21 Musical Sound

Photo openers begin with my granddaughter Gracie (who is seen again opening Part 8 on page 657). The second photo is CCSF's finest, Norm Whitlatch, whose teaching career wonderfully emphasized the laboratory. Photo 2 is the niece and daughter of Stella and Jojo Dimamco. Mirium, at the right, is the sister of Abby who opens Part Four of this edition. Photo 4 is of physics instructor Lynda Williams of Santa Rosa Junior College in California. Lynda enjoys her musical performances, and especially enjoys entertaining at physics teacher functions.

The personal profile is of Jean Baptiste Fourier.

As in the preceding chapter, this chapter should be supported with lively lecture demonstrations. This material is not prerequisite to following material, and the entire chapter can be disregarded if a short treatment of sound is desired. In any event, the material in this chapter should be treated lightly. Like the periodic table, please make it clear that you don't expect this detailed material to be learned. Learning that there's physics in music is enough. Let this be a light-weight chapter.

Jojo Dijamco tells me that equal-tempered tuning is a compromise of scales so the frequency ratios are imperfect. In practice, equal-tempered tuning is adjusted for individual instruments (e.g., a piano or harp) so that the imperfections are minimized. Musicians consider the imperfections acceptable. Ideal tuning would require an instrument to be retuned whenever the key changes. This is not practical and is the reason that the compromise offered by the equal-tempered tuning is preferred. Johann Sebastian Bach wrote the *Well-Tempered Clavier* in the mid 1700s to show that equal-tempered tuning could work musically.

On the helium high-pitched voice: In the voice box are vocal folds. The higher-speed sound in helium enhances the higher frequencies in the voice spectrum. Thus the quality of the voice is changed, not the fundamental frequency.

If you don't know the names of the celebrities throughout the chapter, your students likely will. They are Jennifer Lopez on page 392, Mick Jagger and Jay-Z on page 393, Paul McCartney on page 395, Beyonce on page 396, Adele on page 397, and Bob Marley on page 398.

The sound emitted 10 cm away from some bats ranges from 122 to 134 decibels. Home fire alarms reach about 108 decibels. Fortunately for humans, we can't hear the high-frequency sound of bats. Otherwise they'd drive people batty.

There are no **Practicing Physics** worksheets, no problems in the **Problems Book,** no **Laboratory** experiments or activities, no **Hewitt-Drew-It! Screencasts** for this chapter. There are, however, four **Next-Time Questions** on musical sounds and pitch.

If you play a musical instrument, play it briefly for your class, explaining the physics of the instrument. Whereas anyone else doing the same would be no big deal, your students will love seeing and hearing you play music. Too often we're seen as nerds who can relate only to physics. Break this stereotype and add glee to your classroom! Feynman, who never fit the nerd profile, helped the image of physicists enormously by his drum playing.

SUGGESTED LECTURE PRESENTATION

Bring out the oscilloscopes, the audio oscillator, microphones, loudspeakers, and musical instruments.

Pitch, Loudness, and Quality: Waveforms can be displayed on the screen of an oscilloscope. An audio oscillator connected to a loudspeaker and an oscilloscope will demonstrate the relationships between pitch, frequency, and wavelength, and between amplitude and loudness. You can speak into the loudspeaker and display a wave pattern on the oscilloscope screen, showing that the loudspeaker serves as a microphone. (It may or may not be appropriate to briefly discuss the electromagnetic induction that takes place in the electromagnet of the loudspeaker at this point.) The waveforms of various musical instruments can be displayed and compared on the oscilloscope screen. Show the different harmonics for the same notes played on different instruments. Discuss quality.

If you display a decibel meter, show that for mid-range frequencies a decibel is the just-noticeable sound level difference that humans can detect.

Demonstrate Chladni figures with a fastened metal plate, violin bow, and fine sand. Or show the Ealing Film Loop of the same (perchance you have any of those still around). Discuss nodes and antinodes.

