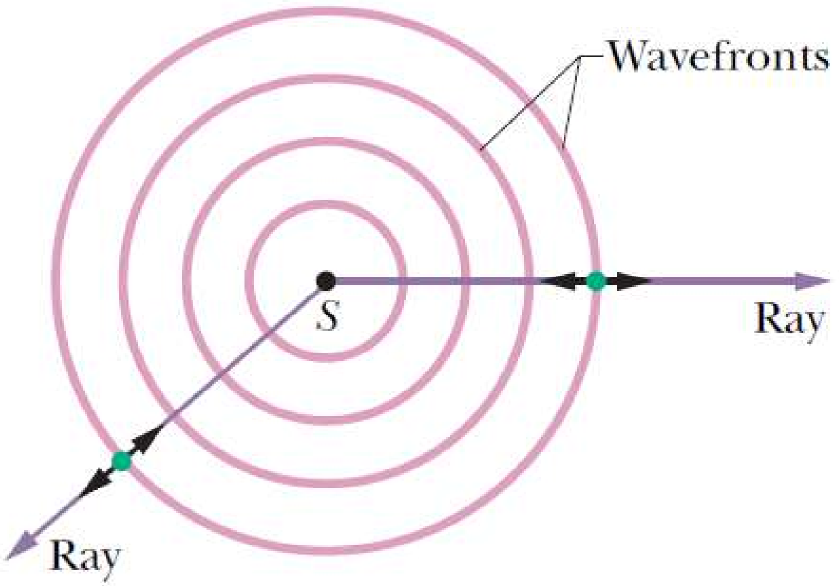
GPN1-U11

17-2 | Sound Waves



the wavefronts are spherical and spread out in three dimensions, and there the waves are said to be *spherical.* As the wavefronts move outward and their radii become larger, their curvature decreases. Far from the source, we approximate the wavefronts as planes (or lines on two-dimensional drawings), and the waves are said to be *planar.* ***Plane wave(平面波).***

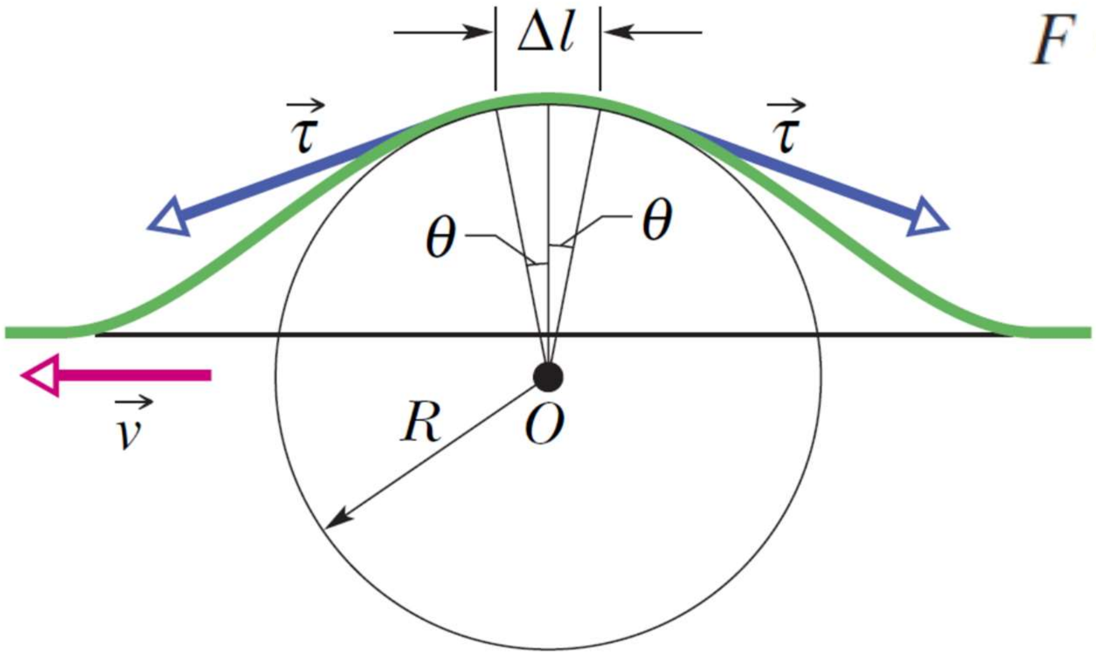
17-3 | The Speed of Sound

$$v = \sqrt{\frac{\tau}{\mu}} = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}},$$

$$v = \sqrt{\frac{B}{\rho}} \qquad B = -\frac{\Delta p}{\Delta V/V}$$

bulk modulus 體積彈性係數

Medium	Speed (m/s)
Gases	
Air (0°C)	331
Air (20°C)	343
Helium	965
Hydrogen	1284
Liquids	
Water (0°C)	1402
Water (20°C)	1482
Seawater[b]	1522
Solids	
Aluminum	6420
Steel	5941
Granite	6000



$$F = 2(\tau \sin \theta) \approx \tau(2\theta) = \tau \frac{\Delta l}{R}$$

$$2\theta = \Delta l / R.$$

$$\Delta m = \mu \, \Delta l \qquad a = \frac{v^2}{R}$$

$$\frac{\tau \, \Delta l}{R} = (\mu \, \Delta l) \frac{v^2}{R}.$$

$$v = \sqrt{\frac{\tau}{\mu}}$$

The speed of a wave along a stretched ideal string depends only on the tension and linear density of the string and not on the frequency of the wave.

波沿拉伸的理想弦的速度僅取決於弦的張力和線密度，而不取決於波的頻率。

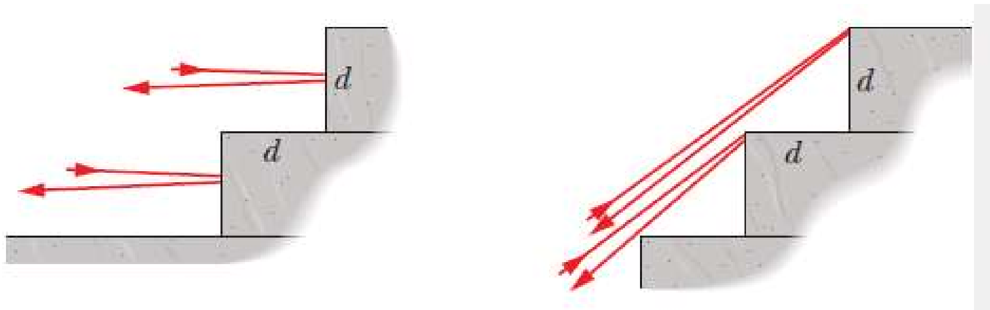
a pyramid in the Mayan ruins at Chichen Itza, Mexico

https://www.youtube.com/watch?v=UwvEoPgYA0o

When a sound pulse, as from a handclap, is produced at the foot of the stairs at the Mayan pyramid, the sound waves reflect from the steps in succession, the closest (lowest) one first and the farthest (highest) one last. The depth and height of the steps are d=0.263 m, and the speed of sound is 343 m/s. The paths taken by the sound waves to and from the steps near the bottom of the stairs are approximately horizontal. The slanted paths taken by the sound waves to and from the steps near the top are approximately 45° to the horizontal. At what frequency f_{bot} do the echo pulses arrive at the listener from the bottom steps? At what frequency f_{top} do they arrive from the top steps a short time later?

