20 Sound

- 20.1 Nature of Sound
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The most influential physicist in my career is my dear friend Ken Ford, to whom the previous edition of this book was dedicated. He is shown in the photo opener in his passionate pursuit of flying—particularly soaring. He has written a book about this passion—*In Love With Flying*, H Bar Press, 2007. I gladly use his profile to open this chapter. The second opening photo is physics friends Chris Chiaverina and Tom Rossing. For a great teaching resource, read their *Teaching Light and Color* (AAPT 2001), a collection of scientific papers, articles, and brief excerpts from books intended to provide source material for teaching light and color with references to 281 books, papers, and websites. Photo 3 is Norwegian physics friends Cathrine W. Tellefsen and Ellen K. Henriksen, enchanting their class with a novel display of waves. The fourth photo is family friend little Emily Ackerman of San Francisco.

This chapter lends itself to interesting lecture demonstrations: A ringing doorbell inside a vacuum jar being evacuated—the easily seen vibrations of a tuning fork illuminated with a strobe lamp—resonance and beats with a pair of tuning forks mounted on sound boxes—and the movie (8-mm film loop) of the "Tacoma Narrows Bridge Collapse."

I incorporate the Tacoma Narrows film loop in my treatment of resonance in *Conceptual Physics Alive*! DVD on Sound II. I kid around and claim, in the voice-over, that a cat is responsible for the collapse. So if you show the DVD and that type of humor is not your style, consider turning the audio off.

Forced vibrations, resonance, and interference provide a very useful background for the same concepts applied to light in Chapters 26, and 27. A great sounding-board demo is placing a music box mechanism on your chalkboard or whiteboard, and comparing the loud sound it produces with the almost imperceptible sound when held in air. Arbor Scientific has these (Product P7-7330).

J. David Gavenda (University of Texas at Austin) points out that *propagate* is a better term than *conductor* for the transmission of sound. Conduction infers diffusion; a process such as occurs in electrical and thermal conduction. The transmission of sound through wood, steel, and other materials involves media boundaries that reflect waves and confine them so they can't spread in 3 dimensions. Also, a speaking tube is analogous to a light pipe; both have one-dimensional propagation because of internal reflection.

Practicing Physics Book:
- Wave Superposition

Problem Solving Book:
A chapter with ample numbers of sound problems
Laboratory Manual:

- How Quiet Low Sound *Sound Wave Manipulation and Interpretation* (Experiment)
- Fork it Over *Determination of the Speed of Sound in Air* (Experiment)
- Sound Off *Sound Wave Cancellation* (Demonstration)
- Wah-Wahs and Touch Tones *Sound Wave Interference* (Tech Lab)

Next-Time Questions:
• Concert Hall •Sound From a Train

Hewitt-Drew-It Screencasts:
•*Reflection and Refraction of Sound* •*Resonance of Sound* •*Wave Interference*

SUGGESTED LECTURE PRESENTATION

Origin of Sound: Begin by stating that the source of sound or all wave motion, is a vibrating object. Ask your class to imagine a room filled with Ping-Pong balls and that you hold a giant Ping-Pong paddle. When you shake the paddle to-and-fro you set up vibrations of the balls. Ask how the frequency of the vibrating balls will compare with the frequency of the vibrating paddle. Sound is understood if we "think small."

> DEMONSTRATION: Tap a large tuning fork and show that it is vibrating by dipping the vibrating prongs in a cup of water. The splashing water is clear evidence that the prongs are moving! (Small forks do not work as well.)
>
> DEMONSTRATION: Hold an aluminum rod (a meter long or so) horizontally at the midpoint and strike one end with a hammer. You will create vibrations that travel and reflect back-and-forth along the length of the rod. The sustained sound heard is due to energy "leaking" from the ends, about 1% with each reflection. So at any time the sound inside is about 100 times as intense as that heard at the ends. (This is similar to the behavior of light waves in a laser.) Shake the rod to-and-fro as Paul Doherty does and illustrate the Doppler effect.
>
> DEMONSTRATION: Rub some pine pitch or rosin on your fingers and stroke the aluminum rod. If you do it properly, it will "sing" very loudly. Do this while holding the rod at its midpoint and then at different places to demonstrate harmonics. (Of course you practiced this first!)

