Seeing and Hearing
Tutorial 2 – Answers

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Example 17.1 Speed of Sound in a Liquid

Interactive

(A) Find the speed of sound in water, which has a bulk modulus of 2.1×10^9 N/m^2 at a temperature of 0°C and a density of 1.00×10^3 kg/m^3.

Solution Using Equation 17.1, we find that

$$v_{\text{water}} = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.1 \times 10^9 \text{ N/m}^2}{1.00 \times 10^3 \text{ kg/m}^3}} = \boxed{1.4 \text{ km/s}}$$

In general, sound waves travel more slowly in liquids than in solids because liquids are more compressible than solids. Note that the speed of sound in water is lower at 0°C than at 25°C (Table 17.1).

(B) Dolphins use sound waves to locate food. Experiments have shown that a dolphin can detect a 7.5-cm target 110 m away, even in murky water. For a bit of "dinner" at that distance, how much time passes between the moment the dolphin emits a sound pulse and the moment the dolphin hears its reflection and thereby detects the distant target?

Solution The total distance covered by the sound wave as it travels from dolphin to target and back is 2×110 m = 220 m. From Equation 2.2, we have, for 25°C water

$$\Delta t = \frac{\Delta x}{v_x} = \frac{220 \text{ m}}{1\,533 \text{ m/s}} = \boxed{0.14 \text{ s}}$$

1. Why are sound waves characterized as longitudinal?

$\boxed{2.}$ If an alarm clock is placed in a good vacuum and then activated, no sound is heard. Explain.

3. A flowerpot is knocked off a balcony 20.0 m above the sidewalk and falls toward an unsuspecting 1.75-m-tall man who is standing below. How close to the sidewalk can the flower pot fall before it is too late for a warning shouted from the balcony to reach the man in time? Assume that the man below requires 0.300 s to respond to the warning.

Q17.1 Sound waves are longitudinal because elements of the medium—parcels of air—move parallel and antiparallel to the direction of wave motion.

Q17.2 We assume that a perfect vacuum surrounds the clock. The sound waves require a medium for them to travel to your ear. The hammer on the alarm will strike the bell, and the vibration will spread as sound waves through the body of the clock. If a bone of your skull were in contact with the clock, you would hear the bell. However, in the absence of a surrounding medium like air or water, no sound can be radiated away. A larger-scale example of the same effect: Colossal storms raging on the Sun are deathly still for us.

What happens to the sound energy within the clock? Here is the answer: As the sound wave travels through the steel and plastic, traversing joints and going around corners, its energy is converted into additional internal energy, raising the temperature of the materials. After the sound has died away, the clock will glow very slightly brighter in the infrared portion of the electromagnetic spectrum.

P17.3 Sound takes this time to reach the man: $\frac{(20.0\text{ m}-1.75\text{ m})}{343\text{ m/s}}=5.32\times10^{-2}\text{ s}$

so the warning should be shouted no later than before the pot strikes. $0.300\text{ s}+5.32\times10^{-2}\text{ s}=0.353\text{ s}$

Since the whole time of fall is given by $y=\frac{1}{2}gt^2$: $18.25\text{ m}=\frac{1}{2}\left(9.80\text{ m/s}^2\right)t^2$

$t=1.93\text{ s}$

the warning needs to come $1.93\text{ s}-0.353\text{ s}=1.58\text{ s}$

into the fall, when the pot has fallen $\frac{1}{2}\left(9.80\text{ m/s}^2\right)(1.58\text{ s})^2=12.2\text{ m}$

to be above the ground by $20.0\text{ m}-12.2\text{ m}=\boxed{7.82\text{ m}}$

Note: Use the following values as needed unless otherwise specified: the equilibrium density of air at 20°C is $\rho = 1.20\ \text{kg/m}^3$. The speed of sound in air is $v = 343\ \text{m/s}$. Pressure variations ΔP are measured relative to atmospheric pressure, $1.013 \times 10^5\ \text{N/m}^2$.
Problem 70 in Chapter 2 can also be assigned with this section.

7. A bat (Fig. P17.7) can detect very small objects, such as an insect whose length is approximately equal to one wavelength of the sound the bat makes. If a bat emits chirps at a frequency of 60.0 kHz, and if the speed of sound in air is 340 m/s, what is the smallest insect the bat can detect?

10. A sound wave in air has a pressure amplitude equal to $4.00 \times 10^{-3}\ \text{N/m}^2$. Calculate the displacement amplitude of the wave at a frequency of 10.0 kHz.

11. A sinusoidal sound wave is described by the displacement wave function

$$s(x, t) = (2.00\ \mu\text{m}) \cos[(15.7\ \text{m}^{-1})x - (858\ \text{s}^{-1})t]$$

(a) Find the amplitude, wavelength, and speed of this wave. (b) Determine the instantaneous displacement from equilibrium of the elements of air at the position $x = 0.050\,0$ m at $t = 3.00$ ms. (c) Determine the maximum speed of the element's oscillatory motion.

