# Phys101 Lectures 32, 33

# Sound, Decibels, Doppler Effect

**Key points:**

- **Intensity of Sound: Decibels**
- **Doppler Effect**

***Ref: 12-1,2,7.***

# Characteristics of Sound

**Sound** can travel through any kind of **matter**, but not through a **vacuum**.

**TABLE 12–1 Speed of Sound in Various Materials (20°C and 1 atm)**

| Material | Speed (m/s) |
|---|---|
| Air | 343 |
| Air (0°C) | 331 |
| Helium | 1005 |
| Hydrogen | 1300 |
| Water | 1440 |
| Sea water | 1560 |
| Iron and steel | ≈5000 |
| Glass | ≈4500 |
| Aluminum | ≈5100 |
| Hardwood | ≈4000 |
| Concrete | ≈3000 |



The **speed** of sound is different in different materials; in general, it is slowest in **gases**, faster in **liquids**, and fastest in **solids**.

The speed depends somewhat on **temperature**, especially for gases.

# Characteristics of Sound

**Loudness: related to intensity of the sound wave**

**Pitch: related to frequency**

**Audible range: about 20 Hz to 20,000 Hz; upper limit decreases with age**

**Ultrasound: above 20,000 Hz;**

**Infrasound: below 20 Hz**

# Intensity of Sound: Decibels

**TABLE 12–2 Intensity of Various Sounds**

| Source of the Sound | Sound Level (dB) | Intensity ($W/m^2$) |
|---|---|---|
| Jet plane at 30 m | 140 | 100 |
| Threshold of pain | 120 | 1 |
| Loud rock concert | 120 | 1 |
| Siren at 30 m | 100 | $1 \times 10^{-2}$ |
| Auto interior, at 90 km/h | 75 | $3 \times 10^{-5}$ |
| Busy street traffic | 70 | $1 \times 10^{-5}$ |
| Talk, at 50 cm | 65 | $3 \times 10^{-6}$ |
| Quiet radio | 40 | $1 \times 10^{-8}$ |
| Whisper | 20 | $1 \times 10^{-10}$ |
| Rustle of leaves | 10 | $1 \times 10^{-11}$ |
| Threshold of hearing | 0 | $1 \times 10^{-12}$ |



The **intensity** of a wave is the **energy** transported per unit **time** across a unit **area**.

The human ear can detect sounds with an intensity as low as **$10^{-12}$ W/m²** and as high as **1 W/m²**.

Perceived **loudness**, however, is not proportional to the intensity.

# Sound Level: Decibels

**The loudness of a sound is much more closely related to the logarithm of the intensity.**

**Sound level is measured in decibels (dB) and is defined as:**

$$\beta\,(\text{in dB}) = 10 \log \frac{I}{I_0}.$$

**$I_0$ is taken to be the threshold of hearing:**

$$I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2.$$

**Example: Sound intensity on the street.**

**At a busy street corner, the sound level is 75 dB. What is the intensity of sound there?**

$$\beta \text{ (in dB)} = 10 \log \frac{I}{I_0}.$$

$$75 = 10\, log \frac{I}{I_0}$$

$$log \frac{I}{I_0} = 7.5$$

$$\frac{I}{I_0} = 10^{7.5}$$

$$I = 10^{7.5} I_0 = 10^{7.5} \times 10^{-12} = 10^{-4.5} = 3.16 \times 10^{-5}\, W / m^2$$

## Example: Loudspeaker response.

**A high-quality loudspeaker is advertised to reproduce, at full volume, frequencies from 30 Hz to 18,000 Hz with uniform sound level ± 3 dB. That is, over this frequency range, the sound level output does not vary by more than 3 dB for a given input level. By what factor does the intensity change for the maximum change of 3 dB in output sound level?**

$$\text{Given } \Delta\beta = \beta_2 - \beta_1 = 3dB, \quad \text{find}: \frac{I_2}{I_1}$$

