The Doppler Effect

Have you ever noticed how the sound of an emergency vehicle's siren changes as it comes toward you and quickly changes to a lower sound after it passes by? The change in the characteristics of the sound are caused by changes in the frequency of the sound waves as the vehicle passes by. As the siren approaches you (the observer), the waves are compressed and the sound entering your ear is higher than the frequency of the sound originally emitted by the siren. As the vehicle passes you, the source is now moving away from you, so the effect is the opposite: the frequency of the sound detected by your ear is less than the frequency originally emitted by the siren (**Figure 1**). This phenomenon is called the **Doppler effect**. A simple situation is shown in **Figure 2**.

Doppler effect when a source of sound approaches an observer, the observed frequency of the sound increases; when the source moves away from an observer, the observed frequency of the sound decreases

WEB **LINK**

To see an animation of the Doppler effect,

GO TO NELSON SCIENCE

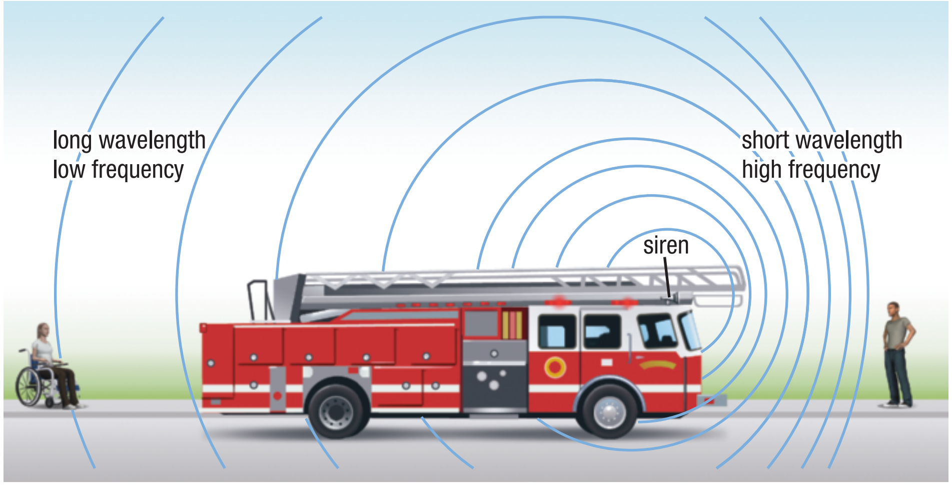

Figure 1 As the moving siren passes an observer, the observer hears a change in the siren's sound. The sound waves are compressed as the siren approaches the observer and more spread out as the siren passes the observer.

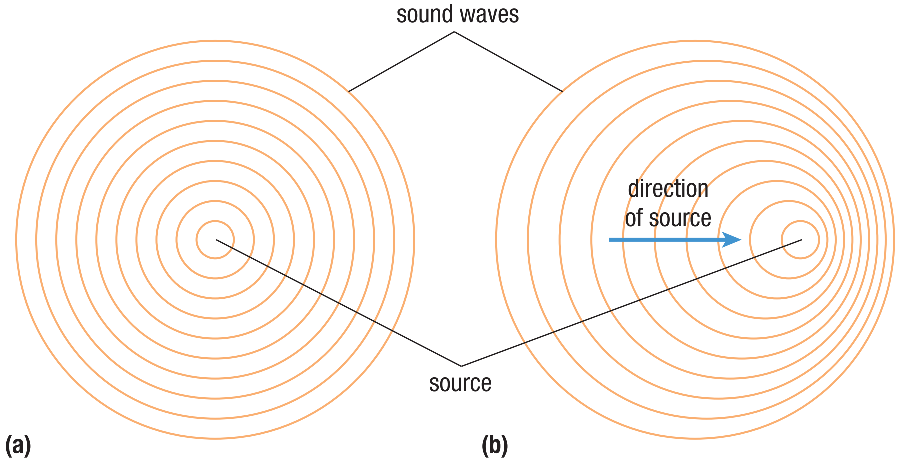

Figure 2 In (a), a stationary source emits sound with a particular frequency. In (b), the source is moving to the right. This motion has the effect of decreasing the distance between the crests of the sound waves in front of the source and increasing the crest-to-crest distance of the waves behind the moving source. A detector placed in front of the moving source will detect sound with a higher frequency, and a detector placed behind the moving source will detect sound with a lower frequency.

Not all moving sources of sound will generate a Doppler effect. The speed of the moving source must be a reasonable fraction of the speed of sound. The speed of sound is approximately 332 m/s. The speed of the siren on an emergency vehicle is approximately 30 m/s. So the vehicle speed is approximately 10 % of the speed of sound—a reasonable fraction. In addition, the moving source of sound has to have a component of its velocity vector moving parallel to the detector. So a sound source in a circular orbit around a detector, for instance, would not generate a Doppler effect.