Nature of Sound in Air:

> DEMONSTRATION: Ring the doorbell suspended in a bell jar that is being evacuated of air. While the loudness of sound diminishes, discuss the movement of sound through different media—gases, liquids, and solids. Ask why sound travels faster in warm air—then faster through moist air.

Media That Transmit Sound: Discuss the speed of sound through different media—four times as fast in water than in air—about eleven times as fast in steel. The elasticity of these materials rather than their densities accounts for the different speeds. Cite how Native Americans used to place their ears to the ground to hear distant hoof beats. And how one can put the ear to a track to listen for distant trains.

Speed of Sound: Discuss the speed of sound and how one can estimate the distance from a lightning storm.

Compute or state that a radio signal takes about $^1/8$ second to go completely around the world, while in the same time sound travels about 42.5 m. Pose the following: Suppose a person attends a concert that is being broadcast over the radio, and that he sits about 45 m from the stage and listens to the radio broadcast with a transistor radio over one ear and the nonbroadcast sound signal with the other ear. Which signal will reach his ear first? The answer is that the radio signal would reach his ear first, even if the radio signal traveled completely around the world before reaching his radio! Note the Next-Time Question that features this idea.

Reflection of Sound: Bats and echoes, charting of the ocean bottom, reverberations in the shower, and acoustics in music halls—go to it.

Refraction of Sound: Explain refraction with a chalkboard drawing similar to Figure 20.9. As an example different than the sound of the bugle waking the dog, consider the temperature inversion over a lake at night, and how one can hear whispers of people on the opposite side of the lake. You may want to follow this up with the similar case of refraction by wind, where wind speed is greater higher up than near the ground.

Ultrasound technology is a useful medical application of sound refraction (Figure 20.10).

An even more fascinating example of reflection and refraction of sound is the dolphin. Dolphins have been doing all along what humans have just learned to do. Add to the material about dolphins in the chapter, that unlike humans, dolphins breathe voluntarily. They cannot be put to sleep for medical operations because they will cease breathing and die. They are subject to drowning, as any mammal is. When in trouble other dolphins hold the troubled dolphin at the surface so breathing can take place. When sick, they will beach themselves so they won't drown. Many shipwrecked sailors owe their lives to dolphins who have beached them. Fascinating creatures!

Forced Vibrations, Natural Frequency: Tap various objects around you and explain what is happening at the atomic level—that crystalline or molecular structures are made to vibrate, and that due to the elasticity and bonding of the material constituents, natural modes of vibration are produced. Objects have their own characteristic frequencies. The organs of humans have a natural frequency of about 7 hertz.

Resonance:

> DEMONSTRATION: Show resonance with a pair of tuning forks, explaining how each set of compressions from the first fork push the prongs of the second fork in rhythm with its natural motion. That's family friend Ryan Patterson in Figure 20.13. Compare resonance to pushing somebody on a playground swing (as my grandson Manuel Hewitt shows in Figure 20.16). If you have a strobe-light handy, illuminate resonating forks with it and see glee in your students!

When you are adjusting the frequency of one of your tuning fork boxes, by moving the weights up or down the prongs, call attention to the similarity of this with tuning a radio receiver. When one turns the knob to select a different station, one is adjusting the frequency of the radio set to resonate with incoming stations.

Cite other examples of resonance—the chattering vibration of a glass shelf when a radio placed on it plays a certain note—the loose front end of a car that vibrates at only certain speeds—crystal wine glass shattering by a singer's voice—troops breaking step in bridge crossing.

Conclude your treatment of resonance with the exciting film loop "The Tacoma Narrows Bridge Collapse." This short film is a most impressive physics film. (Again, it is on "Sound II" of the *Conceptual Physics Alive!* DVD.) If you show it, be prepared to answer to my assertion in the film that a cat brought down the bridge due to resonance with its steady steps as it crossed the bridge. When challenged myself on this point, I say it's in the book. Then my students read about the mild gale. How carefully do your students read the text?

Interference: Introduce interference by sketching a sine wave on the board—a water wave. Then superpose another identical wave on it and ask what happens. Nothing spectacular, simply a wave of twice the amplitude. Now repeat and superpose the second wave a half-wavelength out of step. State that physics types don't say "out of step," but "out of phase." Same thing.