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

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

$$3 = 10\,log\,\frac{I_2}{I_1}$$

$$\frac{I_2}{I_1} = 10^{0.3} = 2.0$$

**3 dB means 2 times in intensity (or energy, power etc.)**

## Conceptual Example: Trumpet players.

**A trumpeter plays at a sound level of 75 dB. Three equally loud trumpet players join in. What is the new sound level?**

$$\beta_1 = 10\,log\,\frac{I_1}{I_0}$$

$$\beta_4 = 10\,log\,\frac{4I_1}{I_0}$$

$$\beta_4 = 10\left(log\,4 + log\,\frac{I_1}{I_0}\right)$$

$$= 10\,log\,4 + 10\,log\,\frac{I_1}{I_0}$$

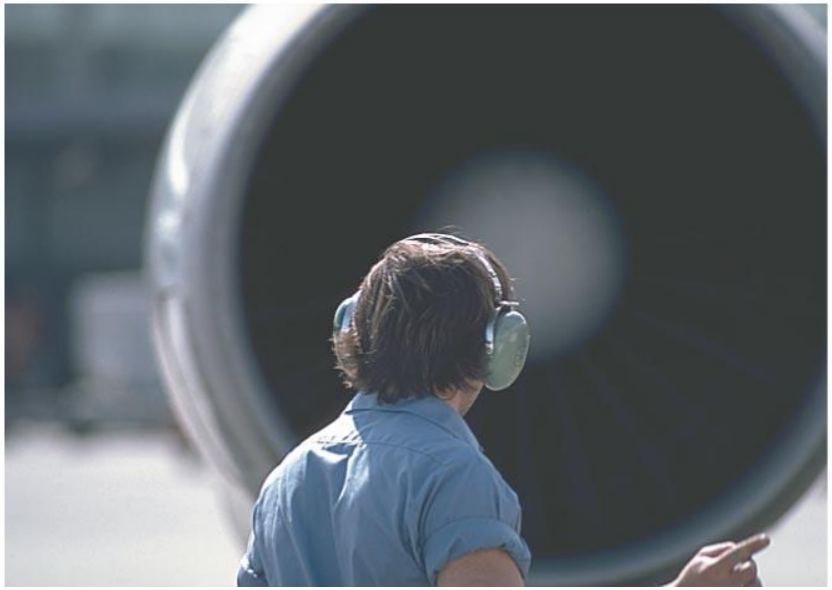
$$= 6 + \beta_1$$

$$= 6 + 75$$

$$= 81\,dB$$

**Example: Airplane roar.**

**The sound level measured 30 m from a jet plane is 140 dB. What is the sound level at 300 m? (Ignore reflections from the ground.)**



**At 30 m:**

$$\text{Sound intensity}: I_1$$

$$\text{Sound level}: \beta_1$$

$$\beta_1 = 10\,log\,\frac{I_1}{I_0} = 140\,dB$$

**At 300 m:**

$$\text{Sound intensity}: I_2$$

$$\text{Sound level}: \beta_2$$

$$I \propto \frac{1}{r^2} \quad \Rightarrow \quad \frac{I_2}{I_1} = \frac{r_1^2}{r_2^2}, \quad I_2 = \frac{r_1^2}{r_2^2} I_1 = \left(\frac{30}{300}\right)^2 I_1 = 0.01 I_1$$

$$\beta_2 = 10\,log\,\frac{I_2}{I_0} = 10\,log\left(\frac{0.01 I_1}{I_0}\right) = 10\left(log\,0.01 + log\,\frac{I_1}{I_0}\right)$$

$$= 10\times(-2) + 10\,log\,\frac{I_1}{I_0} = -20 + \beta_1 = -20 + 140 = 120 dB$$

**Example: How tiny the displacement is.**

**Calculate the displacement of air molecules for a sound having a frequency of 1000 Hz at the threshold of hearing.**

**[Solution]**

$$I = \frac{\overline{P}}{S} = 2\pi^2 \left(\rho S l\right) f^2 A^2 / t = 2\pi^2 \rho v f^2 A^2$$

