19 Waves and Vibrations

19.1 Good Vibrations
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19.4 Wave Motion
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19.8 Shock Waves

The darling little gal on the Part Four Opener is Abby Dimanjo, daughter of Stella and Jojo Dimanjo. Stella was my last CCSF teaching assistant before I retired in 2000. She is now a dentist with her own practice and Jojo is nicely employed at Google.

Chapter photo openers begin with Diane Reindeau, a prize-winning physics teacher at Deerfield High School in Deerfield, IL, and a column editor for The Physics Teacher magazine of AAPT. She has also written Think and Rank questions for both this and my high-school book. Photos 1 and 2 are friend Frank Oppenheimer, one of the most humble of great men I have known. His devotion to elevating the thinking of youngsters was unparalleled—what the Exploratorium that he founded was all about. Photo 4 is Jill Johnsen and Diane Markham of CCSF, and lastly, photo 5 is my multi-talented nephew, John Suchocki.

Some teachers begin the study of physics with waves, vibrations, and sound, topics that have greater appeal to many students than mechanics. Your course could begin with Part 4 and then move to Part 6, Light. If this chapter is used as a launch point, only the concept of speed needs to be introduced, which your students intuitively understand anyway.

Water waves are thought to be simple, but they're not. For most waves, gravity is the restoring force governing wave displacement, whereas for very short waves, like ripples of wavelength less than a few millimeters, surface tension provides the restoring force. The speed of waves depends on the depth of the water compared with the wavelength of the waves. Waves on the open sea, caused by winds, are rarely longer than 300 meters and never travel more than 100 km/h. Tsunami waves, caused by earthquakes and land slides, on the other hand, often measure 150 km from crest to crest and in deep water can travel as fast as a jetliner—some 800 km/h. Since they may be less than a meter high, they pass completely unnoticed by ships at sea. A tsunami, interestingly, may consist of ten or more waves forming what is called a "tsunami wave train." The individual waves follow one behind the other, between 5 and 90 minutes apart. Tsunamis are of particular interest to the author, especially when living in Hilo, Hawaii where two devastating tsunamis have occurred in the past half-century.

The treatment of shock waves in this chapter is quite simplified. Be advised that actual shock waves can be more complex than I've indicated.

This chapter serves as a necessary background for the following two chapters, as well as a useful background to the chapters in Part 5.

A Doppler ball is a 5-inch foam ball within which is a battery-powered buzzer. Start the buzzer and play catch, or swing it in a circle from the end of a piece of string. It is available from Arbor Scientific (Product #P7-7120).

Practicing Physics Book:

- Vibration and Wave Fundamentals • Shock Waves

Problem Solving Book:
An ample supply of problems involving vibrations and waves

Laboratory Manual:
- Slow-Motion Wobbler *Slowing Vibrations with a Strobe Light* (Demonstration)
- Water Waves in an Electric Sink *Wave Mechanics Simulation* (Tech Lab)

Next-Time Questions in Instructors Resource DVD:
- Standing Wave • Shock Wave • Flash Frequency

Hewitt-Drew-It! Screencasts: •*Good Vibrations and Waves* •*Types of Waves*

SUGGESTED LECTURE PRESENTATION

Vibration of a Pendulum: Demonstrate the periods of pendula of different lengths, and compare the strides of short and tall people, and animals with short and long legs. (Relate this to rotational inertia, as studied in mechanics.)

Wave Description: Move a piece of chalk up and down, tracing and retracing a vertical straight line on the board. Call attention to how "frequently" you oscillate the chalk, and relate this to the definition of frequency. Also discuss the idea of amplitude. With appropriate motions, show different frequencies and different amplitudes. Then do the same while walking across the front of the board tracing out a sine wave. Show waves of different wavelengths.

> DEMONSTRATION: Show waves on a Bell Telephone torsion type wave machine shown in the chapter opener photo (if you're fortunate enough to have one).
>
> DEMONSTRATION: In jest, do as Tom Gordon at Bronx High School does and suspend a harmonica from a spring, bob it up and down, and ask, "What do we have here?" [Answer: Simple "harmonica" motion!]

Swing a pendulum to-and-fro and discuss the reciprocal relationship between frequency and period: $f = 1/T$, and $T = 1/f$. Or $fT = Tf = 1$.