Musical Instruments: Although *standing longitudinal waves* are not treated in the text, you may wish to introduce this topic and relate it to musical instruments. If so, begin by demonstrating the resonance of standing air columns with a resonance water tube (a long glass tube partially filled with water, the level of which can be adjusted by raising or lowering an external reservoir). Hold a vibrating tuning fork over the open tube and adjust the water level until the air in the tube resonates loudly to the sound being sent into it by the fork. Show and explain that several heights will result in resonance. Measure the wavelengths of a high and a low frequency sound. Consider doing as Paul Hickman does and drop a couple of Alka-Seltzer tablets into the water. The air column above soon is filled with CO_2 and the tone of the reverberating sound undergoes a marked change. Relate the relative sizes of the respective sound cavities to the relative sizes of musical instruments; the bigness of a bass fiddle, and the smallness of a piccolo. These ideas underlie the tones one produces when blowing over the top of a soda pop bottle.

If you demonstrate resonance with the standard tube of water, consider a non-water alternative. Do as James Warden does and use a short piece of dowel that just slips in a vertical tube and suspend it with a string. Position the tuning fork at the bottom of the pipe instead of at the top. Since the sliding node can be moved much more quickly and accurately than a water column, you or your students can locate resonances within a few seconds. (Page 308, *The Physics Teacher*, May 2005.)

Tom Senior with novel sound producing items (photo with Think and Explain 56), shares simple physics on the Internet. (http://www.youtube.com/results?search_query=thomasjsenior&search_type=&aq=f)

Fourier Analysis: You may want to discuss Fourier Analysis and the superposition of waves and show on the board how the composite wave in Figure 21.6 is a sum of the fundamental and the second and third harmonics.

Figure 21.6 is also reinforced in the **Practice Book** page on wave superposition for the previous chapter.

Ask your class how many grooves there are on a typical record. (Remember them?) [The answer is one!]

DVDs are treated in the chapter. Interestingly, DVD and CD technology was preceded by digital audio players beginning in 1979 with the famed Sony Walkman audio cassette player. Portable music went digital in the 1980s. Technology continually changed the means of getting music from musicians to consumers. The music industry’s salvation today, if any, may come from paid access to songs streaming from the Internet. (My classroom videos also are now streamed by Arbor Scientific!) The technology moves so fast, and to us who have been around for awhile, the fact that CDs are now history, is astounding!

Answers and Solutions **for Chapter 21**

Reading Check Questions

1. Music is composed of periodic notes; noise is irregular.
2. The three characteristics are pitch, loudness, and quality.
3. High-pitched notes have high frequencies.
4. The highest pitch decreases with age.
5. A decibel is a measure of sound intensity.
6. Zero decibels corresponds to the lowest-intensity of sound we can hear.
7. A sound of 30 dB is 1000 times more intense than the threshold of hearing.
8. Loudness is more subjective.
9. The loudest sounds we can tolerate have intensities a trillion times greater than the faintest sounds.
10. The fundamental frequency is the lowest pitch of a note.
11. The frequency of the second harmonic is twice, or 400 Hz.
12. The frequency of the third harmonic is three times, or 600 Hz.
13. Musical quality is determined by the variety of partial tones.
14. The different sounds are the result of different partial tones.
15. The three classes are vibrating strings, vibrating air columns, and percussion.
16. Stringed instruments have lower efficiency at producing sound so must be more numerous to balance fewer and louder wind instruments.
17. Fourier discovered that complex waves can be disassembled into simple sine waves that add together.
18. The purpose of the extended range is to better approximate the original sound.
19. Phonographs captured sound by analog, CDs by digital.
20. Blue light is of a higher frequency and shorter wavelength, which means more information can fit in the same-sized space, which means higher resolution.

Think and Do

21. First find a clock that ticks!

22. And what is your range if you should be a singer?

23. This activity can be interesting!

Think and Solve

24. For the highest frequencies, $\lambda = v/f$ = (340 m/s)/(20,000 Hz) = 0.017 m or 17 mm. For the lowest frequencies, $\lambda = v/f$ = (340 m/s)/(20 Hz) = 17 m.

