Answer to Essential Question 21.4: If a sound's intensity level increases by 5 dB, equation 21.7 tells us that: $0.5 = \log\left(\frac{I_f}{I_i}\right)$, which gives a ratio of final to initial intensity of $10^{0.5} = 3.2$. In other words, every 5 dB increase corresponds to increasing the sound intensity by a factor of 3.2.

21-5 The Doppler Effect for Sound

We have probably all had the experience of listening to the siren on an emergency vehicle as it approaches us, and hearing a shift in the frequency of the sound when the vehicle passes us. This shift in frequency is known as the Doppler effect, and it occurs whenever the wave source or the detector of the wave (your ear, for instance) is moving relative to the medium the wave is traveling in. Applications of the Doppler effect for sound include Doppler ultrasound, a diagnostic tool used to study blood flow in the heart. There is a related but slightly different Doppler effect for electromagnetic waves, which we will investigate in the next chapter, that has applications in astronomy as well as in police radar systems to measure the speed of a car.

EXPLORATION 21.5 – Understanding the Doppler effect

Let's explore the principles behind the Doppler effect. We will begin by looking at the situation of a stationary source of sound, and a moving observer.

Step 1 – ***Construct a diagram showing waves expanding spherically from a stationary source that is broadcasting sound waves of a single frequency. If you, the observer, remain stationary, you hear sound of the same frequency as that emitted by the source. Use your diagram to help you explain whether the frequency you hear when you move toward the source, or away from the source, is higher or lower than the frequency emitted by the source.***

We can represent the expanding waves as a set of concentric circles centered on the stationary source, as in Figure 21.6. This picture shows a snapshot of the waves at one instant in time, but remember that the waves are expanding outward from the source at the speed of sound. If you are stationary at position A, the waves wash over you at the same frequency as they were emitted. If you are at position A but moving toward the source, however, the frequency you observe increases, because you are moving toward the oncoming waves. Conversely, if you move away from the source (and you are traveling at a speed less than the speed of sound), you observe a lower frequency as you try to out-run the waves.

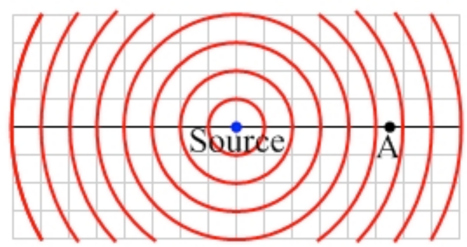

Figure 21.6: Waves emitted by a stationary source expand out away from the source, giving a pattern of concentric circles centered on the source. You, the observer, are at point A. If you are moving, the frequency of the waves you receive depends on both your speed and the direction of your motion.

Step 2 – ***Starting with the usual relationship connecting frequency, speed, and wavelength, $f = v / \lambda$, think about whether the observer moving toward or away from a stationary source effectively changes the wave speed or the wavelength. If the speed of sound is v and the observer's speed is v_o, write an equation for the frequency heard by the observer.*** As we can see from the pattern in Figure 21.6 above, the wavelength has not changed. What changes, when you move through the pattern of waves, is the speed of the waves with respect to you. When you move toward the source, the effective speed of the waves (the relative speed of the waves with respect to you) is $v + v_o$, while when you move away from the source the wave speed is effectively $v - v_o$. The frequency you observe, f', is thus the effective speed over the wavelength:

$$f' = \frac{v \pm v_o}{\lambda} = \frac{v}{\lambda}\left(\frac{v \pm v_o}{v}\right) = f\left(\frac{v \pm v_o}{v}\right),$$ (Eq. 21.9: **Frequency for a moving observer**)

where f is the frequency emitted by the source, and where we use the + sign when the observer moves toward the source, and the – sign when the observer moves away from the source.

Step 3 – ***Construct a diagram showing waves expanding from a source that is moving to the right at half the speed of sound while broadcasting sound waves of a single frequency. Use your diagram to help you explain whether the frequency you hear when you are stationary is higher or lower than that emitted by the source, when the source is moving toward you and when the source is moving away from you.***

In this situation, the result is quite different from that in Figure 21.6, because each wave is centered on the position of the source at the instant the wave was emitted. Because the waves are emitted at different times, and the source is moving, we get the picture shown in Figure 21.7. To the left of the source, such as at point B, the waves are more spread out. Thus, when the source is moving away from the observer, the observed frequency is less than the emitted frequency. The reverse is true for a point to the right of the source: the waves are closer together than usual, so an observer in this region (such as at point A) observes a greater frequency than the emitted frequency.

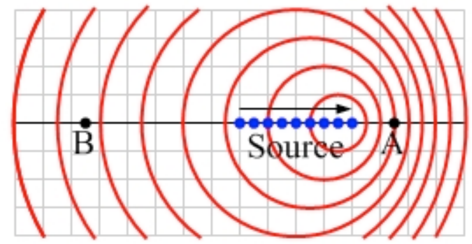

Figure 21.7: When a source of waves is moving relative to the medium, the wave pattern is asymmetric. An observer for which the source moves away observes a lower-frequency wave, while, when the source is moving toward the observer, a higher-frequency wave is observed. In the case shown, the source is moving to the right at half the wave speed.

Step 4 – ***Starting with the usual relationship connecting frequency, speed, and wavelength, $f = v / \lambda$, think about whether the source moving toward or away from a stationary observer effectively changes the wave speed or the wavelength. If the speed of sound is v and the source's speed is v_s, write an equation for the frequency heard by the observer.*** As we can see from the pattern in Figure 21.7, the movement of the source changes the wavelength. The waves still travel at the speed of sound, however. What changes, when you move through the pattern of waves, is the speed of the waves with respect to you. When the source moves toward the observer, the effective wavelength is $(v - v_s)/f$, while when the source moves away the wavelength is effectively $(v + v_s)/f$. The frequency you observe, f', is thus the speed over the effective wavelength:

$$f' = \frac{v}{\lambda'} = \frac{v}{v \mp v_s} f \,,$$ (Eq. 21.10: **Frequency for a moving source**)

where f is the frequency emitted by the source. Use the – sign when the source moves toward the observer, and the + sign when the source moves away from the observer.

Key idea for the Doppler effect: Motion of a source of sound, or motion of an observer, can cause a shift in the observed frequency of a wave. **Related End-of-Chapter Exercises: 23, 24.**

Essential Question 21.5: Is the Doppler effect simply a relative velocity phenomenon? For instance, is the situation of an observer moving at speed v_1 toward a stationary source the same as a source moving at speed v_1 toward a stationary observer?