constant (cV or cP).

Example: A tub can hold up to 404 kg of water. It has two taps. One tap produces cool water at 15.0°C, and the other produces hot water at 45.0°C. How much cool water should you add in order to have a full tub of warm water at 37.0°C?

The heat lost by the hot water must raise the temperature of the cold water.

$$Q_C + Q_H = 0 \qquad cm_c\Delta T_c + cm_H\Delta T_H = 0 \qquad m_c\Delta T_c + m_H\Delta T_H = 0$$

$$m_c(T_f - T_C) + m_H(T_f - T_H) = 0 \qquad m_c(37.0°\text{C} - 15.0°\text{C}) + m_H(37.0°\text{C} - 45.0°\text{C}) = 0$$

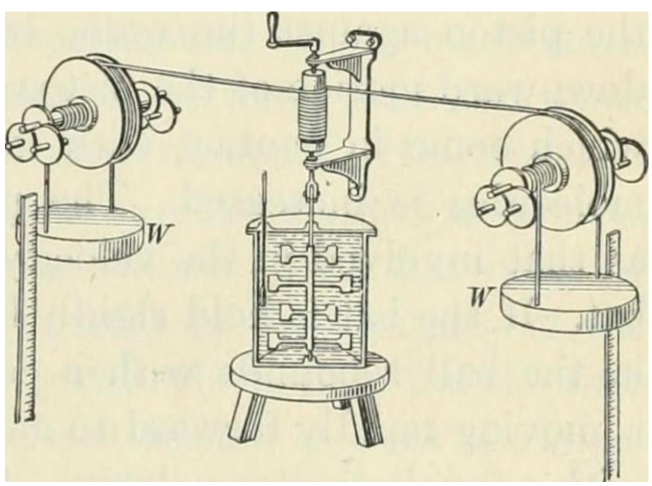
$$m_c(22.0°\text{C}) - m_H(8.0°\text{C}) = 0 \qquad m_c(22.0°\text{C}) - (m_{Tot} - m_c)(8.0°\text{C}) = 0$$

$$m_c(22.0°\text{C}) - m_{Tot}(8.0°\text{C}) + m_c(8.0°\text{C}) = 0 \qquad m_c(30.0°\text{C}) = m_{Tot}(8.0°\text{C})$$

$$m_c = m_{Tot}\frac{(8.0°\text{C})}{(30.0°\text{C})} = (404\ kg)\frac{(8.0°\text{C})}{(30.0°\text{C})} = 108\ kg$$

Calories and James Joule

- Initially it wasn't known that heat and mechanical energy were equivalent. Consequently, heat had its own units (calorie).
- A **calorie** is defined as the amount of heat needed to raise the temperature of one gram of water by 1°C.
- In 1847, James Joule performed a definitive experiment showing that heat and mechanical energy were equivalent.



- Falling masses were used to turn agitators inside an insulated fluid.
- The potential energy of the masses was converted into a rise in temperature of the fluid.

$$1\ cal = 4.186\ J$$

Nutritionist use "Calories" to measure the energy value of food, but these are actually kilo-calories.

"cal" = calorie. "Cal" = kcal = kilo-calorie.