瑪雅金字塔的樓梯腳下產生來自拍手的聲音脈衝時，聲波會連續從台階反射，最接近（最低）的最先，最遠的（ 最高）最後一個台階的深度和高度為 d=0.263 m，聲速為 343 m/s。 聲波進出樓梯底部附近的台階所經過的路徑大致是水平的。 聲波進出靠近頂部的台階所經過的傾斜路徑與水平面成大約 45°。 迴聲脈衝以什麼頻率 f_{bot} 從底部階梯到達聽者？ 它們在短時間內從頂部台階到達的頻率 f_{top} 是多少？

$$\Delta t_{bot} = \frac{L}{v} = \frac{2d}{v} = \frac{2(0.263\ \text{m})}{343\ \text{m/s}} = 1.533 \times 10^{-3}\ \text{s}.$$



$$f_{bot} = \frac{1}{\Delta t_{bot}} = \frac{1}{1.533 \times 10^{-3}\ \text{s}} = 652\ \text{Hz}.$$

$$\Delta t_{top} = \frac{L}{v} = \frac{2\sqrt{2}d}{v} = \frac{2\sqrt{2}(0.263\ \text{m})}{343\ \text{m/s}} = 2.168 \times 10^{-3}\ \text{s},$$

$$f_{top} = \frac{1}{\Delta t_{top}} = \frac{1}{2.168 \times 10^{-3}\ \text{s}} = 461\ \text{Hz}.$$

17-4 | Traveling Sound Waves

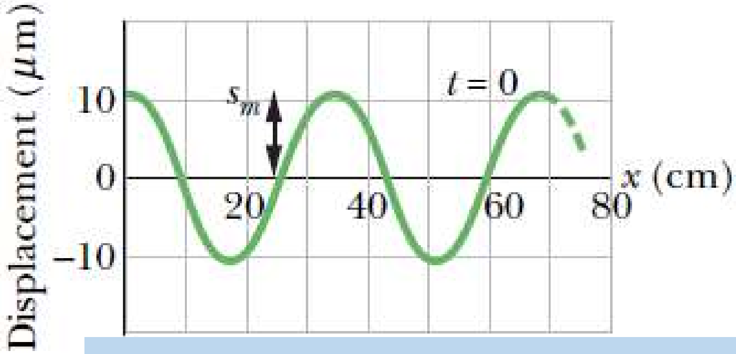
As the wave moves, the air pressure at any position x

$$s(x,t) = s_m \cos(kx - \omega t).$$

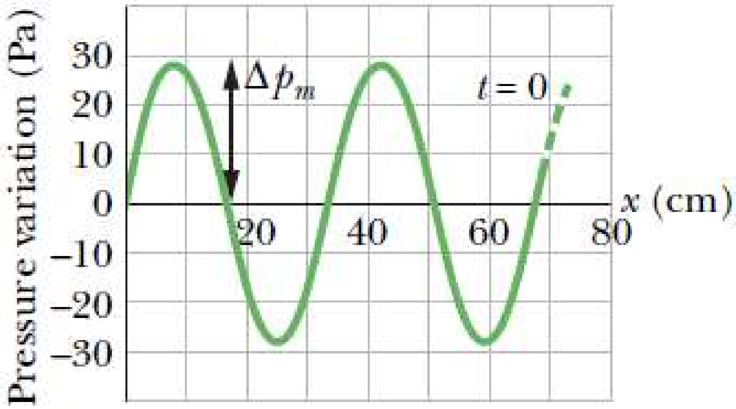
Δp_m is the **pressure amplitude,**

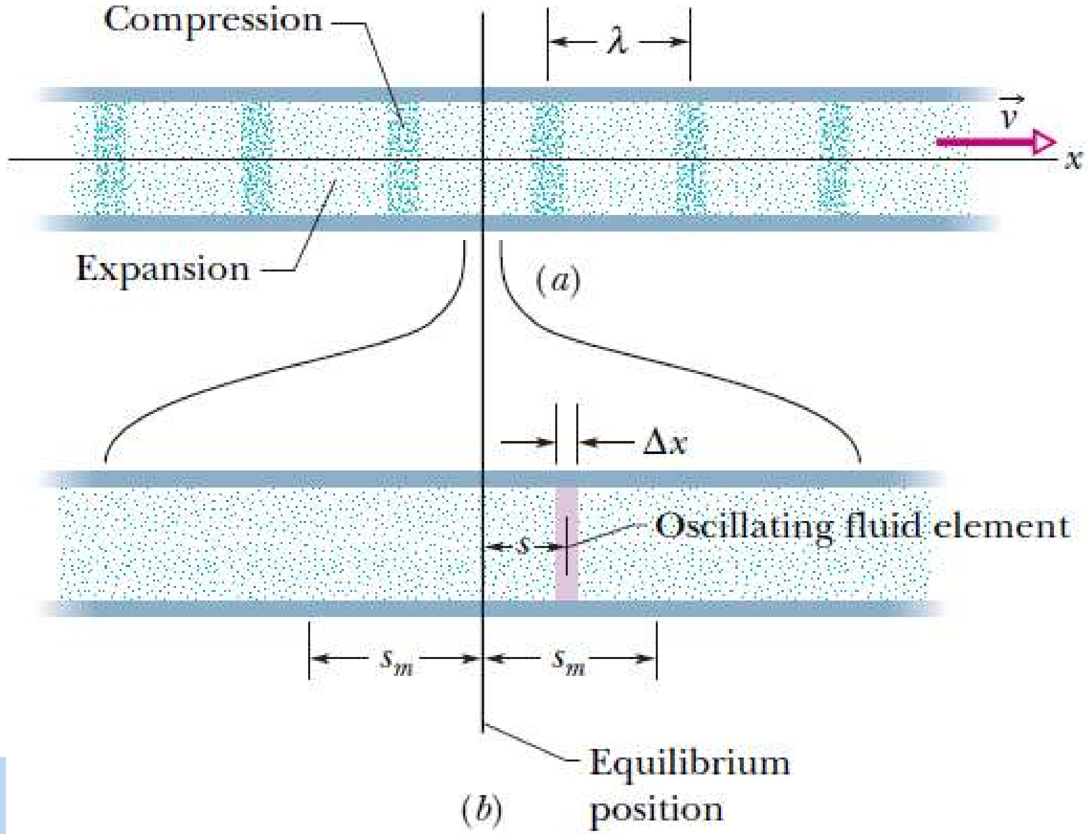
$$\Delta p(x,t) = \Delta p_m \sin(kx - \omega t).$$

$$\Delta p_m = (v\rho\omega)s_m.$$



The displacement and pressure variation are 90° out of phase.





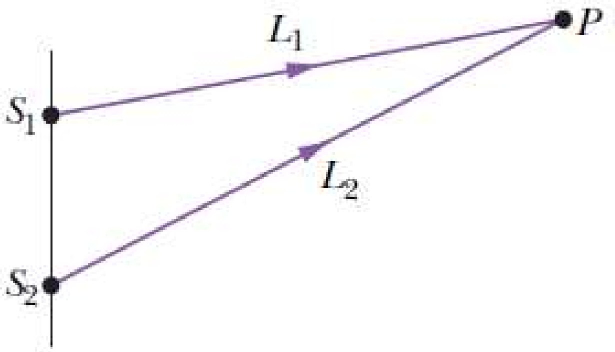
$$\Delta p = -B\frac{\Delta s}{\Delta x} = -B\frac{\partial s}{\partial x}.$$

$$\frac{\partial s}{\partial x} = \frac{\partial}{\partial x}[s_m \cos(kx - \omega t)] = -ks_m \sin(kx - \omega t).$$

$$\Delta p(x,t) = \Delta p_m \sin(kx - \omega t).$$

$$\Delta p_m = (v\rho\omega)s_m.$$

17-5 | Interference



path length difference $\Delta L = |L_2 - L_1|$.

$$\frac{\phi}{2\pi} = \frac{\Delta L}{\lambda},$$

$$\phi = \frac{\Delta L}{\lambda} 2\pi.$$

Fully constructive interference occurs

$$\phi = m(2\pi), \qquad \text{for } m = 0, 1, 2$$

$$\frac{\Delta L}{\lambda} = 0, 1, 2, \ldots$$

Fully destructive interference occurs when

ϕ is an odd multiple of π .

