1 Topics Covered

- **Mechanical Waves**: Recall that mechanical waves are waves that travel in a medium. Solids can support both longitudinal and transverse waves, but fluids (either liquids or gases) can only support longitudinal waves.

- **Sound Waves**: Sound waves are traveling mechanical waves of pressure variation.

- **Mathematical Description of 1-D Sound Waves**:
  - **Pressure**: If the undisturbed pressure in a tube of fluid is $P_0$, the pressure wave is given by $P(x,t) = P_0 + \Delta P(x,t) = P_0 + \Delta P_m \sin (kx - \omega t + \phi)$, where $\Delta P_m$ is the amplitude of the pressure variation.
  - **Density**: If the undisturbed density in a tube of fluid is $\rho_0$, the density wave is given by $\rho(x,t) = \rho_0 + \Delta \rho(x,t) = \rho_0 + \Delta \rho_m \sin (kx - \omega t + \phi)$, where $\Delta \rho_m$ is the amplitude of the density variation.
  - **Position**: The displacement of a piece of fluid in a tube is given by $s(x,t) = s_m \cos (kx - \omega t + \phi)$, where $s_m$ is the amplitude of the position variation.
  - **Amplitude**: The amplitudes of the pressure, density, and displacement variations associated with a sound wave are related by $s_m = \frac{\Delta \rho_m}{\rho_0} = \frac{\Delta P_m}{kB}$, where $B$ is the bulk modulus of the medium.

- **Links to Experience**:
  - **Pitch**: The frequency of a sound wave determines its pitch.
  - **Loudness**: The pressure amplitude of a sound wave determines its loudness.
  - **Tone**: The shape of the wave determines its tone (real sound waves are not usually sinusoidal).

- **Speed of Sound**:
  - **In a Fluid**: The speed of a longitudinal wave in a fluid is given by $v = \sqrt{B/\rho_0}$, where $B$ is the bulk modulus of the medium.
  - **In a Solid Rod**: The speed of a longitudinal wave in a solid rod is given by $v = \sqrt{Y/\rho_0}$, where $Y$ is Young’s modulus for the medium.
  - **In an Ideal Gas**: The speed of a longitudinal wave in an ideal gas is given by $v = \sqrt{\gamma RT/M}$, where $\gamma$ is the ratio of the heat capacities (you’ll understand later), $R$ is the gas constant, $T$ is the temperature in Kelvin, and $M$ is the molar mass of the gas.
  - **Oldies**: Remember that there is a general formula for wave speed ($v = \lambda f$) and one for waves on a string ($v = \sqrt{T/\mu}$, where $T$ is tension and $\mu$ is linear mass density).

- **Intensity**: Recall that intensity is the power per unit area. There are several formulas for intensity: $I = \frac{1}{2} \Delta P_m^2 \omega_2 s_m^2 = \frac{P_m^2}{2\rho_0} = \frac{P_m^2}{2\sqrt{\rho_0 B}}$.

- **Decibel Intensity Scale**: The decibel scale conveniently expresses the intensity $I$ of a sound wave by comparing it to a reference level $I_0$. The formula is $\beta = 10 \log \frac{I}{I_0}$. (The units in this scale are $dB$.)
**Doppler Effect**: If either a source of sound or a listener is moving with respect to the medium that carries the sound, the listener will perceive a different frequency than what was emitted. Let $v$ be the speed of sound, $v_S$ be the speed of the source with respect to the medium, and $v_L$ be the speed of the listener with respect to the medium. (The direction from the listener to the source is taken to be positive.) If sound is emitted at a frequency $f_0$, the sound heard by the listener will have frequency $f = f_0 \left( \frac{v + v_L}{v + v_S} \right)$.

## 2 Problems

1. Suppose a piston is generating sound waves at a frequency of 40 kHz in a tube filled with an ideal gas.
   (a) Treat the air as an ideal gas with $\gamma = 1.40$ and $M = 30 \text{ g/mol}$. The gas constant is, as usual, 8.31 $\text{J/k mol}$.
   If the temperature is 300 K, what is the speed of sound in the gas?
   (b) If the undisturbed density of the gas is $\rho_0 = 10 \text{ kg/m}^3$, what is its bulk modulus?
   (c) If the pressure amplitude is 1 Pa, find the displacement amplitude and the density amplitude.
   (d) If the displacement is zero when $x = 0$ and $t = 0$, write the equations for pressure, density, and displacement. Assume that $P_0 = 0$.
   (e) Graph the pressure, density, and displacement waves when $t = 0$.
   (f) If pressure is at a maximum, what do you know about density? If density is at a minimum, what do you know about displacement? If displacement is zero, what do you know about pressure?

2. Suppose you are standing 3 m away from a jackhammer and you measure its intensity to be 120 dB.
   (a) The usual value for $I_0$ is $I_0 = 10^{-12} \text{W/m}^2$. What is the intensity of the sound wave as it hits your ear?
   (b) If the speed of sound in the air is 344 m/s and the density of air is 1.2 kg/m$^3$, what is the amplitude of the pressure variations caused by the jackhammer?
   (c) Find the total power delivered by the jackhammer to the air.
   (d) How far away would you have to stand in order for the jackhammer to have an intensity of 30 dB?

3. Trains always whistle as they go by a station. The speed of sound is 344 m/s.
   (a) You stand still on a platform and watch a train approach. How fast must the train be going if the sound you hear has double the frequency of the emitted whistle?
   (b) As another train arrives, the breeze begins to blow at 10 m/s in the train’s direction. Now how fast must the train be going if the sound you hear has double the frequency of the emitted whistle?
   (c) When the third train arrives, the breeze has stopped and you are walking away from it at 10 m/s. Now how fast must the train be going if the sound you hear has double the frequency of the emitted whistle?