P17.7 $\lambda = \frac{v}{f} = \frac{340 \text{ m/s}}{60.0 \times 10^3 \text{ s}^{-1}} = \boxed{5.67 \text{ mm}}$

P17.10 $\Delta P_{\max} = \rho v \omega s_{\max}$

$$s_{\max} = \frac{\Delta P_{\max}}{\rho v \omega} = \frac{\left(4.00 \times 10^{-3} \text{ N/m}^2\right)}{\left(1.20 \text{ kg/m}^3\right)(343 \text{ m/s})(2\pi)\left(10.0 \times 10^3 \text{ s}^{-1}\right)} = \boxed{1.55 \times 10^{-10} \text{ m}}$$

P17.11 (a) $A = \boxed{2.00 \ \mu\text{m}}$

$$\lambda = \frac{2\pi}{15.7} = 0.400 \text{ m} = \boxed{40.0 \text{ cm}}$$

$$v = \frac{\omega}{k} = \frac{858}{15.7} = \boxed{54.6 \text{ m/s}}$$

(b) $s = 2.00 \cos\left[(15.7)(0.050\,0) - (858)\left(3.00 \times 10^{-3}\right)\right] = \boxed{-0.433 \ \mu\text{m}}$

(c) $v_{\max} = A\omega = (2.00 \ \mu\text{m})\left(858 \text{ s}^{-1}\right) = \boxed{1.72 \text{ mm/s}}$

18. The area of a typical eardrum is about $5.00 \times 10^{-5}\ \text{m}^2$. Calculate the sound power incident on an eardrum at (a) the threshold of hearing and (b) the threshold of pain.

$\boxed{19.}$ Calculate the sound level in decibels of a sound wave that has an intensity of $4.00\ \mu\text{W/m}^2$.

20. A vacuum cleaner produces sound with a measured sound level of 70.0 dB. (a) What is the intensity of this sound in W/m^2? (b) What is the pressure amplitude of the sound?

21. The intensity of a sound wave at a fixed distance from a speaker vibrating at 1.00 kHz is $0.600\ \text{W/m}^2$. (a) Determine the intensity if the frequency is increased to 2.50 kHz while a constant displacement amplitude is maintained. (b) Calculate the intensity if the frequency is reduced to 0.500 kHz and the displacement amplitude is doubled.

22. The intensity of a sound wave at a fixed distance from a speaker vibrating at a frequency f is I. (a) Determine the intensity if the frequency is increased to f' while a constant displacement amplitude is maintained. (b) Calculate the intensity if the frequency is reduced to $f/2$ and the displacement amplitude is doubled.

*P17.18 The sound power incident on the eardrum is $\wp = IA$ where I is the intensity of the sound and $A = 5.0\times10^{-5}\ \text{m}^2$ is the area of the eardrum.

(a) At the threshold of hearing, $I = 1.0\times10^{-12}\ \text{W/m}^2$, and

$$\wp = \left(1.0\times10^{-12}\ \text{W/m}^2\right)\left(5.0\times10^{-5}\ \text{m}^2\right) = \boxed{5.00\times10^{-17}\ \text{W}}.$$

(b) At the threshold of pain, $I = 1.0\ \text{W/m}^2$, and

$$\wp = \left(1.0\ \text{W/m}^2\right)\left(5.0\times10^{-5}\ \text{m}^2\right) = \boxed{5.00\times10^{-5}\ \text{W}}.$$

P17.19 $$\beta = 10\log\left(\frac{I}{I_0}\right) = 10\log\left(\frac{4.00\times10^{-6}}{1.00\times10^{-12}}\right) = \boxed{66.0\ \text{dB}}$$

P17.20 (a) $$70.0\ \text{dB} = 10\log\left(\frac{I}{1.00\times10^{-12}\ \text{W/m}^2}\right)$$

Therefore, $I = \left(1.00\times10^{-12}\ \text{W/m}^2\right)10^{(70.0/10)} = \boxed{1.00\times10^{-5}\ \text{W/m}^2}$.

(b) $I = \dfrac{\Delta P_{\max}^2}{2\rho v}$, so

$$\Delta P_{\max} = \sqrt{2\rho v I} = \sqrt{2\left(1.20\ \text{kg/m}^3\right)\left(343\ \text{m/s}\right)\left(1.00\times10^{-5}\ \text{W/m}^2\right)}$$

$$\Delta P_{\max} = \boxed{90.7\ \text{mPa}}$$

P17.21 $I = \frac{1}{2}\rho\omega^2 s_{\max}^2 v$

(a) At $f = 2\,500\text{ Hz}$, the frequency is increased by a factor of 2.50, so the intensity (at constant $s_{\max}$) increases by $(2.50)^2 = 6.25$.

Therefore, $6.25(0.600) = \boxed{3.75\text{ W/m}^2}$.

(b) $\boxed{0.600\text{ W/m}^2}$

P17.22 The original intensity is $I_1 = \frac{1}{2}\rho\omega^2 s_{\max}^2 v = 2\pi^2\rho v f^2 s_{\max}^2$

(a) If the frequency is increased to f' while a constant displacement amplitude is maintained, the new intensity is

$I_2 = 2\pi^2\rho v(f')^2 s_{\max}^2$ so $\frac{I_2}{I_1} = \frac{2\pi^2\rho v(f')s_{\max}^2}{2\pi^2\rho v f^2 s_{\max}^2} = \left(\frac{f'}{f}\right)^2$ or $\boxed{I_2 = \left(\frac{f'}{f}\right)^2 I_1}$.