Distinguish between wiggles in time—vibrations, and wiggles in space and time—waves. Stress the sameness of the frequency of a wave and the frequency of its vibrating source.

Wave Speed: Explain or derive the wave speed = frequency x wavelength formula. Support this with examples, first the freight car question early in the chapter, and then the water waves as in Think and Solve 36. If you discuss electromagnetic waves, be sure to contrast them with longitudinal sound waves and distinguish between them. You may refer ahead to the family of electromagnetic waves in Figure 26.3 later in the book.

Transverse and Longitudinal Waves:

DEMONSTRATION: You and a student hold the ends of a stretched spring or a Slinky and send transverse pulses along it, stressing the idea that only the disturbance rather than the medium moves along the spring. Shake it and produce a sine wave. Then send a stretch or compression down the spring, showing a longitudinal pulse, and wave. After some discussion, produce standing waves. (Impressive interference demos of sound are treated in the lecture for the next chapter.)

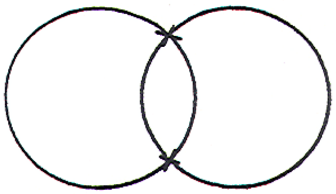
Interference: Explain interference, beginning with water waves, and then apply your explanation to standing waves. If you still have an overhead projector, overhead transparencies showing various interference patterns may simplify your presentation.

CHECK QUESTION: Can waves overlap in such a way as to produce a zero amplitude? [Yes, this is the destructive interference that is characteristic of all waves.]

Doppler Effect: Introduce the Doppler Effect by throwing a ball, perhaps sponge rubber or Styrofoam, around the room. In the ball you first place an electronic whistle that emits a sound of about 3000 Hz. Relate this to the sound of a siren on a fire engine (Figure 19.17) and radar of the highway patrol. (Note that sound requires a medium; radar is an E & M wave and requires none.)

DEMONSTRATION: Show a Slinky lying on a table, slightly stretched. Put your hand in the middle and move it, say, to the right. Your class easily notices the compression of the part of the Slinky to the right and the corresponding rarefaction to the left. This shows that waves are bunched in the direction of motion and stretched in the opposite direction.

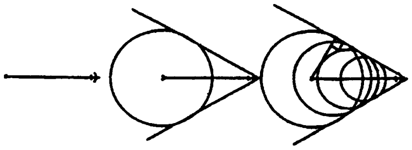
Wave Barriers, Bow Waves, and Shock Waves: Describe the Doppler effect via the bug in water sequence as treated in the text. From this lead into bow and shock waves. After sketching Figures 19.15, 19.16, and 19.18, ask the class to consider the waves made by two stones thrown in the water. Sketch the overlapping waves as shown to the right. Ask where the water is highest above the water level, then indicate the two places where the waves overlap with X's. Then show that this is what happens with a bow wave, that a series of such overlaps make up the envelope of many circular waves forming a V-shape. Then discuss the shock waves produced by supersonic aircraft.



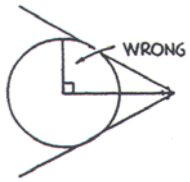
Note in Figure 19.19 I similarly position X's where the waves overlap. For more and closer waves than is shown in the drawing, the regions of overlap would be closer to the edge. I've been criticized for not placing the X's on the edge in this figure. But doing so would contradict the drawing above.

The analogy between bow waves in water and shock waves in air is very useful. Questions raised by students about shock waves and the sonic boom can be effectively answered by translating the question from one of an aircraft in the air to one of a speedboat knifing through the water, much easier-to-visualize.

Shock Wave Construction: Parallel the exercise on page 83 of the Practicing Physics book and construct a shock wave on the board by the following sequence: First place your chalk on the board anywhere to signify time zero. Draw a meter-long horizontal line, say to the right, to represent how far an aircraft has traveled in a certain time. Suppose it travels twice the speed of sound (Mach 2). Then during the time it travels your one meter, the sound it made initially has traveled half this distance, which you mark on the midpoint of your line. State that the initial sound has expanded spherically, which you represent two-dimensionally by drawing a circle as shown.