$$\phi = (2m + 1)\pi, \qquad \text{for } m = 0, 1, 2, \ldots$$

$$\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5, \ldots$$

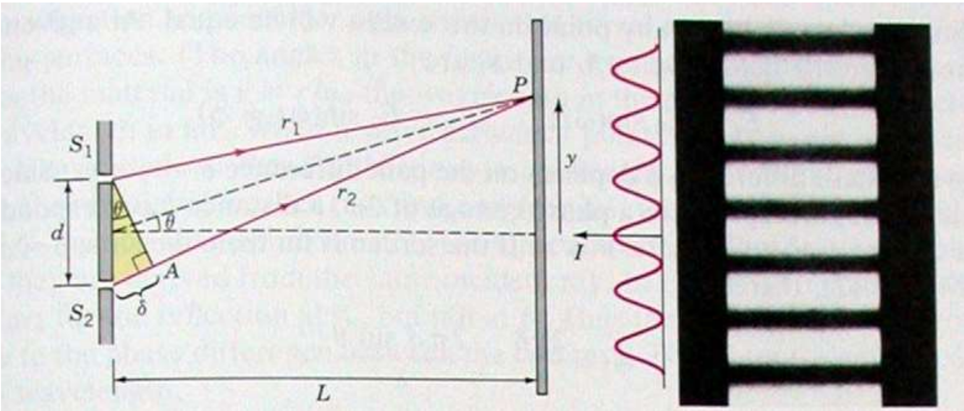
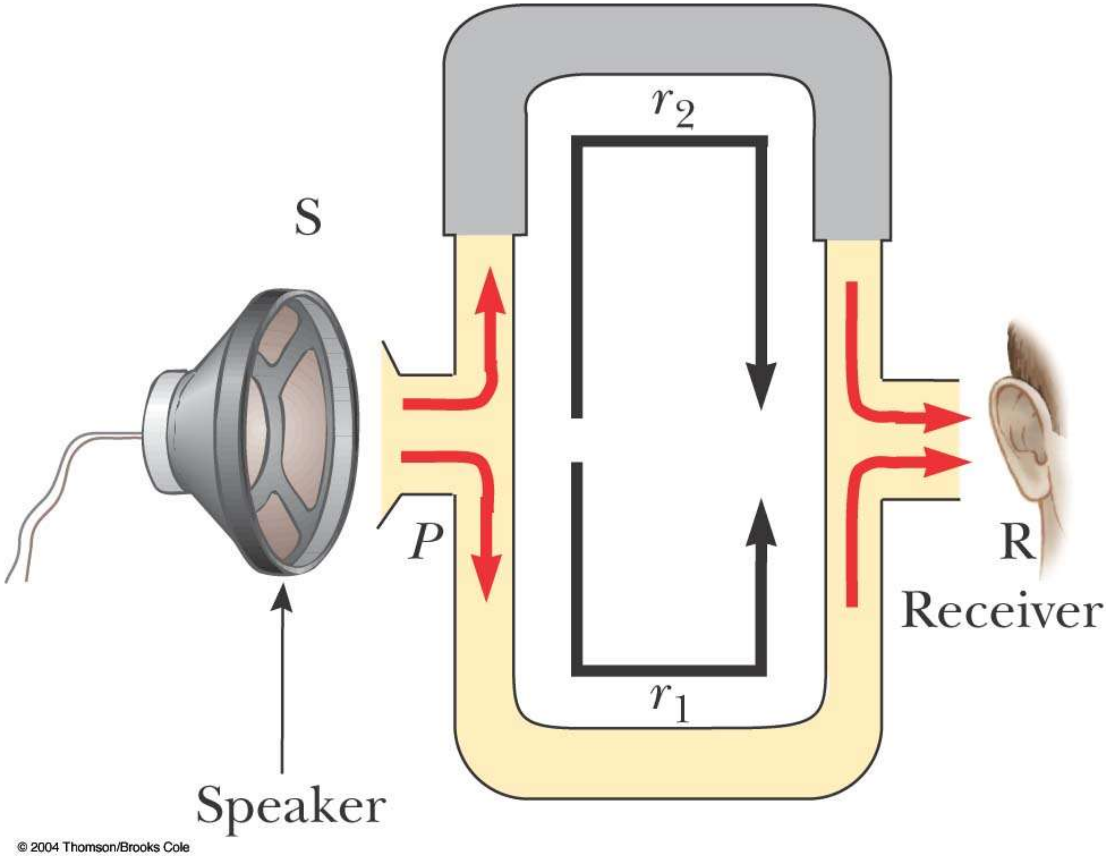
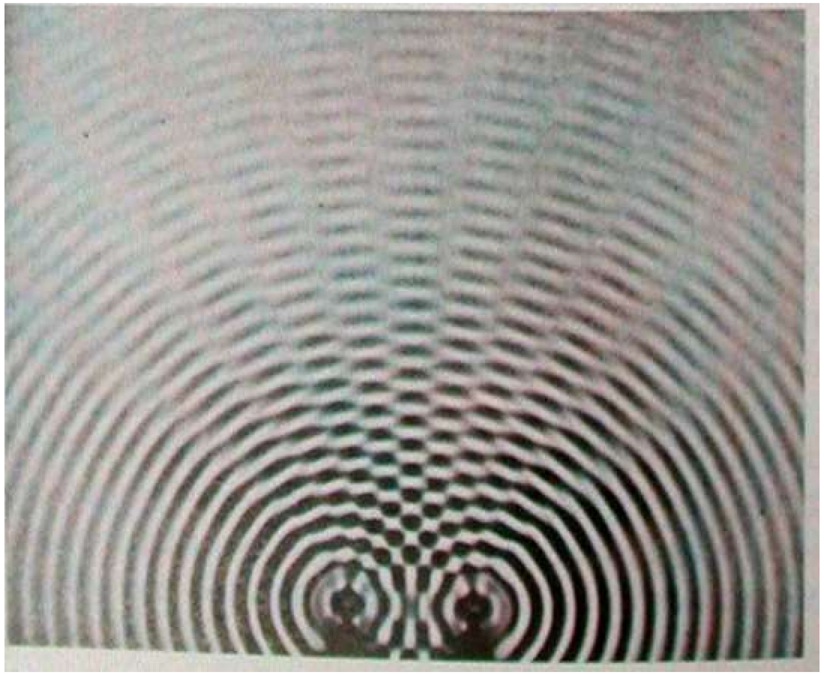


FIGURE 37.9 Thomas Young (1773–1829).