> DEMONSTRATION: Play a stereo radio, tape or CD player, on a mono setting and demonstrate the different quality of sound when the speakers, set apart from each other, are out of phase. I have mine connected to a DPDT switch to flip the phase. The difference in sound is obvious, especially for students on the center line. You might point out in Figure 20.18 that in position *b* cancellation

will occur for a few particular wavelengths, whereas in position *a* cancellation can occur for all wavelengths—when both speakers emit the same signal. Of course, wall reflections fill in any pure cancellations. In an acoustic chamber, however, cancellation would occur.

> DEMONSTRATION: Do the demo shown in Figure 20.19 and face the stereo speakers toward each other, at arm's length apart. Flip one speaker out of phase and gradually bring them closer. The volume of sound fades dramatically as they are brought face to face. Interference. This may likely be one of the more memorable of your demos.

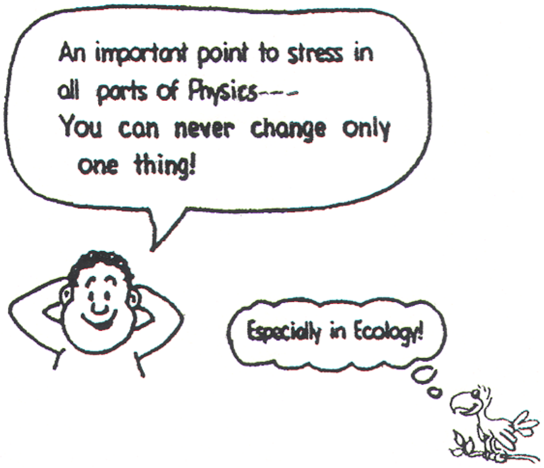
The question may arise as what happens to the sound energy when sound cancels. Interestingly, each radio loudspeaker is also a microphone. When the speakers face each other they "drive" each other, inducing back voltages in each other that reduce the currents in each. Thus energy is diminished, but not canceled.

> DEMONSTRATION: Show the reason for speakers mounted in boxed enclosures by producing a bare speaker connected to a music source. The sound is "tinny." State why; that as compressions are produced by one side of the speaker cone, rarefactions are produced by the other. Superposition of these waves results in destructive interference. Then produce a square piece of board (plywood or cardboard) close to a meter on a side with a hole the size of the speaker in its center. Place the speaker at the hole and let your class hear the difference in the fullness of the sound that results. You have diminished the superposition of waves that previously canceled. The effect is dramatic.

I kid around about my keen ability to completely cancel sound by striking one tuning fork and then the other at precisely the time to produce cancellation. When I do this I quickly grab and release the prongs of the sounding fork while not really making contact with the second. It is especially effective for students who weren't watching carefully. I exclaim that when I'm lucky enough to achieve complete cancellation on the first try, I never repeat it. Is this real physics? No, but it's a mood elevator so that my students are receptive to the real physics I discuss the rest of the time.

Beats: Acknowledge you were kidding around before about producing interference with the pair of tuning forks, but now you're for real with them. Strike the slightly different frequency forks and hear the beats. This is even nicer when your students see an oscilloscope trace what they hear.

> DEMONSTRATION: Do as Paul Hickman does and sound a tuning fork mounted on a sounding board and position the open end at various places from a reflecting wall. Areas of cancellation and reinforcement are readily located.