Explain that this circle represents only one of the nearly infinite circles that make up the shock wave, which you draw. The shock wave should be a 60 degrees wedge (30 degrees above your horizontal line, and 30 degrees below). The next line you draw is important: Draw the radius of the circle, from its center to a point tangent to the shock wave. Explain how the speed of the craft is simply the ratio of the horizontal line to this radial distance. (If your students are science students, at this point and not before, introduce the sine function). Now your test of all this: Construct a shock wave of a different angle on the board and ask your class to estimate the speed of the craft that generated it. In making constructions, working backwards now, the most common student error is constructing the right angle from the horizontal line rather than from the shock wave line that is tangent to the circle.



Answers and Solutions for Chapter 19

Reading Check Questions

1. A wiggle in time is a vibration; a wiggle in space and time is a wave.
2. The source of all waves is a vibration.
3. The period is the time for a complete to-and-fro swing.
4. A long pendulum has a longer period.
5. A sine curve is a pictorial representation of a wave.
6. Period, the time for a complete vibration; amplitude, the maximum displacement of a wave; wavelength, the length of one cycle of a wave; frequency, the rate of vibration.
7. There are 101.7 million vibrations per second.
8. Frequency and period are reciprocals of each other.
9. Energy.
10. The medium does not travel with a wave.
11. In a transverse wave vibrations are perpendicular to the direction of wave travel.
12. In a longitudinal wave, vibrations are parallel to wave travel.
13. The wavelength of a longitudinal wave is the distance between successive compressions or rarefactions.
14. Wave speed = frequency x wavelength.
15. When more than one wave occupies the same space at the same time the displacements add at every point.
16. When constructive interference occurs, waves build up. When destructive interference occurs, waves are diminished.
17. All waves can show interference.
18. A node is the part of a standing wave with zero or minimum displacement; an antinode is a part of a standing wave having maximum displacement.
19. Standing waves can be formed in either transverse or longitudinal waves.
20. What changes in the Doppler effect is frequency, not wave speed.
21. The Doppler effect can be observed with both transverse and longitudinal waves.
22. A blue shift refers to the Doppler effect for waves from an incoming source; red shift for waves from a receding source.
23. To keep up with produced waves, the bug must swim at wave speed; to produce a bow wave, faster than wave speed.
24. A supersonic aircraft, by definition, can fly faster than the speed of sound.
25. The faster the source, the narrower the V shape.
26. A shock wave in air is 3-dimensional.
27. False; the source may have exceeded the speed of sound earlier.
28. False; a speeding bullet or a circus whip can produce a sonic boom.

Think and Do

29. An activity to do!
30. Standing waves can be produced in both a wine glass and a metal bowl (with some practice).
31. Open ended.

Plug and Chug

32. (a) $f = 1/T = 1/0.10\text{ s} = 10\text{ Hz}$;
    (b) $f = 1/5 = 0.2\text{ Hz}$;
    (c) $f = 1/(1/60)\text{ s} = 60\text{ Hz}$.
33. Using $T = 1/f$, (a) 0.10 s.
    (b) 5 s.
    (c) $^1/60$ s.
34. $v = f\lambda = (2\text{ Hz})(1.5\text{ m}) = 3\text{ m/s}$.
35. $v = f\lambda = (200\text{ Hz})(1.7\text{ m}) = 340\text{ m/s}$.

Think and Solve

36. The skipper notes that 15 meters of wave pass each 5 seconds, or equivalently, that 3 meters pass each 1 second, so the speed of the wave must be

    $$\text{Speed} = \frac{\text{distance}}{\text{time}} = \frac{15\text{ m}}{5\text{ s}} = 3\text{ m/s}.$$

    Or in wave terminology:

    Speed = frequency × wavelength = (1/5 Hz)(15 m) = 3 m/s.

37. (a) Frequency = 2 bobs/second = 2 hertz;

(b) Period = 1/f = 1/2 second;
(c) and the amplitude is the distance from the equilibrium position to maximum displacement, one-half the 20-cm peak-to-peak distance or 10 cm.

38. $d = vt$ = (340 m/s)(1/600 s) = 0.57 m. Or use speed = wavelength × frequency to get wavelength = speed/frequency = (340 m/s)/(600 Hz) = 0.57 m.

39. (a) Period = 1/frequency = 1/(256 Hz) = 0.00391 s, or 3.91 ms.
(b) Speed = wavelength × frequency, so wavelength = speed/frequency = (340 m/s)/(256 Hz) = 1.33 m.