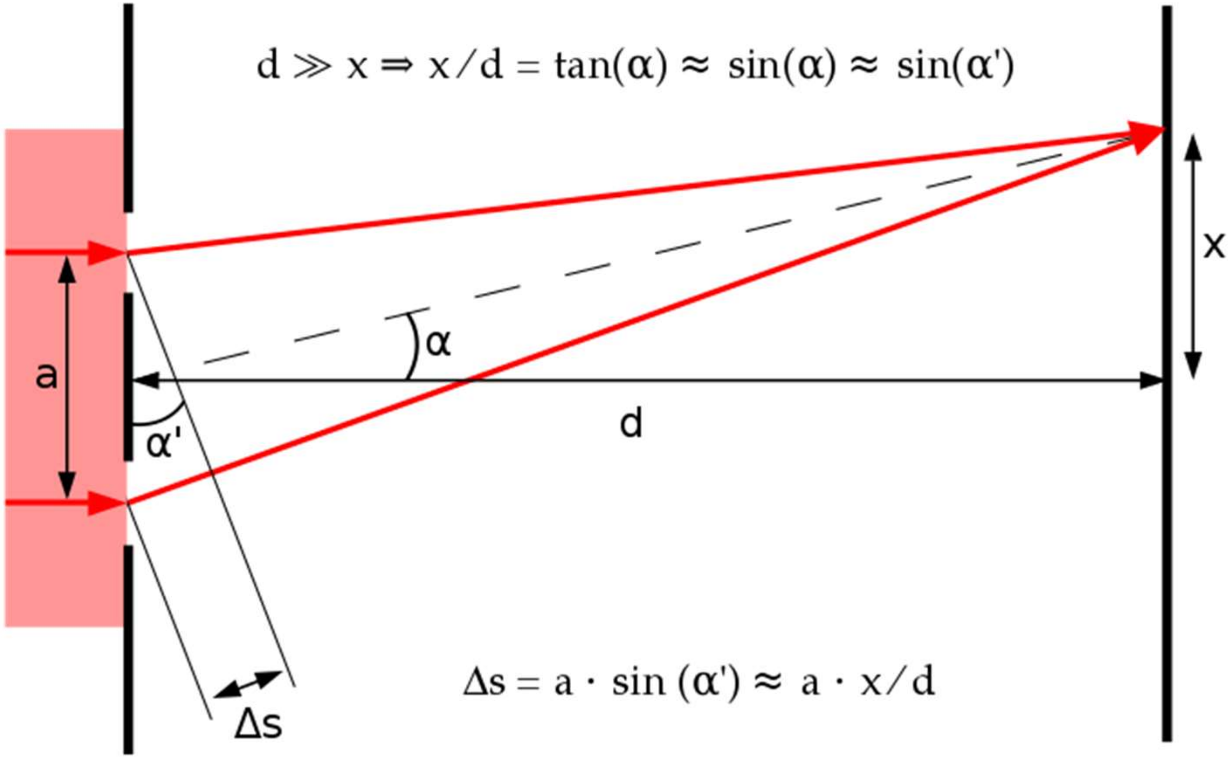


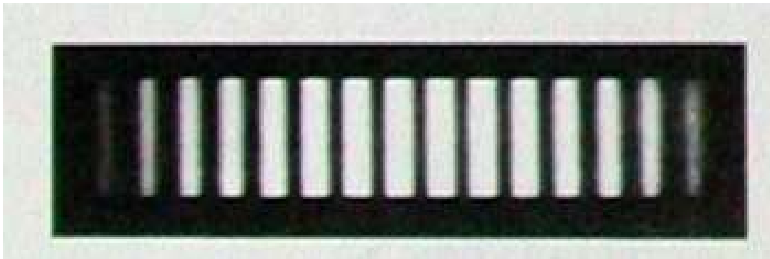
水波槽中兩個波源的干涉現象
造成黑白相間的條紋。

藉由改變r2的行進路徑長度，耳朵
將會聽到因為干涉現象而造成聲音
的強弱變化。

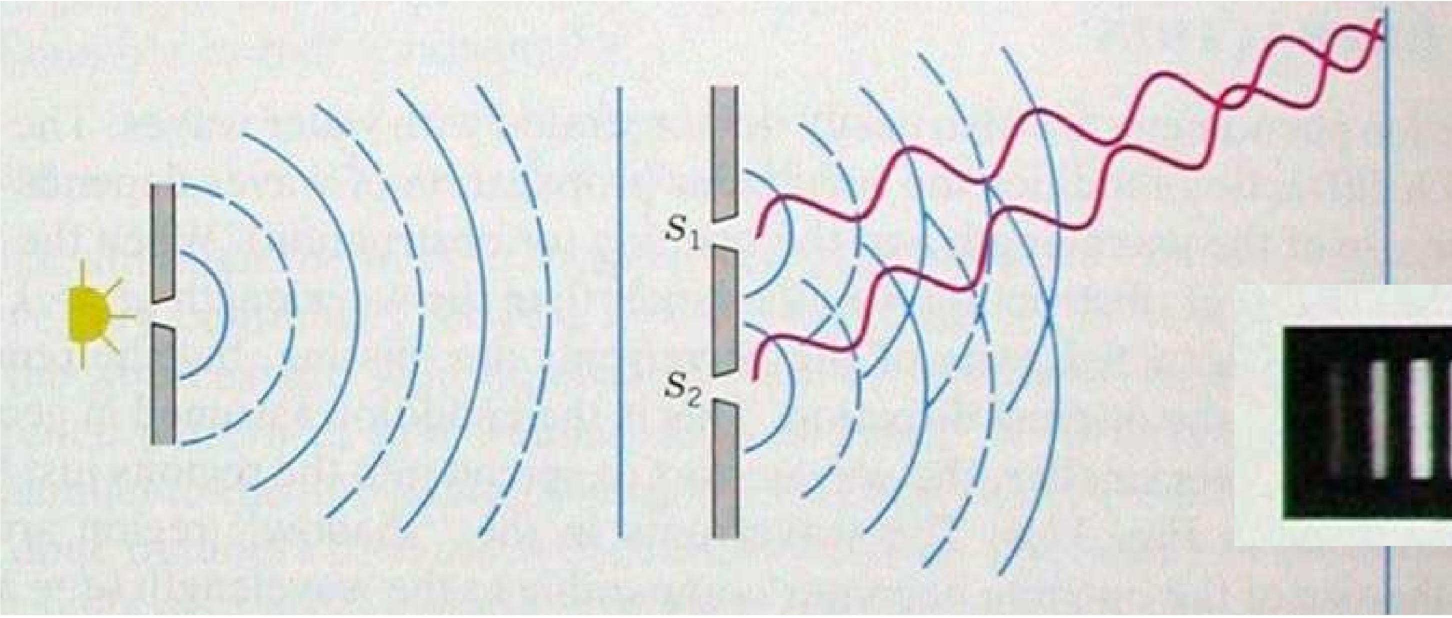
英國物理學者托馬斯·楊(Thmoas Young)於1801年做實驗演示光的干涉演示，稱為楊氏雙縫實驗。這實驗對於光波動說給出有力支持，由於實驗觀測到的干涉條紋是艾薩克·牛頓所代表的光微粒說無法解釋的現象，雙縫實驗使大多數的物理學家從此逐漸接受了光波動說。

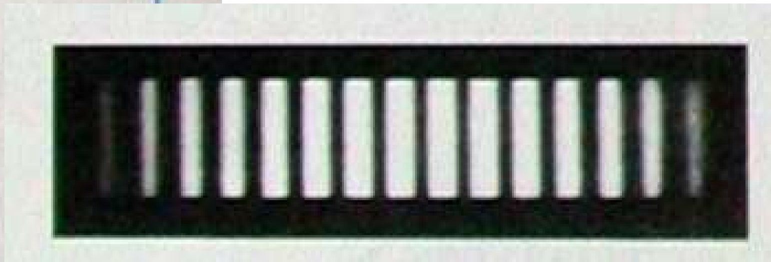
FIGURE 37.9 Thomas Young (1773–1829).