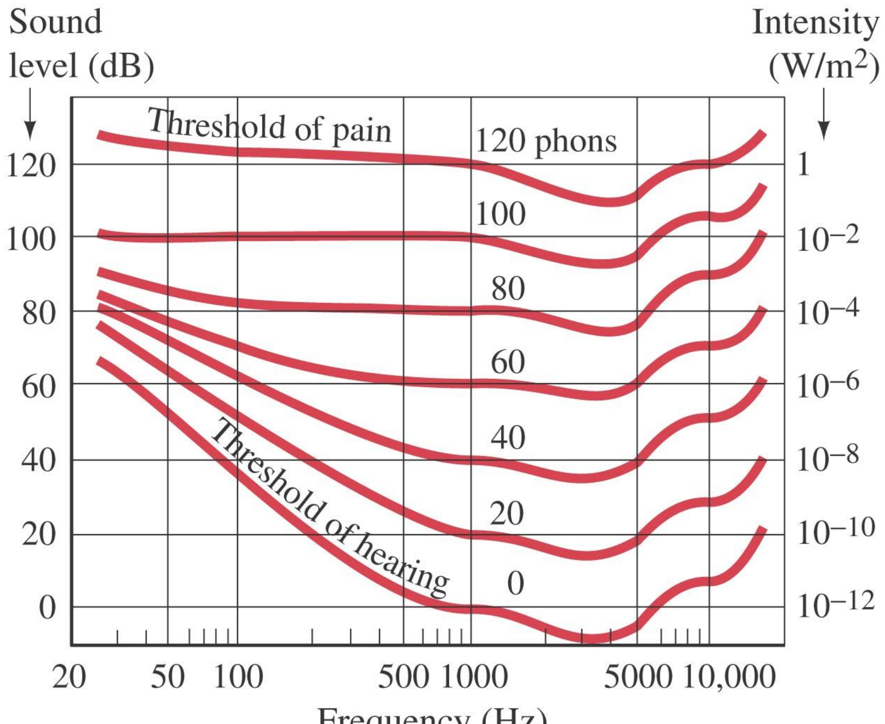
$$A^2 = \frac{I}{2\pi^2 \rho v f^2}$$

$$A = \frac{1}{\pi f} \sqrt{\frac{I}{2\rho v}}$$

$$A = \frac{1}{1000\pi} \sqrt{\frac{10^{-12}}{2 \times 1.29 \times 343}} = 1.1 \times 10^{-11} m$$

# Intensity of Sound: Decibels

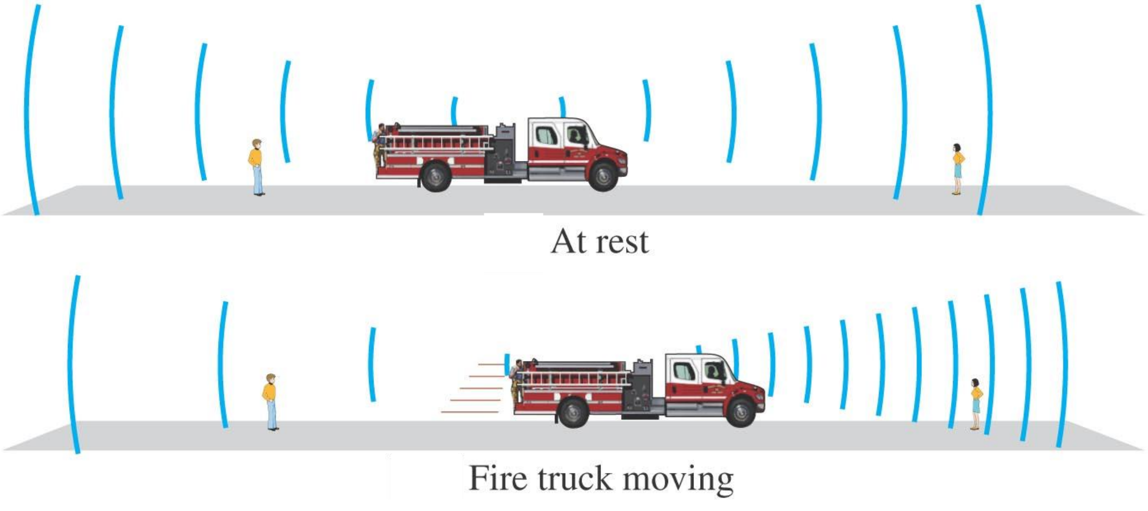
The ear's **sensitivity** varies with **frequency**. These curves translate the intensity into sound level at different frequencies.