25. Period = $1/f$ = 1/440 second (0.0023 s, or 2.3 ms).

26. Period = $1/f$ = 1/264 second (0.0038 s, or 3.8 ms).

27. The decibel scale is based upon powers of 10. The ear responds to sound intensity in logarithmic fashion. Each time the intensity of sound is made 10 times larger, the intensity level in decibels increases by 10 units. So a sound of
    (a) 10 dB is ten times more intense than the threshold of hearing.
    (b) 30 dB is one thousand times more intense than the threshold of hearing.
    (c) 60 dB is one million times more intense than the threshold of hearing.

28. Sound at 40 dB is 10 thousand times more intense (each *additive* increment of 10 dB corresponds to a *factor* 10 in intensity).

29. A sound of 40 dB is ten times as intense as a sound of 30 dB.

30. One octave above 1000 Hz is 2000 Hz, and two octaves above 1000 Hz is 4000 Hz. One octave below 1000 Hz is 500 Hz, and two octaves below 1000 Hz is 250 Hz.

31. The second harmonic is the first octave (twice the fundamental frequency) and the fourth harmonic is the second octave (four times the fundamental frequency), so there is one harmonic, the third, between the first and second octaves. The third octave, with a frequency eight times the frequency of the fundamental, is the same as the eighth harmonic, so there are three harmonics (the fifth, sixth, and seventh) between the second and third octaves. (You can also get the answers by thinking about

wavelengths. The second harmonic has half the wavelength of the fundamental, the third harmonic has one-third the wavelength, the fifth harmonic has one-fifth the wavelength, and so on. The wavelengths of the octaves are one-half, one-fourth, one-eighth, and so on, so they correspond to the second, fourth, eighth, and so on harmonics.)

Think and Rank

32. a. C, B, A
    b. C, B, A
    c. A, B, C

33. A, C, B

Think and Explain

34. Agree, for pitch is the subjective form of frequency.

35. Higher pitch means higher frequency.

36. Agree.

37. The strings warm up and expand during play. Hence they should be tuned while warm so re-tuning is minimized while on stage.

38. Amplitude likely increases.

39. A low pitch will be produced when a guitar string is (a) lengthened, (b) loosened so that tension is reduced, and (c) made more massive, usually by windings of wire around the string. That's why bass strings are thick—more inertia.

40. Pitch depends on frequency. It does not depend on loudness or quality.

41. The frequencies of the sound and the oscillating string are the same.

42. Different strings have different mass and different tension. For a single string, a finger can change the length of vibrating part.

43. If the wavelength of a vibrating string is reduced, such as by pressing it with your finger against a fret, the frequency of the vibration increases. This is heard as an increased pitch.

44. The wavelength is the length of two loops, 60 cm.

45. The longer tines have greater rotational inertia, which means they'll be more resistant to vibrating, and will do so at lower frequency.

46. The greater mass increases the inertia of the string, which decreases the frequency at which it will vibrate.

47. The thinner string has less mass and less inertia, and therefore a higher frequency.

48. The sounding board of the guitar presents more area of vibration, which produces louder sound. With no sounding board on the work bench, the sound is not as loud.

49. A plucked guitar string would vibrate for a longer time without a sounding board because less air is set into motion per unit of time, which means the energy of the vibrating string decreases more slowly.

50. The fundamental for a string occurs when only two nodes exist; one at each end of the string, so that it vibrates in one segment. By touching the midpoint, a third node is imposed there and the string vibrates in two segments. The wavelength is diminished by one-half, so the frequency increases by two. (Note the speed of the wave along the string doesn't change; speed = frequency x wavelength.)

51. In addition to pieces of paper at the supporting ends of the string, when a string vibrates in two segments a piece may be placed at the node in its center. For three segments, two pieces can be supported, each one third the total distance from each end.

52. Both produce different quality sounds because of different intensity overtones.

53. The amplitude in a sound wave corresponds to the overpressure of the compression or equivalently the underpressure of the rarefaction.