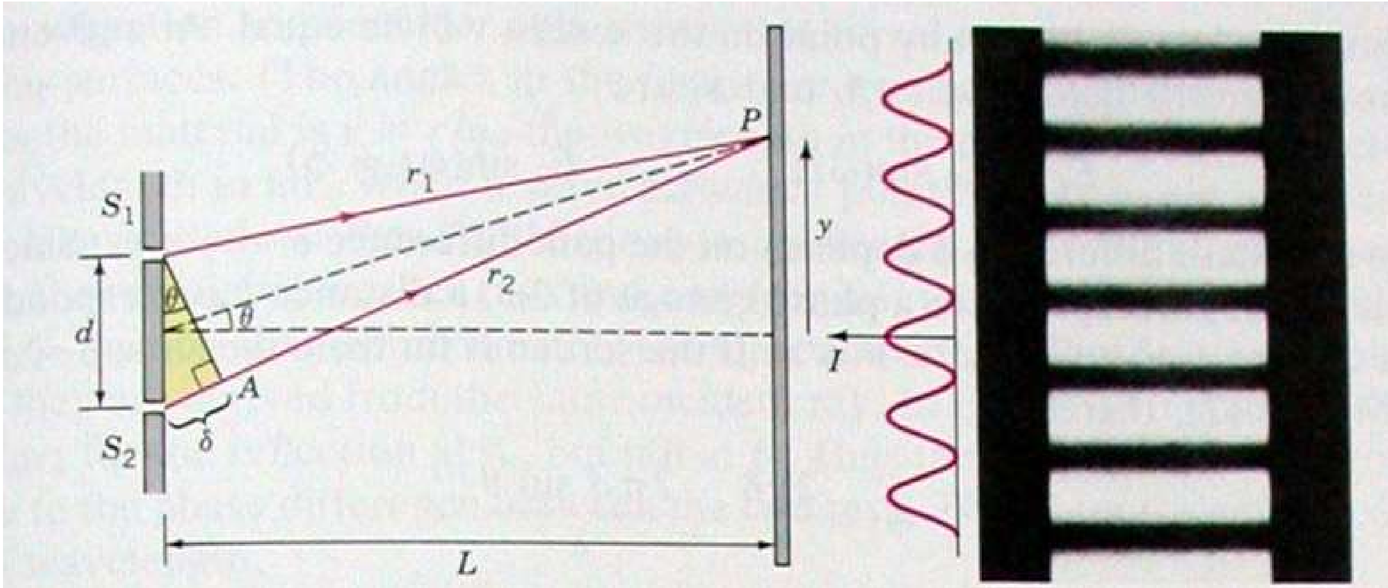




Thomas Young
的雙狹縫實驗





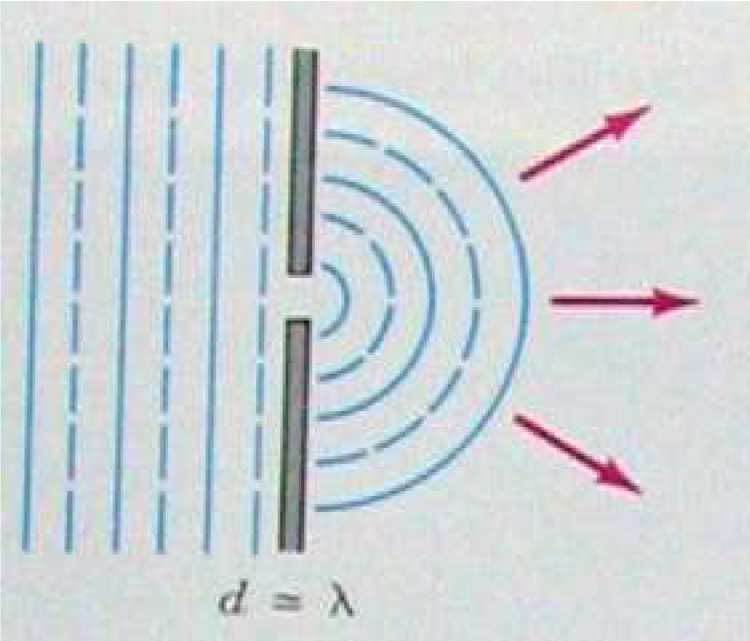


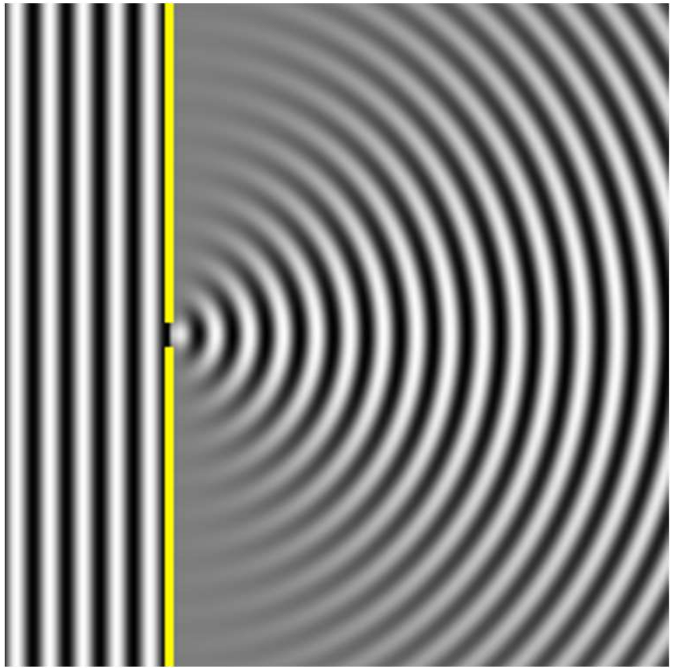
$$d \sin \theta = m\lambda$$

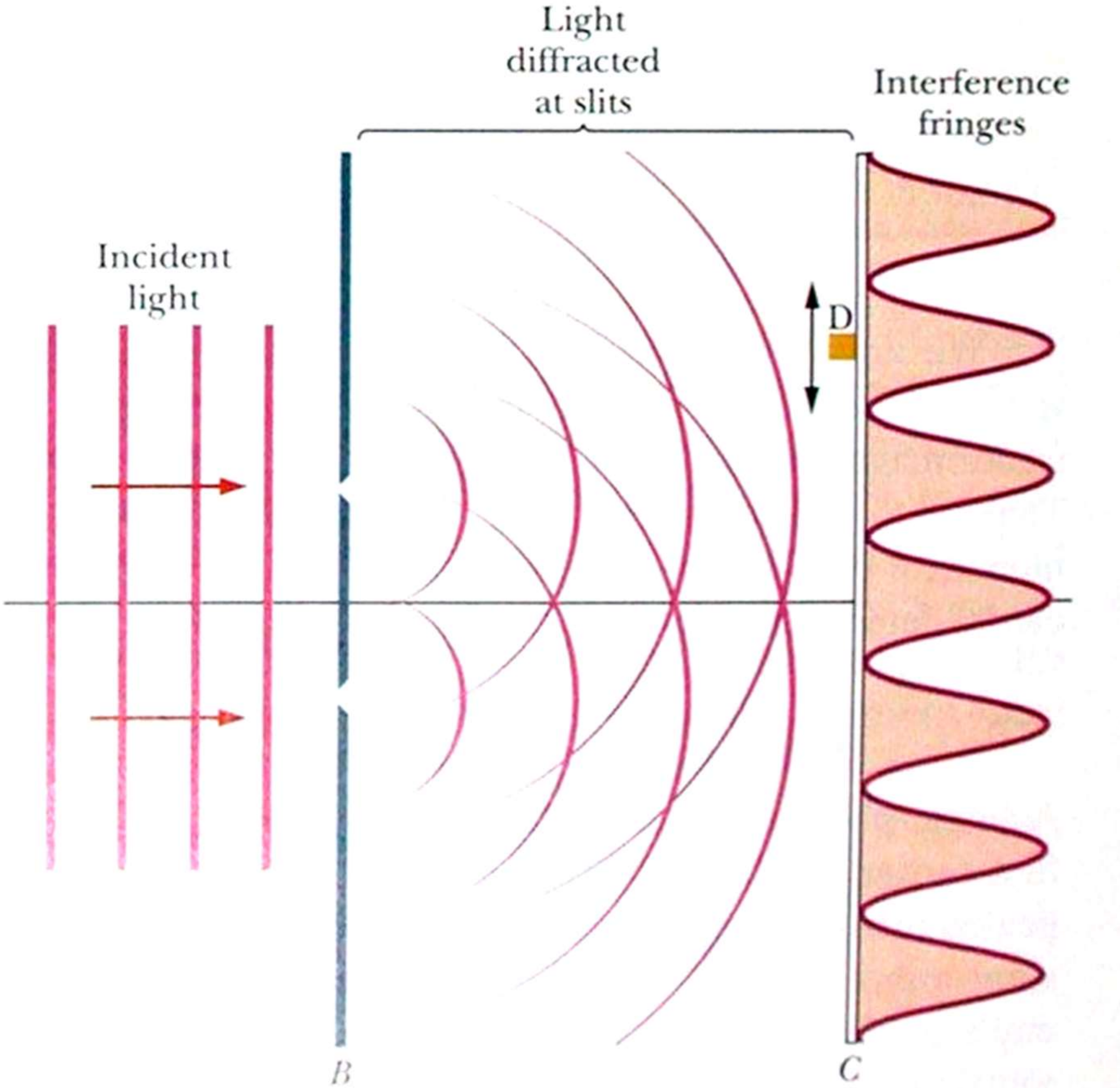
$$d \sin \theta = \left(m + \frac{1}{2}\right) \lambda$$