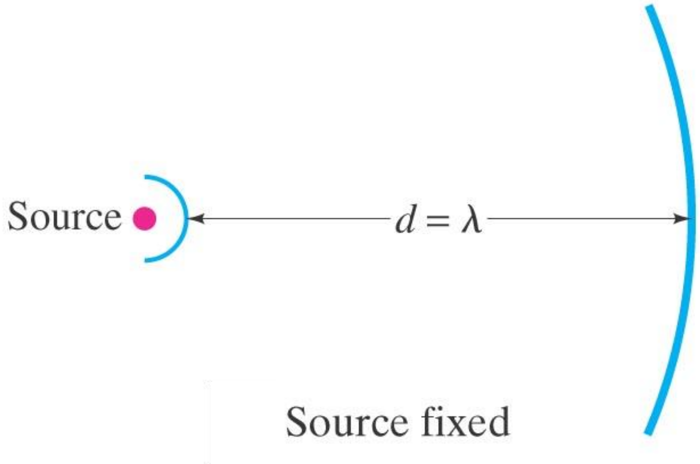


# Doppler Effect

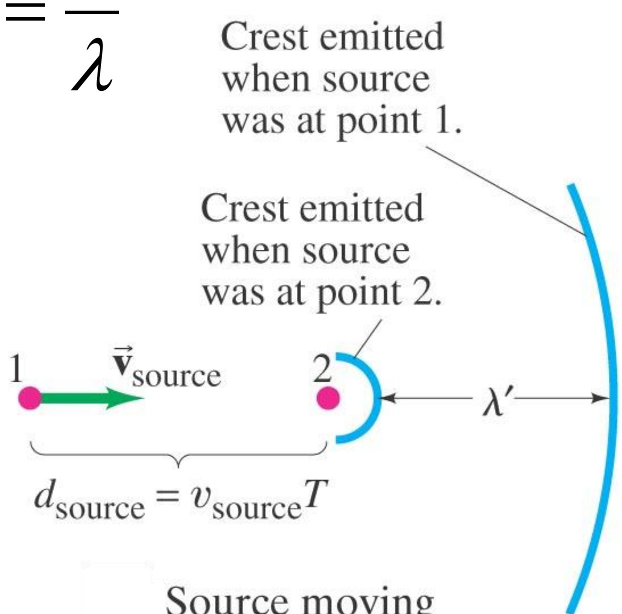
The **Doppler effect** occurs when a **source** of sound is **moving** with respect to an **observer**.

A source moving **toward** an observer appears to have a **higher** frequency and **shorter** wavelength; a source moving **away** from an observer appears to have a **lower** frequency and **longer** wavelength.






$$f = \frac{v}{\lambda}$$




$v$ – velocity of sound

**If we can figure out what the change in the wavelength is, we also know the change in the frequency.**

**<u>When the source is approaching</u>, the observed wavelength is shorter:**

$$\lambda' = \lambda - v_{source}T$$

**Then the observed frequency is:**

$$f' = \frac{v}{\lambda'} = \frac{v}{\lambda - v_{source}T}$$

$$= \frac{v}{\lambda\left(1 - \frac{v_{source}T}{\lambda}\right)} = \frac{f}{1 - \frac{v_{source}T}{\lambda}}$$

$$= \frac{f}{1 - \frac{v_{source}}{v}} > f$$

# Doppler Effect

**The change in the frequency is given by:**

$$f' = \frac{f}{\left(1 - \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}.$$

