Objectives: After completing this module, you should be able to:

• Compute intensity and intensity levels of sounds and correlate with the distance to a source.

• Apply the Doppler effect to predict apparent changes in frequency due to relative velocities of a source and a listener.
Acoustics is the branch of science that deals with the physiological aspects of sound. For example, in a theater or room, an engineer is concerned with how clearly sounds can be heard or transmitted.
Audible Sound Waves

Sometimes it is useful to narrow the classification of sound to those that are audible (those that can be heard). The following definitions are used:

- **Audible sound**: Frequencies from 20 to 20,000 Hz.
- **Infrasonic**: Frequencies below the audible range.
- **Ultrasonic**: Frequencies above the audible range.
## Comparison of Sensory Effects With Physical Measurements

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Physical properties are measurable and repeatable.
Sound intensity is the power transferred by a sound wave per unit area normal to the direction of wave propagation.

\[ I = \frac{P}{A} \]

Units: W/m²
Isotropic Source of Sound

An isotropic source propagates sound in ever-increasing spherical waves as shown. The Intensity $I$ is given by:

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}$$

Intensity $I$ decreases with the square of the distance $r$ from the isotropic sound source.
Comparison of Sound Intensities

The inverse square relationship means a sound that is twice as far away is one-fourth as intense, and one that is three times as far away is one-ninth as intense.

\[ I_1 = \frac{P}{4\pi r_1^2} \quad I_2 = \frac{P}{4\pi r_2^2} \]

\[ P = 4\pi r_1^2 I_1 = 4\pi r_2^2 I_2 \]

\[ I_1 r_1^2 = I_2 r_2^2 \]
Example 1: A horn blows with constant power. A child 8 m away hears a sound of intensity 0.600 W/m². What is the intensity heard by his mother 20 m away? What is the power of the source?

Given: \( I_1 = 0.60 \text{ W/m}^2;\) \( r_1 = 8 \text{ m, } r_2 = 20 \text{ m}\)

\[
I_1 r_1^2 = I_2 r_2^2 \quad \text{or} \quad I_2 = \frac{I_1 r_1^2}{r_2^2} = I_1 \left( \frac{r_1}{r_2} \right)^2
\]

\[
I_2 = 0.60 \text{ W/m}^2 \left( \frac{8 \text{ m}}{20 \text{ m}} \right)^2
\]

\[
I_2 = 0.096 \text{ W/m}^2
\]
Example 1: (Cont.) What is the power of the source? Assume isotropic propagation.

Given: \( I_1 = 0.60 \text{ W/m}^2; \quad r_1 = 8 \text{ m} \)
\( I_2 = 0.0960 \text{ W/m}^2; \quad r_2 = 20 \text{ m} \)

\[
I_1 = \frac{P}{4\pi r_1^2} \quad \text{or} \quad P = 4\pi r_1^2 I_1 = 4\pi (8 \text{ m})^2 (0.600 \text{ W/m}^2)
\]

\[
P = 7.54 \text{ W}
\]

The same result is found from: \( P = 4\pi r_2^2 I_2 \)
Range of Intensities

The hearing threshold is the standard **minimum** of intensity for audible sound. Its value $I_0$ is:

Hearing threshold: $I_0 = 1 \times 10^{-12} \text{ W/m}^2$

The pain threshold is the **maximum** intensity $I_p$ that the average ear can record without feeling or pain.

Pain threshold: $I_p = 1 \text{ W/m}^2$
Due to the wide range of sound intensities (from $1 \times 10^{-12}$ W/m² to 1 W/m²) a logarithmic scale is defined as the intensity level in decibels:

\[
\beta = 10 \log \frac{I}{I_0} \text{ decibels (dB)}
\]

where $\beta$ is the intensity level of a sound whose intensity is $I$ and $I_0 = 1 \times 10^{-12}$ W/m².
Example 2: Find the intensity level of a sound whose intensity is $1 \times 10^{-7}$ W/m$^2$.

\[ \beta = 10 \log \frac{I}{I_0} = 10 \log \frac{1 \times 10^{-7} \text{W/m}^2}{1 \times 10^{-12} \text{W/m}^2} \]

\[ \beta = 10 \log 10^5 = (10)(5) \]

Intensity level: $\beta = 50$ dB
Intensity Levels of Common Sounds.

- Leaves or whisper: 20 dB
- Normal conversation: 65 dB
- Subway: 100 dB
- Jet engines: 140-160 dB

Hearing threshold: 0 dB  Pain threshold: 120 dB
Comparison of Two Sounds

Often two sounds are compared by intensity levels. But remember, intensity levels are logarithmic. A sound that is 100 times as intense as another is only 20 dB larger!