波的繞射現象

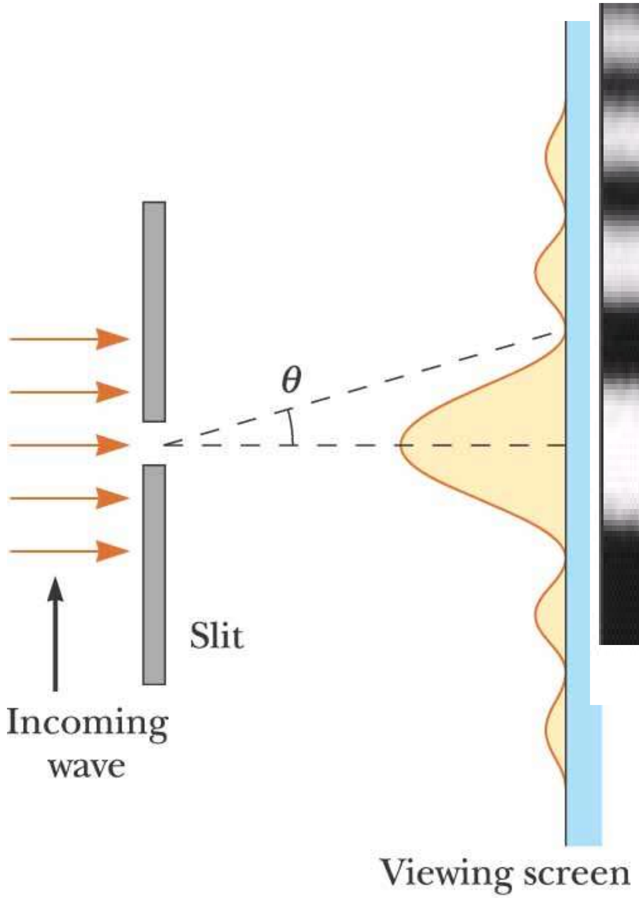
光的波動性



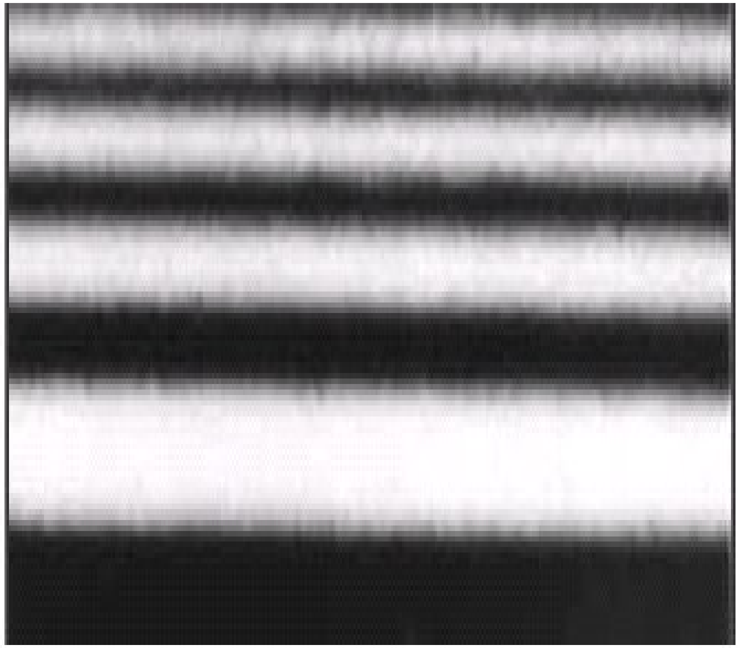


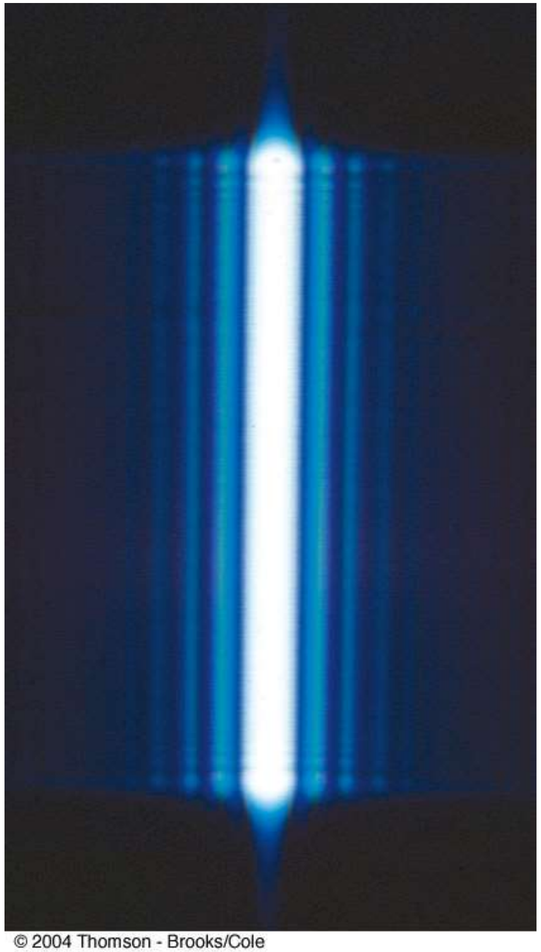


光的單狹縫繞射實驗



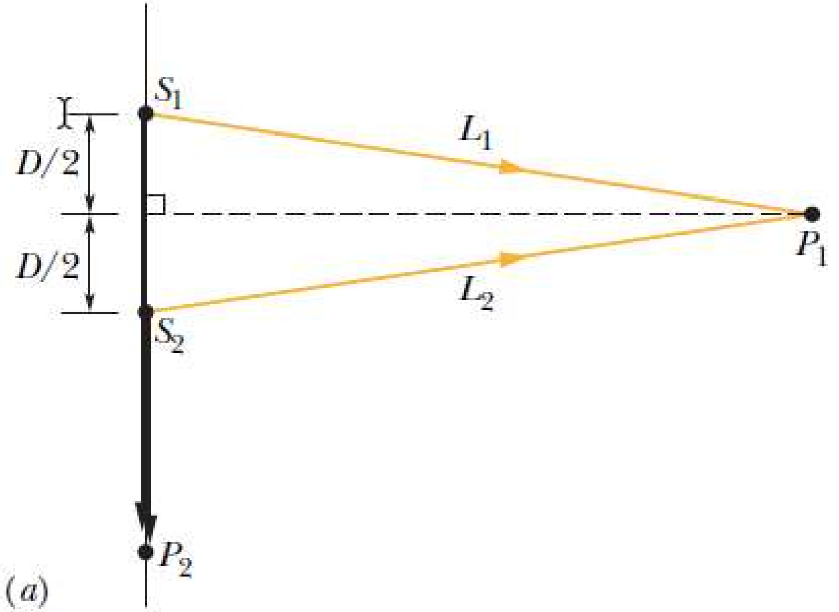
(a)





Sample Problem 17-3 Build your skill

In Fig. 17-9*a*, two point sources S_1 and S_2, which are in phase and separated by distance $D = 1.5\lambda$, emit identical sound waves of wavelength λ.



(*a*)

(a) What is the path length difference of the waves from S_1 and S_2 at point P_1, which lies on the perpendicular bisector of distance D, at a distance greater than D from the sources? What type of interference occurs at P_1?

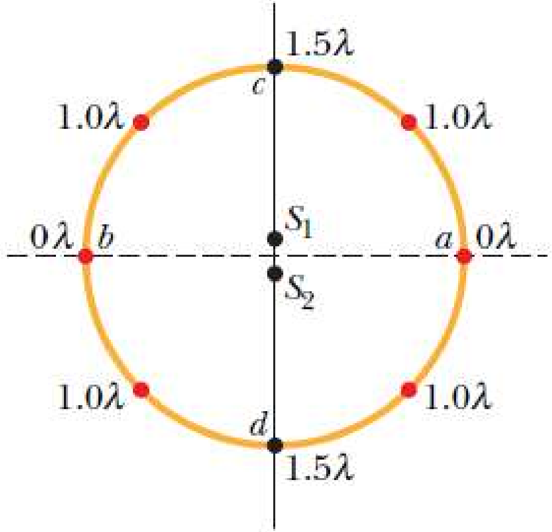
Reasoning: Because the waves travel identical distances to reach P_1, their path length difference is

$$\Delta L = 0. \quad \text{(Answer)}$$

(b) What are the path length difference and type of interference at point P_2 in Fig. 17-9*a*?

$$\Delta L = 1.5\lambda.$$

the waves are exactly out of phase at P_2 and undergo fully destructive interference there.



(*b*)

(c) Figure 17-9*b* shows a circle with a radius much greater than D, centered on the midpoint between sources S_1 and S_2. What is the number of points N around this circle at which the interference is fully constructive?

there must be one point along the circle between *a* and *d* at which $\Delta L = \lambda$,

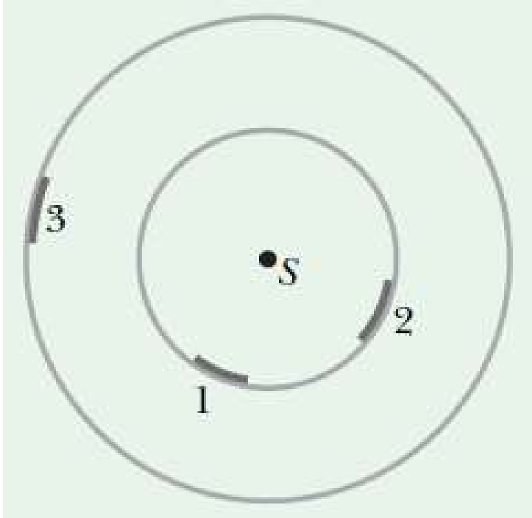
$$N = 6.$$

17-6 | Intensity and Sound Level

The **intensity** I of a sound wave at a surface is the average rate per unit area at which energy is transferred by the wave through or onto the surface

$$I = \frac{P}{A},$$

$$I = \tfrac{1}{2}\rho v \omega^2 s_m^2.$$



$$dK = \tfrac{1}{2}\,dm\,v_s^2.$$

$$v_s = \frac{\partial s}{\partial t} = -\omega s_m \sin(kx - \omega t).$$

$$dm = \rho A\,dx$$

$$dK = \tfrac{1}{2}(\rho A\,dx)(-\omega s_m)^2 \sin^2(kx - \omega t).$$

$$\frac{dK}{dt} = \tfrac{1}{2}\rho A v \omega^2 s_m^2 \sin^2(kx - \omega t).$$

$$\left(\frac{dK}{dt}\right)_{avg} = \tfrac{1}{2}\rho A v \omega^2 s_m^2 [\sin^2(kx - \omega t)]_{avg} = \tfrac{1}{4}\rho A v \omega^2 s_m^2.$$

$$I = \frac{2(dK/dt)_{avg}}{A} = \tfrac{1}{2}\rho v \omega^2 s_m^2,$$

$$P_{avg} = 2\left(\frac{dK}{dt}\right)_{avg} = \tfrac{1}{2}\mu v \omega^2 y_m^2$$