54. The pattern shown to the left has the higher frequency and therefore the higher pitch.

55. The pattern on the right has the greater amplitude and is therefore louder.

56. The lower pitch is produced by longer standing waves set up in longer straws. Likewise for the long larger pipes behind Tom. Lower pitches for both.

57. Sound intensity is a purely objective and physical attribute of a sound wave and can be measured by various acoustical instruments. Loudness, though closely related, is a physiological sensation, and can vary from person to person or for one person at different times.

58. The person with the more acute hearing is the one who can hear the faintest sounds—the one who can hear 5 dB.

59. An electronic organ produces the sounds of various musical instruments by duplicating and superimposing the sine waves that make up the overall waves produced by these instruments.

60. Helium, nitrogen, and oxygen molecules molecules at the same temperature have the same kinetic energies. Kinetic energy equals ½ mv^2. Helium, with its smaller mass is compensated for by a greater speed (Chapter 17).

61. Your voice sounds fuller in a shower principally because of the small enclosure that causes your voice to reverberate as it reflects from wall to wall.

62. The limited range of frequencies transmitted by a telephone can’t match the full range in music. Especially, it cuts off the higher-frequency overtones of music that contribute to its quality.

63. The range of human hearing, from about 20 Hz to about 20,000 Hz, is a factor of about 1000. This is ten octaves because ten doublings of frequency gives a factor of approximately 1000 (1024 to be exact). The range of a piano is a little more than seven octaves.

64. The second harmonic has twice the frequency, 524 Hz.
65. Frequency of second harmonic is twice the fundamental, or 440 Hz. The third is three times the harmonic, or 660 Hz.

66. The first harmonic is the fundamental, which is the same 440 Hz. The second harmonic is twice this, 880 Hz. The third harmonic is three times the first, 3 times 440 = 1320 Hz.

67. Not including endpoints, there are 5 nodes in a standing wave three-wavelengths long, and 7 nodes in a standing wave four-wavelengths long. (Make a drawing and count them!)

68. Although the speed of sound past a listener on a windy day will change, the wavelength also correspondingly changes, resulting in no change in frequency or pitch. Look at it this way: Suppose a friend is placing bottles on a conveyor belt, say at a “frequency” of one each second. Then you, at the other end of the belt, take off one bottle each second. Now suppose your friend increases the speed of the belt, but still places one bottle on each second. Can you see that the bottles (farther apart now) will still arrive to you at the rate of one per second?

69. A Fourier analyzer is a device that sorts out the individual sine waves from a mixture of two or more sine waves, which is just what the human ear does. You hear the pure tones that make up a complex tone.

70. Blue light is higher-frequency light, with shorter waves that allow closer spacing of the pits.

71. Open-ended.

Think and Discuss

72. The sound of commercials is concentrated at frequencies to which the ear is most sensitive. Whereas the overall sound meets regulations, our ears perceive the sound as distinctly louder.

73. The length of a flute is crucial to the notes it plays. Expansion or contraction of the flute with temperature can change its pitch, and therefore change the tuning between the instruments.

74. Agree, for your friend is correct.

75. When the piano string is struck it will oscillate not only in its fundamental mode of 220 Hz when tuned, but also in its second harmonic at 440 Hz. If the string is out of tune, this second harmonic will beat against the 440 Hz tuning fork. You tune the string by listening for those beats and then either tightening or loosening the string until the beating disappears.

76. By controlling how hard he blows and how he holds his mouth, the bugler can stimulate different harmonics. The notes you hear from a bugle are actually harmonics; you don't hear the fundamental.

77. We each perceive what we have been taught or have learned to perceive. This applies to our appreciation of art, our taste for food, and drink, and to the value we give to that which we smell, and to the textures we touch. Our perception of what is real in terms of religious beliefs, political beliefs, and our notions about where we fit in the scheme of things, is a product of what we have learned (or have not learned).

78. The likelihood is high that you subject yourself to louder sounds than your grandparents experienced—particularly via earphones.