Answer to Essential Question 25.4: One way to answer this question is to set up a ratio of the double-source equation to the single-slit equation:

$$\frac{d\sin\theta}{a\sin\theta} = \frac{m_d\lambda}{m_s\lambda} \quad \Rightarrow \quad \frac{d}{a} = \frac{m_d}{m_s}\text{, for the same angle, }\theta.$$

The position corresponding to $m_s = 1$ is where we find the first zero on one side of the central maximum in the single-slit pattern. Looking at the double-slit pattern in Figure 25.19, and counting the peak in the center of that pattern as $m_d = 0$, we see that the peak at $m_d = 5$ lines up with the first zero in the single-slit pattern, and is thus a missing order. With $m_d / m_s = 5/1$, we have $d/a = 5$ here.

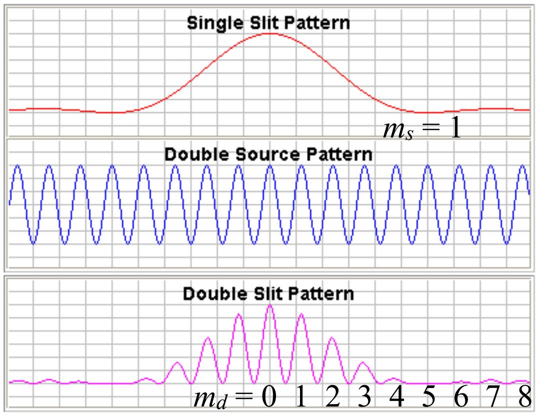


Figure 25.19: In this case, the first zero in the single-slit pattern corresponds to the same position, and therefore the same angle, as the $m_d = 5$ peak in the double-source pattern, leading to a missing order in the double-slit pattern.

25-5 Reflection

As we have discussed in Chapter 21 for waves on a string, when a wave reflects from the fixed end of a string, the reflected wave is inverted. When a wave reflects from the free end of a string, the reflected wave is upright.

What happens when the end of the string is neither perfectly free nor perfectly fixed, such as when a light string is tied to a heavy string? As shown in Figure 25.20 (a) and (b), when a wave is traveling along the light string, the point where the strings meet acts more like a fixed end than a free end. Part of the wave is transmitted onto the heavy string, and the part that reflects back along the light string is inverted. Conversely, as in Figure 25.20 (c) and (d), when a wave is traveling along the heavy string, the point where the strings meet acts more like a free end. Part of the wave is again transmitted into the second medium, while the part that reflects is upright.

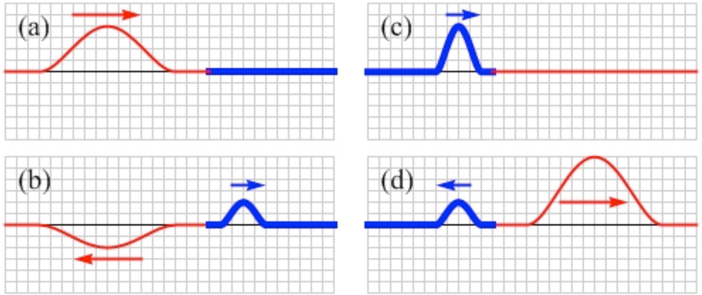
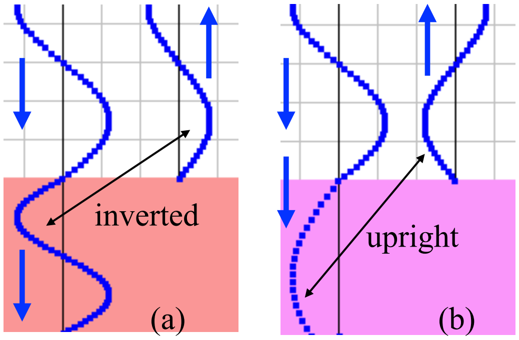


Figure 25.20: (a) When a wave traveling on a light string encounters the boundary between the light string and a heavy string, part of the wave is transmitted onto the heavy string, and part reflects back onto the light string, as in (b). The boundary acts like a fixed end, so the reflected wave is inverted. (c) If the wave is traveling along the heavy string before striking the boundary, the part of the wave that reflects is reflected upright, as in (d). In this situation, the speed of the wave on the light string is three times the speed of the wave on the heavy string.