Answers and Solutions for Chapter 20

Reading Check Questions

1. Sound is a form of energy.
2. The higher the frequency, the higher the pitch.
3. A young person can normally hear from 20 to 20,000 hertz.
4. Infrasonic sound is less than 20 hertz, while ultrasonic is above 20,000 hertz.
5. Air is a poorer conductor than solids and liquids.
6. In a vacuum there is no medium to compress and expand.
7. A compression is a region of compressed air; a rarefaction is a region of low-pressure air.
8. Both compressions and rarefactions travel in the same direction of the wave they comprise.
9. Sound speed depends on wind conditions, temperature, and humidity of air. It does not depend on loudness or frequency of the sound.
10. Sound speed is 340 m/s in 20°C dry air.
11. Sound travels faster in warm air.
12. There is more energy in ordinary light than in ordinary sound.
13. Sound energy dissipates to thermal energy.
14. An echo is reflected sound.
15. A reverberation is sound multiply reflected.
16. Refraction is caused by bending due to differences in sound speed.
17. Sound bends downward when speed is less near the ground.
18. Sound refracts in water due to different speeds in different water temperatures.
19. Ultrasound is sound composed of frequencies higher than the range of human hearing.
20. Sound is louder due to more surface vibrating.
21. An object’s elasticity, size, and shape determine natural frequency.
22. When forced vibrations match natural frequency, resonance occurs.
23. By tuning the radio to a certain frequency, you are adjusting the receiver circuit to vibrate at that station’s frequency only.
24. Wind-generated resonance destroyed the bridge.
25. Waves will cancel when they are identical and out of phase.
26. All waves exhibit interference.
27. The result is cancellation of sound.
28. Interference is the phenomena underlying beats.
29. A beat frequency of 4 Hz results.
30. A radio wave is electromagnetic, while a sound wave is a mechanical phenomenon.

Think and Do

31. Sound should be louder beneath the water. Tub resonance can be fun.

32. Note the different patterns with different types of music.

Think and Solve

33. Wavelength = speed/frequency = $\frac{340 \text{ m/s}}{340 \text{ Hz}} = 1$ m.

    Similarly for a 34,000 hertz wave; wavelength = $\frac{340 \text{ m/s}}{34\ 000 \text{ Hz}} = 0.01$ m = 1 cm.

34. $v = f\lambda$, so $\lambda = v/f$ = (1530 m/s)/7 Hz = **219 m**.

35. The ocean floor is 4590 meters down. The 6.0-second time delay means that the sound reached the bottom in 3.0 seconds. Distance = speed × time = 1530 m/s × 3.0 s = 4590 m.

36. Assuming the speed of sound to be 340 m/s, the cave wall is 17 meters away. This is because the sound took 0.10 second to reach the wall (and 0.05 second to return).

    Distance = speed x time = 340 m/s × 0.05 s = 17 m.

37. The single blow you hear after you see Sally stop hammering originated with the next-to-last blow you saw. The very first blow would have appeared as silent, and succeeding blows synchronous with successive strikes. In one second sound travels 340 meters in air, the distance between you and Sally.

38. Sound goes from Rip to the mountain in 4 hours and back in another 4 hours to wake him. The distance from Rip to the mountain = speed of sound × time = 340 m/s × 3600 s/h × 4 h = 4.9×10^6 m = 4900 km. (Very far, and due to the inverse-square law, also very weak!)

39. There are 3 possible beat frequencies: 2 Hz, 3 Hz, and 5 Hz. These are of differences in fork frequencies: 261 - 259 = **2 Hz**; 261 - 256 = **5 Hz**; 259 - 256 = 3 Hz.

40. Wavelength = speed/frequency = (1,500 m/s)/(57 Hz) = 26 m. Alternate method: For sounds of the same frequency in different media, wavelengths are proportional to wave speed. So (wavelength in water)/(wavelength in air) = (speed in water)/(speed in air) = (1,500 m/s)/(340 m/s) = 4.4. Multiply 6 m by 4.4 to get 26 m.

Think and Rank

41. B, C, A
42. B, A, C, D

Think and Explain

43. Light travels about a million times faster than sound, hence the delay between what you see and what you hear.

44. Sound does not travel in a vacuum.

45. Between us and other planets is a vacuum. Sound does not travel in a vacuum.

46. The same. The circles formed are relative to the water, and both will travel downstream together.

47. Bees buzz when in flight because they flap their wings at audio frequencies.

48. The shorter wavelengths are heard by bats (higher frequencies have shorter wavelengths).

49. The carrier frequency of electromagnetic waves emitted by the radio station is 101.1 MHz.

50. The wavelength of the electromagnetic wave will be much longer because of its greater speed. You can see this from the equation speed = frequency × wavelength, so for the same frequency greater speed means greater wavelength. Or you can think of the fact that in the time of one period—the same for both waves—each wave moves a distance equal to one wavelength, which will be greater for the faster wave.