Source A

20 dB, $1 \times 10^{-10}$ W/m²

$I_B = 100 \, I_A$

Source B

40 dB, $1 \times 10^{-8}$ W/m²
Consider two sounds of intensity levels $\beta_1$ and $\beta_2$

$$\beta_1 = 10\log \frac{I_1}{I_0}; \quad \beta_2 = 10\log \frac{I_2}{I_0}$$

$$\beta_2 - \beta_1 = 10\log \frac{I_2}{I_0} - 10\log \frac{I_1}{I_0} = 10 \left( \log \frac{I_2}{I_0} - \log \frac{I_1}{I_0} \right)$$

$$\beta_2 - \beta_1 = 10\log \frac{I_2/I_0}{I_1/I_0}$$

$$\beta_2 - \beta_1 = 10\log \frac{I_2}{I_1}$$
**Example 3:** How much more intense is a 60 dB sound than a 30 dB sound?

\[ \beta_2 - \beta_1 = 10 \log \frac{I_2}{I_1} \]

60 dB − 30 dB = 10 log \( \frac{I_2}{I_1} \) and \( \log \frac{I_2}{I_1} = 3 \)

Recall definition: \( \log_{10} N = x \) means \( 10^x = N \)

\( \log \frac{I_2}{I_1} = 3; \quad \frac{I_2}{I_1} = 10^3; \quad I_2 = 1000 I_1 \)
Interference and Beats

Beat frequency = \( f' - f \)
The Doppler Effect

The **Doppler effect** refers to the apparent change in frequency of a sound when there is relative motion of the source and listener.

\[ f = \frac{v}{\lambda} \]

Left person hears lower \( f \) due to longer \( \lambda \).

Right person hears a higher \( f \) due to shorter \( \lambda \).

Apparent \( f_0 \) is affected by motion.
General Formula for Doppler Effect

\[ f_0 = f_s \left( \frac{V + v_0}{V - v_s} \right) \]

**Definition of terms:**
- \( f_0 \) = observed frequency
- \( f_s \) = frequency of source
- \( V \) = velocity of sound
- \( v_0 \) = velocity of observer
- \( v_s \) = velocity of source

Speeds are reckoned as positive for approach and negative for recession.
Example 4: A boy on a bicycle moves north at 10 m/s. Following the boy is a truck traveling north at 30 m/s. The truck’s horn blows at a frequency of 500 Hz. What is the apparent frequency heard by the boy? Assume sound travels at 340 m/s.

The truck is approaching; the boy is fleeing. Thus:

\[ \nu_s = +30 \text{ m/s} \quad \nu_0 = -10 \text{ m/s} \]
Example 4 (Cont.): Apply Doppler equation.

\[ v_s = 30 \text{ m/s} \quad f_s = 500 \text{ Hz} \quad v_0 = -10 \text{ m/s} \]

\[ V = 340 \text{ m/s} \]

\[ f_0 = f_s \left( \frac{V + v_0}{V - v_s} \right) = 500 \text{ Hz} \left[ \frac{340 \text{ m/s} + (-10 \text{ m/s})}{340 \text{ m/s} - (30 \text{ m/s})} \right] \]

\[ f_0 = 500 \text{ Hz} \left[ \frac{330 \text{ m/s}}{310 \text{ m/s}} \right] \]

\[ f_0 = 532 \text{ Hz} \]
**Summary of Acoustics**

**Acoustics** is the branch of science that deals with the physiological aspects of sound. For example, in a theater or room, an engineer is concerned with how clearly sounds can be heard or transmitted.

**Audible sound**: Frequencies from 20 to 20,000 Hz.

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Measurable physical properties that determine the sensory effects of individual sounds

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Summary (Cont.)

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\[ I = \frac{P}{A} = \frac{P}{4\pi r^2} \]

\[ I_1 r_1^2 = I_2 r_2^2 \]
Summary of Formulas:

\[ I = \frac{P}{A} \]

\[ \beta = 10 \log \frac{I}{I_0} \]

\[ \beta_2 - \beta_1 = 10 \log \frac{I_2}{I_1} \]

Hearing threshold: \( I_0 = 1 \times 10^{-12} \text{ W/m}^2 \)

Pain threshold: \( I_p = 1 \text{ W/m}^2 \)

\[ v = f \lambda \]

Beat freq. = \( f'' - f \)

\[ f_0 = f_s \left( \frac{V + v_0}{V - v_s} \right) \]