Calculating the Doppler Effect

If either the detector or the source is moving (or both are moving), the frequency we observe, f_{obs}, and the frequency of the source, f_0, are related by the following formula:

$$f_{obs} = \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right) f_0$$

Note that in this text, we will only consider the case in which the source is moving and the detector is stationary. For example, a person standing at the corner of a street hears the siren of an ambulance speeding by. The speed of sound and the speed of the source are with respect to the medium, which is generally air.

When using the equation, if the source is moving toward the detector, the speed of the sound is considered to be negative. If the source is receding from the detector, the speed of the sound is considered to be positive.

A reasonable simplification is that the speeds of the source and the detector are said to be constant except for their signs, which instantly switch as the source passes the detector. In the following Tutorial we will calculate the change in frequency caused by the Doppler effect.

Tutorial 1 Calculating the Doppler Effect

Sample Problem 1

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 (a) the frequency detected by the observer as the fire truck approaches and (b) the frequency detected by the observer after the truck passes by. The speed of sound in this case is 342 m/s.

(a) **Given:** $v_{detector} = 0$; $v_{source} = -25.0$ m/s; $f_0 = 800.0$ Hz; $v_{sound} = 342$ m/s

Required: f_{obs}

Analysis: The fire truck is approaching the detector, so ensure that v_{source} is negative. The observer is stationary, so $v_{detector}$ is zero. Use the equation to solve for the frequency detected by the observer, f_{obs}.

$$f_{obs} = \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right) f_0$$

Solution:

$$\begin{aligned} f_{obs} &= \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right) f_0 \\ &= \left(\frac{342\text{ m/s} + 0\text{ m/s}}{342\text{ m/s} + (-25.0\text{ m/s})}\right) 800.0\text{ Hz} \\ f_{obs} &= 863\text{ Hz} \end{aligned}$$

Statement: The detected frequency of the approaching fire truck's siren is 863 Hz.

(b) **Given:** $v_{detector} = 0$; $v_{source} = +25.0$ m/s; $f_0 = 800.0$ Hz; $v_{sound} = 342$ m/s

Required: f_{obs}

Analysis: When the fire truck is moving away after passing the observer, the frequency detected will change again. Since the source is now moving away, v_{source} is positive.

$$f_{obs} = \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right) f_0$$

Solution: $f_{obs} = \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right)f_0$

$= \left(\frac{342 \text{ m/s} + 0 \text{ m/s}}{342 \text{ m/s} + (+25.0 \text{ m/s})}\right)800.0 \text{ Hz}$

$f_{obs} = 746 \text{ Hz}$

Statement: The detected frequency of the receding fire truck's siren is 746 Hz.

Practice

1. A police car is approaching at a speed of 20.0 m/s with its siren emitting a frequency of 1.0 kHz. What frequency does a stationary observer detect? The speed of sound in this case is 330 m/s. T/I [ans: 1100 Hz]
2. An ambulance has just passed by your home. You detect that the frequency of the receding siren is 900.0 Hz. If you know that the frequency of the ambulance's siren is 950.0 Hz, how fast is the ambulance moving? The speed of sound in this case is 335 m/s. T/I [ans: 18.6 m/s]

9.5 Summary

- The frequency of a sound wave changes if the source and detector are in relative motion. This phenomenon is called the Doppler effect.
- When a source of sound approaches a stationary observer, the observed frequency increases. When the source moves away from a stationary observer, the observed frequency decreases.
- The formula used to calculate the change in frequencies detected by an observer as a result of the Doppler effect is

$$f_{obs} = \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right)f_0$$

- If the source is approaching the detector, the speed of the source is taken to be negative. If the source is receding from the detector, the speed of the source is taken to be positive.

UNIT TASK BOOKMARK

You can apply what you learned about the Doppler effect to the device you construct, or the technology you research, for the Unit Task described on page 486.

9.5 Questions

1. (a) Define the Doppler effect in your own words.
   (b) Give two examples of the Doppler effect from your experience that are not given in this section. K/U C A
2. Explain why a sound wave has a higher frequency when the source is approaching a stationary observer. K/U
3. A source emitting a sound at 300.0 Hz is moving toward an observer at 25 m/s. The air temperature is 15 °C. What is the frequency detected by the observer? K/U
4. A fire truck emitting a 450 Hz signal passes by a stationary detector. The difference in frequency measured by the detector is 58 Hz. If the speed of sound is 345 m/s, how fast is the fire truck moving? K/U
5. You are in a car moving at 90 km/h, and you see someone at the side of the highway. You use your horn to warn the person. The frequency of the horn is 440 Hz, and the air temperature is 0 °C. Calculate the frequency of the horn the person hears as you approach and as you pass. T/I
6. A source passing a stationary observer is emitting a frequency of 560 Hz. If the speed of sound is 345 m/s, what must the speed of the source be if the frequency source is 480 Hz? K/U T/I
7. Describe what happens to the frequency as a source of sound passes a stationary observer. Is this effect instantaneous? Explain. K/U