The Decibel Scale

$$I = \frac{P_s}{4\pi r^2},$$

sound level ,

$$\beta = (10\text{ dB}) \log \frac{I}{I_0}.$$

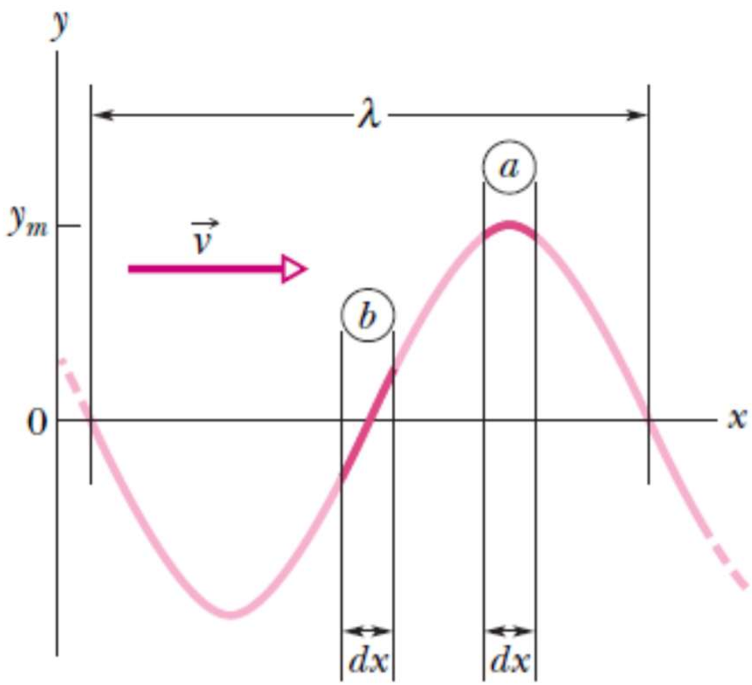
$$I_0 = 10^{-12}\text{ W/m}^2$$

dB is the abbreviation for **decibel**

Some Sound Levels (dB)

Hearing threshold	0
Rustle of leaves	10
Conversation	60
Rock concert	110
Pain threshold	120
Jet engine	130

Energy and Power of a Wave Traveling



a string element of mass dm $\qquad dm = \mu\, dx,$

$$dK = \tfrac{1}{2}\, dm\, u^2,$$

u is the transverse speed of the oscillating string element.

$$u = \frac{\partial y}{\partial t} = -\omega y_m \cos(kx - \omega t).$$

$$dK = \tfrac{1}{2}(\mu\, dx)(-\omega y_m)^2 \cos^2(kx - \omega t).$$

$$\frac{dK}{dt} = \tfrac{1}{2}\mu v \omega^2 y_m^2 \cos^2(kx - \omega t). \qquad dx/dt = v$$

the average value of the square of a cosine function over an integer number of periods is 1/2.

$$\left(\frac{dK}{dt}\right)_{avg} = \tfrac{1}{2}\mu v \omega^2 y_m^2 \,[\cos^2(kx - \omega t)]_{avg} = \tfrac{1}{4}\mu v \omega^2 y_m^2.$$

$$\frac{1}{T}\int_0^T \cos^2\frac{t}{T}\, dt$$

$2\cos^2 x - 1 = \cos 2x$

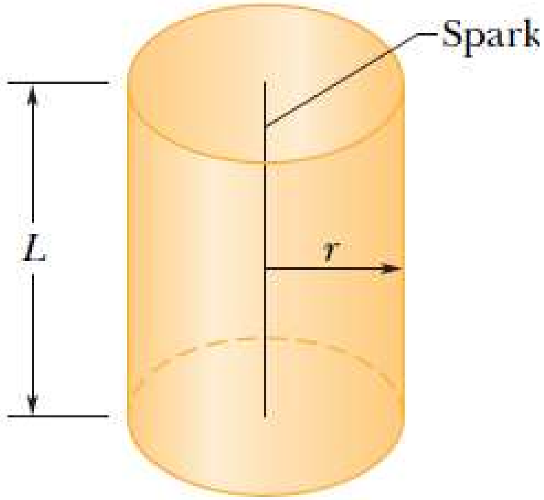
$\cos^2 x = \frac{1}{2}(\cos 2x + 1)$

$$= \frac{1}{T}\int_0^T \frac{1}{2}\left(\cos\frac{2t}{T} + 1\right)dt = \frac{1}{T}\left(\frac{T}{2}\right) = \frac{1}{2}$$

The **average power,** the average rate at which energy of both K and U.

$$P_{avg} = 2\left(\frac{dK}{dt}\right)_{avg} = \tfrac{1}{2}\mu v \omega^2 y_m^2$$

Sample Problem 17-4



An electric spark jumps along a straight line of length $L = 10$ m, emitting a pulse of sound that travels radially outward from the spark. (The spark is said to be a *line source* of sound.) The power of the emission is $P_s = 1.6 \times 10^4$ W.

(a) What is the intensity I of the sound when it reaches a distance $r = 12$ m from the spark?

$$I = \frac{P}{A} = \frac{P_s}{2\pi r L}.$$

$$I = \frac{1.6 \times 10^4 \text{ W}}{2\pi(12 \text{ m})(10 \text{ m})} = 21.2 \text{ W/m}^2 \approx 21 \text{ W/m}^2.$$

(b) At what time rate P_d is sound energy intercepted by an acoustic detector of area $A_d = 2.0$ cm^2, aimed at the spark and located a distance $r = 12$ m from the spark?

$$I = \frac{P_d}{A_d}.$$

I $(= 21.2 \text{ W/m}^2)$

$$P_d = (21.2 \text{ W/m}^2)(2.0 \times 10^{-4} \text{ m}^2) = 4.2 \text{ mW}.$$

If an earplug decreases the sound level of the sound waves by 20 dB, what is the ratio of the final intensity I_f of the waves to their initial intensity I_i?

$$\beta_f = (10\text{ dB})\log\frac{I_f}{I_0},$$

$$\beta_i = (10\text{ dB})\log\frac{I_i}{I_0}.$$

$$\beta_f - \beta_i = (10\text{ dB})\left(\log\frac{I_f}{I_0} - \log\frac{I_i}{I_0}\right).$$