**Source approaching:**
**Higher freq.**
**f’>f**

**Similarly, if the source is moving away from the observer:**

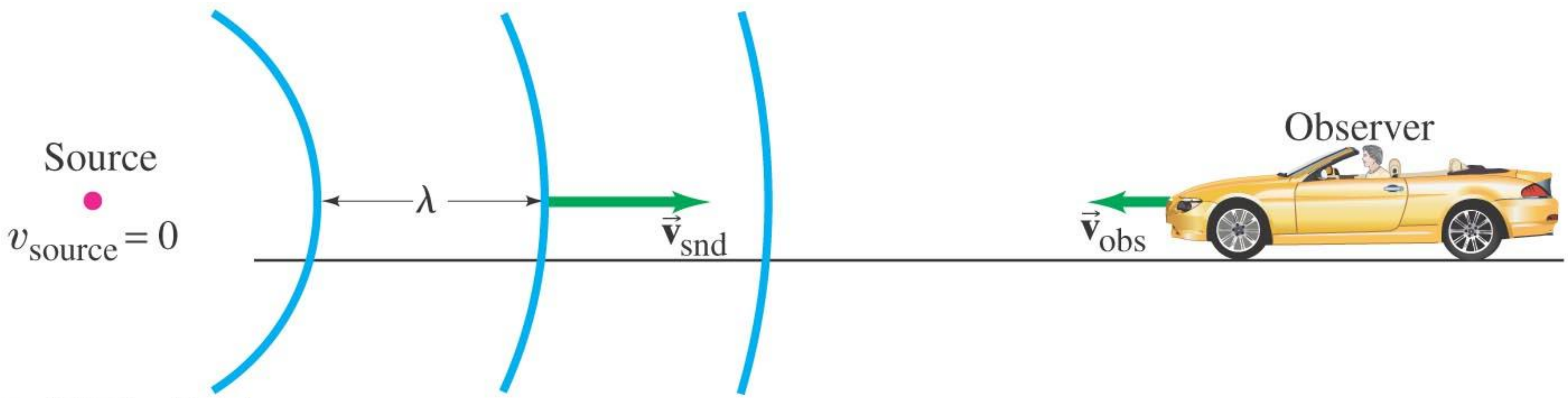
$$f' = \frac{f}{\left(1 + \frac{v_{\text{source}}}{v_{\text{snd}}}\right)}.$$

**Source receding:**
**Lower freq.**
**f’<f**

# Doppler Effect

$$f = \frac{v}{\lambda}$$

**If the observer is moving with respect to the source, things are a bit different. The wavelength remains the same, but the wave speed is different for the observer.**




$$v' = v + v_{obs} \quad \text{when the observer is approaching}$$

$$f' = \frac{v'}{\lambda} = \frac{v + v_{obs}}{\lambda} = \frac{v}{\lambda}\left(1 + \frac{v_{obs}}{v}\right) = f\left(1 + \frac{v_{obs}}{v}\right)$$

**For an observer moving toward a stationary source:**

**Observed sound velocity:** $v' = v + v_{obs}$

**Observed frequency:**

$$f' = \frac{v'}{\lambda} = \frac{v + v_{obs}}{\lambda} = \frac{v}{\lambda}\left(1 + \frac{v_{obs}}{v}\right) = f\left(1 + \frac{v_{obs}}{v}\right)$$

**Observer approaching:**
**Higher freq.**
**f’>f**

**And if the observer is moving away:**

$$v' = v - v_{obs}$$

$$f' = \frac{v'}{\lambda} = \frac{v - v_{obs}}{\lambda} = \frac{v}{\lambda}\left(1 - \frac{v_{obs}}{v}\right) = f\left(1 - \frac{v_{obs}}{v}\right)$$