40. Speed of plane = 1.41 × speed of sound (Mach 1.41). In the time it takes sound to go from A to C, the plane goes from A to B. Since the triangle A-B-C is a 45-45-90 triangle, the distance AB is $\sqrt{2}$ = 1.41 times as long as the distance AC.

41. T = (75 s)/(15 swings) = 5.0 s. From period $T = 2\pi\sqrt{L/g}$, solving for g, we get $g = 4\pi^2 L/T^2 = 4\pi^2(1.00\text{m})/(5\text{ s})^2 = 1.6\text{ m/s}^2$.

Think and Rank

42. a. D, B, A = C
    b. D, A, B, C
    c. C, B, A, D
    d. D, A, B, C
43. A, B, D, C
44. B, A, C
45. A, C, B

Think and Explain

46. The period of a pendulum does not depend on the mass of the bob, but does depend on the length of the string.

47. A shorter pendulum swings to and fro with a higher frequency and shorter period.

48. The period of a pendulum depends on the acceleration due to gravity. Just as in a stronger gravitational field a ball will fall faster, a pendulum will swing to and fro faster. (The exact relationship, $T = 2\pi\sqrt{L/g}$, is shown in Footnote 1 in the chapter). So at mountain altitudes where the gravitational field of the Earth is slightly less, a pendulum will oscillate with a slightly longer period, and a clock will run just a bit slower and will “lose” time.

49. Assuming the center of gravity of the suitcase doesn’t change when loaded with books, the pendulum rate of the empty case and loaded case will be the same. This is because the period of a pendulum is independent of mass. Since the length of the pendulum doesn’t change, the frequency and hence the period are unchanged.

50. The period is actually less when you stand on a playground swing, for the pendulum is effectively shorter. That’s because the center of mass of the pendulum “bob” (you) is raised and is closer to the pivot.

51. The period increases, for period and frequency are reciprocals of each other.

52. Lower frequency produces wave crests farther apart, so wavelength increases. Wavelength and frequency are reciprocals of each other.

53. The wavelength is lengthened to twice. Speed and frequency are directly proportional.

54. Letting $v = f\lambda$ guide thinking, twice the speed means twice the frequency.

55. The periods are equal. Interestingly, an edge-on view of a body moving in uniform circular motion is seen to vibrate in a straight line. How? Exactly in simple harmonic motion. So the up and down motion of pistons in a car engine are simple harmonic, and have the same period as the circularly rotating shaft that they drive.

56. The wad of clay increases rotational inertia and it vibrates slower. When the clay is in the middle, its rotational inertia is less than when at the end, and vibration speed is increased. Rotational inertia is Chapter 8 material. (Interestingly, whereas the period of a pendulum isn't affected by mass, the period of the hacksaw blade is. Why? Because the hacksaw blade's restoring force is not gravity, but the elastic properties of the steel. More mass means more rotational inertia without any more torque, so the period increases.)

57. Wave frequency and shaking frequency are the same, which doesn't depend on the type of wave, for the frequency of all waves is the same as the frequency of the vibrating source.

58. Shake the garden hose to-and-fro at right angles to the hose to produce a sine-like curve.

59. To produce a transverse wave with a Slinky, shake it to and fro in a direction that is perpendicular to the length of the Slinky itself (as with the garden hose in the previous exercise). To produce a longitudinal wave, shake it to-and-fro along the direction of its length, so that a series of compressions and rarefactions is produced.

60. (a) Longitudinal. (b) Transverse (c) Transverse.

61. Violet light has the greater frequency.

62. Frequency and period are reciprocals of one another; $f = 1/T$, and $T = 1/f$. Double one and the other is half as much. So doubling the frequency of a vibrating object halves the period.

63. The frequency of the second hand of a clock is one cycle per minute; the frequency of the minute hand is one cycle per hour; for the hour hand the frequency is one cycle per 12 hours. To express these values in hertz, we need to convert the times to seconds. Then we find for the second hand the frequency = 1/60 hertz: for the minute hand the frequency = 1/3600 hertz; for the hour hand the frequency = 1/(12 × 3600) = 1/(43,200) hertz.

64. As you dip your fingers more frequently into still water, the waves you produce will be of a higher frequency (we see the relationship between "how frequently" and "frequency"). The crests of the higher-frequency waves will be closer together—their wavelengths will be shorter.