An analogous process happens for light, or for any other electromagnetic wave. When a light wave traveling in one medium (medium 1) encounters an interface between that medium and a second medium (medium 2) with a different index of refraction, part of the light wave is transmitted into the second medium, and part is reflected back into the first medium. Whether the reflected wave is inverted or not depends on how the indices of refraction compare, as summarized in the box below, and as shown pictorially in Figure 25.21.

A light wave reflecting from a medium with a higher index of refraction than the medium the wave is traveling in ($n_2 > n_1$) is inverted upon reflection. If the second medium has a smaller index of refraction than the first ($n_2 < n_1$), the wave is reflected upright. For a sine wave, inverting the wave has the same effect as shifting the wave by half a wavelength, so we will treat an inversion upon reflection as a half wavelength shift.

Figure 25.21: (a) When light traveling in one medium reflects from a medium with a larger index of refraction, the part of the wave that is reflected is inverted upon reflection. (b) If the second medium has a smaller index of refraction than the first, the reflected part of the wave reflects upright. In both cases, the reflected wave has been shifted to the right to distinguish it from the incident wave.



EXPLORATION 25.5 – Double-source interference with a single source

Figure 25.22 shows a situation in which a single source of sound waves is located above the floor. At any point, such as at point *A* in the figure, waves are received directly from the source, but waves are also received after being reflected from the floor.

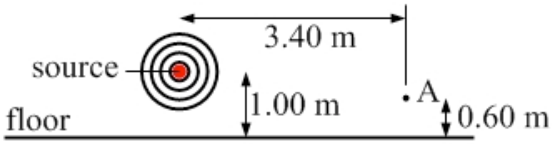


Figure 25.22: A source of sound waves, in air, located above a flat floor.

Step 1 – ***We can treat this situation as if there are two sources of waves. Where, effectively, is the second source located?*** The second source is where the image of the first source is located. Treating the floor like a plane mirror, reflecting the first source in the mirror gives the second source at the position shown in Figure 25.23.

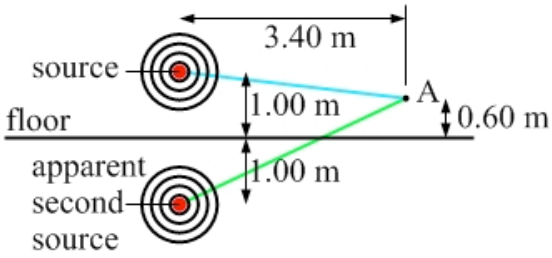


Figure 25.23: The floor acts like a plane mirror for sound waves. Effectively, there is a second source of waves where the image of the first source is created by the mirror.

Step 2 – ***To analyze the interference between the waves from the two sources, we consider the mirror-image source to be 180° out of phase with the first source. Explain why we do this.*** The 180° phase shift comes from the fact that the wave does not actually originate at the second source. Instead, it originates at the first source, and reflects from the floor, producing an inversion of the wave upon reflection. Inverting the wave is equivalent to shifting the wave half a wavelength, which is equivalent to a 180° phase shift.

Key idea: Even reflecting sound waves experience an inversion upon reflection.
Related End-of-Chapter Exercises: 8, 50 – 52.

Essential Question 25.5: Return to the situation described in Exploration 25.5, and assume the speed of sound is 340 m/s. Using the geometry of right-angled triangles, we can determine that point A is a distance of $\sqrt{(3.40\text{ m})^2+(0.40\text{ m})^2}=3.42\text{ m}$ from the source, and a distance of $\sqrt{(3.40\text{ m})^2+(1.60\text{ m})^2}=3.76\text{ m}$ from the apparent second source. What is the lowest frequency sound wave from the source that will produce completely constructive interference at point A?