51. The wavelength of sound from Source A is half the wavelength of sound from Source B.

52.Letting $v = f\lambda$ guide thinking, as frequency increases wavelength decreases.

53. Light travels about a million times faster than sound in air, so you see a distant event a million times sooner than you hear it.

54. The electronic starting gun does not rely on the speed of sound through air, which favors closer runners, but gets the starting signal to all runners simultaneously.

55. When sound passes a particular point in the air, the air is first compressed and then rarefied as the sound passes. So its density is increased and then decreased as the wave passes.

56. At the instant that a high pressure region is created just outside the prongs of a tuning fork, a low pressure region is created between the prongs. This is because each prong acts like a Ping-Pong paddle in a region full of Ping-Pong balls. Forward motion of the paddle crowds Ping-Pong balls in front of it, leaving more space between balls in back of it. A half-cycle later when the prongs swing in toward the center, a high pressure region is produced between the prongs and a low-pressure region is produced just outside the prongs.

57. Because snow is a good absorber of sound, it reflects little sound—hence quietness.

58. The fact that we can see a ringing bell but can't hear it indicates that light is a distinctly different phenomenon than sound. When we see the vibrations of the "ringing" bell in a vacuum, we know that

light can pass through a vacuum. The fact that we can't hear the bell indicates that sound does not pass through a vacuum. Sound needs a material medium for its transmission; light does not.

59. The Moon is described as a silent planet because it has no atmosphere to transmit sounds.

60. If the speed of sound were different for different frequencies, say, faster for higher frequencies, then the farther a listener is from the music source, the more jumbled the sound would be. In that case, higher-frequency notes would reach the ear of the listener first. The fact that this jumbling doesn't occur is evidence that sound of all frequencies travel at the same speed. (Be glad this is so, particularly if you sit far from the stage, or if you like outdoor concerts.)

61. If the frequency of sound is doubled, its speed will not change at all, but its wavelength will be "compressed" to half size. The speed of sound depends only on the medium through which it travels, not on its frequency, wavelength, or intensity (until the intensity gets so great that a shock wave results).

62. Sound travels slower in cold air because the air molecules that compose cold air themselves travel slower and therefore take a bit longer before they bump into each other, which results in slower sound.

63. Refraction is the result of changing wave speeds, where part of a wave travels at a different speed than other parts. This occurs in non-uniform winds and non-uniform temperatures. Interestingly, if winds, temperatures, or other factors could not change the speed of sound, then refraction would not occur. (The fact that refraction does indeed occur is evidence for the changing speeds of sound.)

64. The tremor in the ground can be felt before a distant explosion is heard because sound travels faster in the solid ground than in air.

65. Sound is more easily heard when the wind traveling toward the listener at elevations above ground level travels faster than wind near the ground. Then the waves are bent downward as is the case of the refraction of sound shown in Figure 20.9.

66. In accord with the inverse-square law, the intensity decreases to 1/9 when distance is tripled.

67. An echo is weaker than the original sound because sound spreads and is therefore less intense with distance. If you are at the source, the echo will sound as if it originated on the other side of the wall from which it reflects (just as your image in a mirror appears to come from behind the glass). Also, the wall is likely not a perfect reflector.

68. If a single disturbance at some unknown distance sends longitudinal waves at one known speed, and transverse waves at a lesser known speed, and you measure the difference in time of wave arrival, you can calculate the distance. The wider the gap in time, the greater the distance—which could be in any direction. If you use this distance as the radius of a circle on a map, you know the disturbance occurred somewhere on that circle. If you telephone two friends who have made similar measurements of the same event from different locations, you can transfer their circles to your map, and the point where the three circles intersect is the location of the disturbance.

69. First, in outer space there is no air or other material to carry sound. Second, if there were, the faster-moving light would reach you before the sound.

70.Marchers at the end of a long parade will be out of step with marchers nearer the band because time is required for the sound of the band to reach the marchers at the end of a parade. They will step to the delayed beat they hear.

71. Soldiers break step when crossing a bridge so they will not set the bridge into forced vibration or resonance, which could tear the bridge apart.