65. The frequency of vibration and the number of waves passing by each second are the same.

66. Think of a period as one cycle in time, and a wavelength as one cycle in space, and a little thought will show that in a time of one period, a wave travels a full wavelength. Formally, we can see this as follows:
distance = speed × time
where speed = frequency × wavelength, which when substituted for speed above, gives
distance = frequency × wavelength × time.
distance = 1/period × wavelength × period = wavelength.

67. For mechanical waves, something that vibrates. For E&M waves, vibrating electric charges.

68. Not including endpoints, there are 3 nodes in a wave two wavelengths long, and 5 nodes in a wave three wavelengths long. (Make a drawing and count them!)

69. The energy of a water wave spreads along the increasing circumference of the wave until its magnitude diminishes to a value that cannot be distinguished from thermal motions in the water. The energy of the waves adds to the internal energy of the water.

70. The circular patterns made by expanding waves are evidence that the wave speeds are the same in all directions, because all parts of the circle have gone equal distances from the center in equal times.

71. The speed of light is 300,000 km/s, about a million times faster than sound. Because of this difference in speeds, lightning is seen a million times sooner than it is heard.

72. The nodes are at the fixed points, the two ends of the string. The wavelength is twice the length of the string (see Figure 19.14a).

73. The frequency is doubled.

74. They are higher frequency due to the Doppler effect.

75. (a) The frequency increases. (b) The wavelength decreases. (c) The speed is unchanged (because the air remains motionless relative to you).

76. The Doppler effect is a change in frequency as a result of the motion of source, receiver, or both relative to each other. So if you move toward a stationary sound source, yes, you encounter wave crests more frequently and the frequency of the received sound is higher. Or if you move away from the source, the wave crests encounter you less frequently, and you hear sound of a lower frequency.

77. No, the effects of shortened waves and stretched waves would cancel one another.

78. There is no appreciable Doppler effect when motion of the sound source is at right angles to the listener. In this case, the source is neither approaching and crowding waves, nor receding and spreading waves. (For the record, however, there is a small “quadratic” transverse Doppler effect.)

79. Police use radar waves that are reflected from moving cars. From the shift in the returned frequencies, the speed of the reflectors (car bodies) is determined.

80. Oops, careful. The Doppler effect is about changes in *frequency*, not speed.

81. The bow or shock wave is actually the superposition of many lesser amplitude waves that interfere constructively. When the crest of one wave overlaps the crest of another, and then another, a wave of greater amplitude is produced.

82. A boat that makes a bow wave is traveling faster than the waves of water it generates.

83. A shock wave and the resulting sonic boom are produced whenever an aircraft is supersonic, whether or not the aircraft has just become supersonic or has been supersonic for hours.

84. The speed of the sound source rather than the loudness of the sound is crucial to the production of a shock wave. At subsonic speeds, no overlapping of the waves will occur to produce a shock wave. Hence no sonic boom is produced.

85. Yes, a supersonic fish in water would produce a shock wave and hence a sonic boom for the same reason it would if traveling faster than sound in air.

86 and 87. Open-ended.

Think and Discuss

88. The period is the same, for mass doesn’t affect period.

89. The frequency of a pendulum depends on the restoring force, which is gravity. Similarly, mass doesn’t affect free fall acceleration as is evident in Figure 19.1.

90. That gas can be heard escaping from a gas tap before it is smelled indicates that the pulses of molecular collisions (the sound) travel more quickly than the molecules migrate. (There are three speeds to consider: (1) the average speed of the molecules themselves, as evidenced by temperature—quite fast, (2) the speed of the pulse produced as they collide—about $^3/4$ the speed of the molecules themselves, and (3) the very slow speed of molecular migration.)

91. It’s important to note that wave speed involves the rate of travel while wave frequency involves how frequently vibration occurs. Two different concepts!

92. The Doppler shifts show that one side approaches while the other side recedes, evidence that the Sun is spinning.

93. The fact that you hear an airplane in a direction that differs from where you see it simply means the airplane is moving, and not necessarily faster than sound (a sonic boom would be evidence of supersonic flight). If the speed of sound and the speed of light were the same, then you’d hear a plane

where it appears in the sky. But because the two speeds are so different, the plane you see appears ahead of the plane you hear.

94. The conical angle of a shock wave becomes narrower with increased speeds. We see this in the sketches that depict a plane increasing in speed from left to right.