(b) If the frequency is reduced to $f' = \frac{f}{2}$ while the displacement amplitude is doubled, the new intensity is

$$I_2 = 2\pi^2\rho v\left(\frac{f}{2}\right)^2(2s_{\max})^2 = 2\pi^2\rho v f^2 s_{\max}^2 = I_1$$

or the $\boxed{\text{intensity is unchanged}}$.

Example 16.19

The police car with its 300-Hz siren is moving toward a warehouse at 30 m/s, intending to crash through the door. What frequency does the driver of the police car hear reflected from the warehouse?

16.42. In Example 16.19 (Section 16.8), suppose the police car is moving away from the warehouse at 20 m/s. What frequency does the driver of the police car hear reflected from the warehouse?

Example 16.19 Doppler effect V: A double Doppler shift

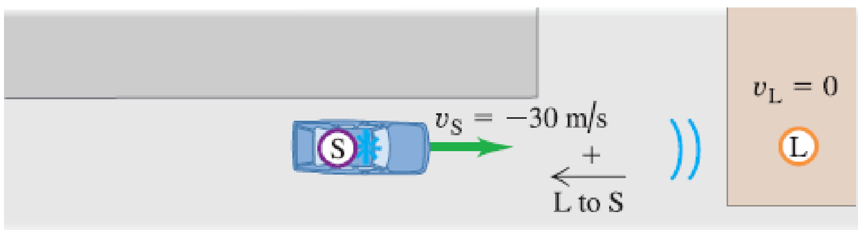
The police car with its 300-Hz siren is moving toward a warehouse at 30 m/s, intending to crash through the door. What frequency does the driver of the police car hear reflected from the warehouse?

SOLUTION

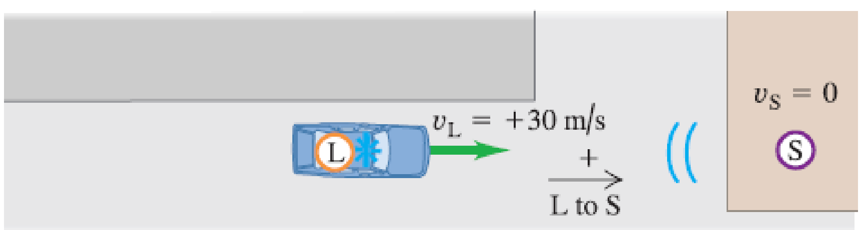
IDENTIFY: In this situation there are *two* Doppler shifts, as shown in Fig. 16.33. In the first shift, the warehouse is the stationary "listener." The frequency of sound reaching the warehouse, which we call f_W, is greater than 300 Hz because the source is approaching. In the second shift, the warehouse acts as a source of sound with frequency f_W, and the listener is the driver of the police car; she hears a frequency greater than f_W because she is approaching the source.

16.33 Two stages of the sound wave's motion from the police car to the warehouse and back to the police car.

(a) Sound travels from police car's siren (source S) to warehouse ("listener" L).



(b) Reflected sound travels from warehouse (source S) to police car (listener L).



SET UP: To determine f_W, we use Eq. (16.29) with f_L replaced by f_W. For this part of the problem, $v_L = v_W = 0$ (the warehouse is at rest) and $v_S = -30$ m/s (the siren is moving in the negative direction from source to listener).

To determine the frequency heard by the driver, which is our target variable, we again use Eq. (16.29) but now with f_S replaced by f_W. For this second part of the problem, $v_S = 0$ because the stationary warehouse is the source and the velocity of the listener (the driver) is $v_L = +30$ m/s. (The listener's velocity is positive because it is in the direction from listener to source.)

EXECUTE: The frequency reaching the warehouse is

$$f_W = \frac{v}{v + v_S} f_S = \frac{340 \text{ m/s}}{340 \text{ m/s} + (-30 \text{ m/s})}(300 \text{ Hz}) = 329 \text{ Hz}$$

Then the frequency heard by the driver is

$$f_L = \frac{v + v_L}{v} f_W = \frac{340 \text{ m/s} + 30 \text{ m/s}}{340 \text{ m/s}}(329 \text{ Hz}) = 358 \text{ Hz}$$

EVALUATE: Because there are two Doppler shifts, the reflected sound heard by the driver has an even higher frequency than the sound heard by a stationary listener in the warehouse.

Example 16.19

First find the frequency at the warehouse

V_s is positive v_L=0

$$f_L = \left(\frac{v+v_L}{v+v_S}\right) f_S = \left(\frac{340+0}{340+30}\right) 300Hz = 276Hz$$

Next find the apparent frequency at the police car

V_s=0 v_L=-30m/s

$$f_L = \left(\frac{v+v_L}{v+v_S}\right) f_S = \left(\frac{340-30}{340+0}\right) 276Hz = 251Hz$$