72. A harp produces relatively softer sounds than a piano because its sounding board is smaller and lighter.

73 Agree with the speed of sound, but not the frequency. Sound's frequency depends only on the vibration of the source itself, not the medium.

74. There are two principal reasons why bass notes are more distinctly heard through walls than higher-frequency notes. One is that waves that vibrate more often per second transfer sound energy into heat more rapidly than waves of lower frequency. The higher-frequency waves are thermally "eaten up" by the material in the walls, while the lower-frequency vibrations pass with less loss through the material. Another reason is that the natural frequency of large walls, floors, and ceilings, is lower than the natural frequency of smaller surfaces. The large surfaces are more easily set into forced vibrations and resonance.

75. The lower strings resonate with the upper strings.

76. Certain dance steps set the floor into vibration that may resonate with the natural frequency of the floor. When this occurs, the floor heaves.

77. These noise-canceling devices use interference to cancel the sound of the jackhammer in the ears of its operator. Because of the resulting low jackhammer noise in the ears of the operator, he can hear your voice clearly. But you, however, without the earphones experience no such cancellation of sound, so the voice of the operator is drowned out by the loud jackhammer noise.

78. Think of pushing a child on a swing: If you pushed twice as often as the child's period, you would push against the child's motion with every other push, and similarly with increased multiples of frequency. Pushing more often than once each period disrupts the motion. On the other hand, if you pushed the child every other swing, your pushes would match the child's motion and amplitude would increase. So sub-multiple pushes will not disrupt motion. Similarly with sound.

79. By resonance, when the buildup of vibrations in the glass exceed the breaking point of the glass.

80. Beats result from interference, and not the Doppler effect.

81. No, for the same word refers to different aspects of music. The beat of music involves rhythm, and the beats of sound involve throbbing due to interference.

82. Waves of the same frequency can interfere destructively or constructively, depending on their relative phase, but to *alternate* between constructive and destructive interference, two waves have to have different frequencies. Beats arise from such alternation between constructive and destructive interference.

83. The piano tuner should loosen the piano string. When 3 beats per second is first heard, the tuner knows he was 3 hertz off the correct frequency. But this could be either 3 hertz above or 3 hertz below. When he tightened the string and increased its frequency, a lower beat frequency would have told him he was on the right track. But the greater beat frequency told him he should have been loosening the string. When there is no beat frequency, the frequencies match.

84. The possible frequencies are 264 + 4 = 268 Hz, or 264 – 4 = 260 Hz.

85. You'll hear sound at a frequency of 2 kHz, the beat frequency of the two higher frequencies.

Think and Discuss

86. The pitch of the tapped glass decreases as the glass is filled. As the mass of the system (glass plus water) increases, its natural frequency decreases. For systems of a given size, more mass usually means lower frequency. This can be seen on a guitar, where the most massive string has the lowest natural pitch. (If you've answered this exercise without actually trying it, shame on you!)

87. Sound travels faster in moist air because the less massive water vapor molecules, H_2O, travel faster than the more massive N_2 and O_2 molecules at the same temperature. This faster motion results in sound traveling faster as discussed in Question 62.

88. The short wavelengths of ultrasound allow the imaging of smaller objects. This is similar to the smaller detail seen by short-wavelength blue light in microscopes, and the still smaller detail seen with ultra-short-wavelength electron microscopes, briefly discussed in Chapter 11. (We will see later in Chapter 29 that shorter wavelengths produce clearer images by decreasing a wave effect called *diffraction*.)

89. The rule is correct: This is because the speed of sound in air (340 m/s) can be rounded off to 1/3 km/s. Then, from distance = speed × time, we have distance = (1/3) km/s × (number of seconds). Note that the time in seconds divided by 3 gives the same value.

90. When you are equally distant from the speakers, their tones interfere constructively. When you step to one side, the distance to one speaker is greater than the distance to the other speaker and the two waves are no longer in phase. They interfere destructively. (If you step far enough to one side, they will interfere constructively again.)

91. Long waves are most canceled, which makes the resulting sound so tinny. For example, when the speaker cones are, say, 4 centimeters apart, waves more than a meter long are nearly 180° out of phase, whereas 2-centimeter waves will be in phase. The higher frequencies are least canceled by this procedure. This must be tried to be appreciated.