**Observer receding:**
**Lower freq.**
**f’<f**

## Example: A moving siren.

**The siren of a police car at rest emits at a predominant frequency of 1600 Hz. What frequency will you hear if you are at rest and the police car moves at 25.0 m/s (a) toward you, and (b) away from you?**

**(a) Moving source, approaching: Higher freq.**

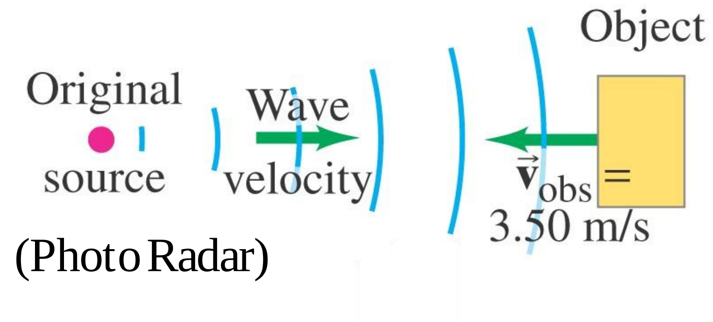
$$f' = \frac{f}{1 - \frac{v_{source}}{v}} = \frac{1600}{1 - \frac{25}{343}} = 1726\,Hz \quad (\text{speed of sound in air}: v = 343\,m/s)$$

**(b) Moving source, receding: Lower freq.**

$$f' = \frac{f}{1 + \frac{v_{source}}{v}} = \frac{1600}{1 + \frac{25}{343}} = 1491\,Hz$$

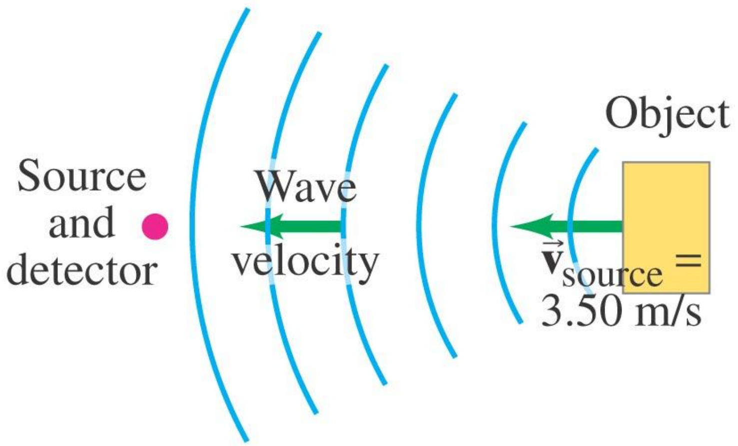
## Example 12-15: Two Doppler shifts.

A 5000-Hz sound wave is emitted by a stationary source. This sound wave reflects from an object moving 3.50m/s toward the source. What is the frequency of the wave reflected by the moving object as detected by a detector at rest near the source?




Frequency received by the moving object:

$$f' = f\left(1 + \frac{v_{obs}}{v}\right) = 5000\left(1 + \frac{3.5}{343}\right) = 5051\,Hz$$




Then, the object becomes a moving source when the sound is reflected back to the detector. The frequency received by the detector is:

$$f'' = \frac{f'}{1 - \frac{v_{source}}{v}} = \frac{5051}{1 - \frac{3.5}{343}} = 5103\,Hz$$

This is known as a double Doppler effect. The moving object first acts as a moving observer and then a moving source.

# Doppler Effect

**All four equations for the Doppler effect can be combined into one; you just have to keep track of the signs!**

$$f' = f\left(\frac{v_{\text{snd}} \pm v_{\text{obs}}}{v_{\text{snd}} \mp v_{\text{source}}}\right).$$

**The signs:**

**Approaching: higher freq.** $f' > f$

**Receding: lower freq.** $f' < f$

# Phys101 Course Evaluation

**April 4 (Today) 12:00noon – April 11.**

**On Webct**

**1% Bonus mark**