$$\log\frac{a}{b} - \log\frac{c}{d} = \log\frac{ad}{bc},$$

$$\beta_f - \beta_i = (10\text{ dB})\log\frac{I_f}{I_i}.$$

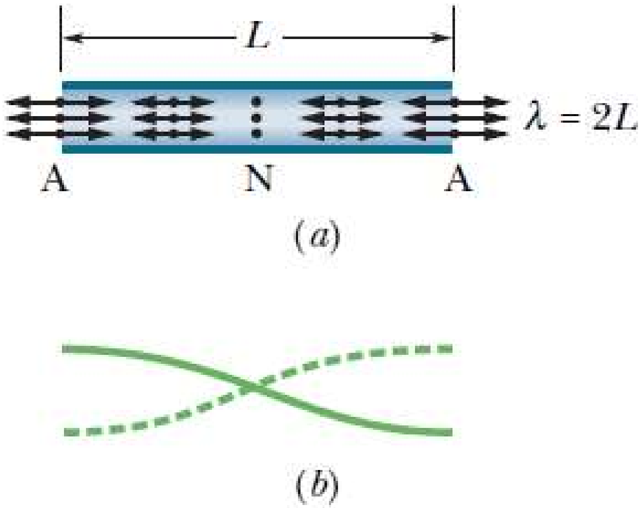
$$\beta_f - \beta_i = -20\text{ dB},$$

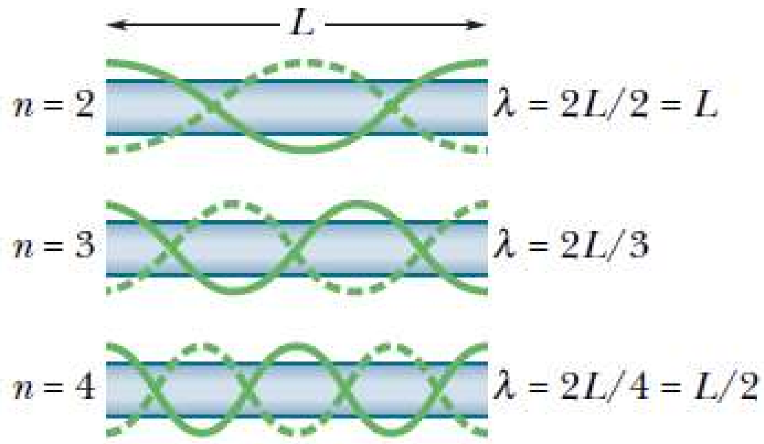
$$\log\frac{I_f}{I_i} = \frac{\beta_f - \beta_i}{10\text{ dB}} = \frac{-20\text{ dB}}{10\text{ dB}} = -2.0.$$

$$\frac{I_f}{I_i} = \log^{-1}(-2.0) = 0.010.$$

17-7 | Sources of Musical Sound

The standing wave pattern of Fig. 17-14*a* is called the *fundamental mode* or *first harmonic*. For it to be set up, the sound waves in a pipe of length L must have a wavelength given by L $\lambda/2$, so that $\lambda = 2L$. Several more standing sound wave patterns for a pipe with two open ends are shown in Fig. 17-15*a* using string wave representations. The *second harmonic* requires sound waves ofwavelength L, the *third harmonic* requires wavelength $2L/3$, and so on.



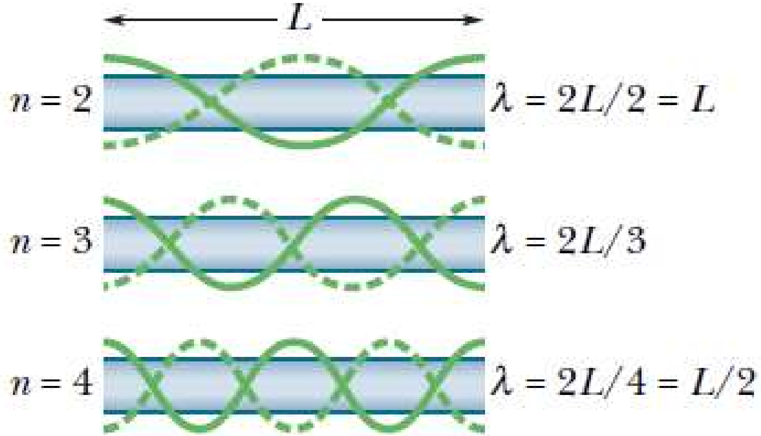


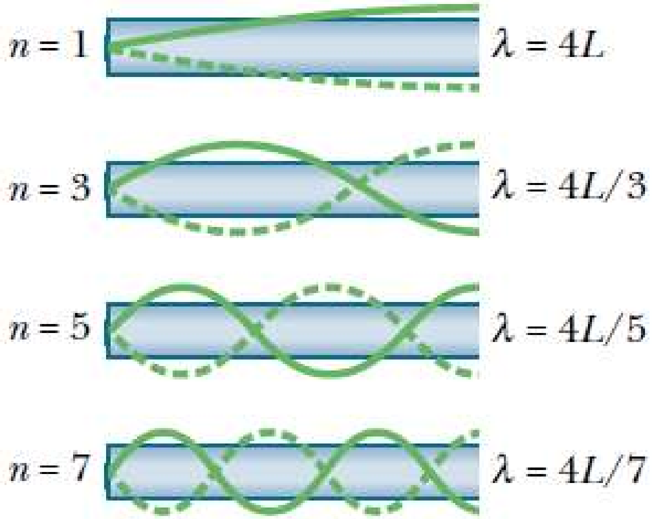
for a pipe with two open ends

$$\lambda = \frac{2L}{n}, \qquad \text{for } n = 1, 2, 3, \ldots,$$

n is called the *harmonic number*

$$f = \frac{v}{\lambda} = \frac{nv}{2L}, \qquad \text{for } n = 1, 2, 3, \ldots$$





for a pipe with two open ends

$$\lambda = \frac{2L}{n}, \qquad \text{for } n = 1, 2, 3, \ldots,$$

n is called the *harmonic number*

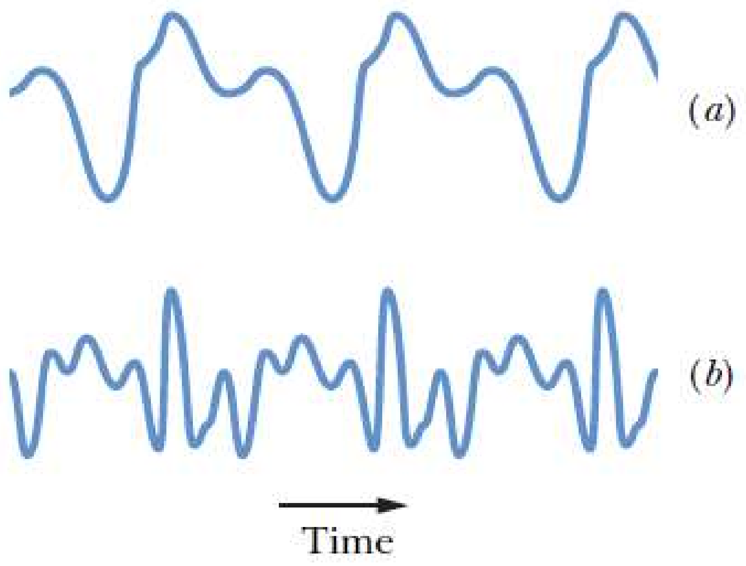
$$f = \frac{v}{\lambda} = \frac{nv}{2L}, \qquad \text{for } n = 1, 2, 3, \ldots$$

(pipe, one open end).

$$\lambda = \frac{4L}{n}, \qquad \text{for } n = 1, 3, 5, \ldots,$$

$$f = \frac{v}{\lambda} = \frac{nv}{4L}, \qquad \text{for } n = 1, 3, 5, \ldots$$

In any oscillating system that gives rise to a musical sound, whether it is a violin string or the air in an organ pipe, the fundamental and one or more of the higher harmonics are usually generated simultaneously. Thus, you hear them together—that is, superimposed as a net wave. When different instruments are played at the same note, they produce the same fundamental frequency but different intensities for the higher harmonics. For example, the fourth harmonic of middle C might be relatively loud on one instrument and relatively quiet or even missing on another. Thus, because different instruments produce different net waves, they sound different to you even when they are played at the same note. That would be the case for the two net waves shown in Fig. 17-17, which were produced at the same note by different instruments.



The wave forms produced by (*a*) a flute and (*b*) an oboe when played at the same note, with the same first harmonic frequency.

Sample Problem 17-6

Weak background noises from a room set up the fundamental standing wave in a cardboard tube of length $L =$ 67.0 cm with two open ends. Assume that the speed of sound in the air within the tube is 343 m/s.

(a) What frequency do you hear from the tube?

$$f = \frac{nv}{2L} = \frac{(1)(343 \text{ m/s})}{2(0.670 \text{ m})} = 256 \text{ Hz}.$$

(b) If you jam your ear against one end of the tube, what fundamental frequency do you hear from the tube?

$$f = \frac{nv}{4L} = \frac{(1)(343 \text{ m/s})}{4(0.670 \text{ m})} = 128 \text{ Hz}.$$

If the background noises set up any higher harmonics, they will be *odd* multiples of 128 Hz. That means that the frequency of 256 Hz (which is an even multiple) cannot now occur.

17-8 | Beats

If we listen, a few minutes apart, to two sounds whose frequencies are, say, 552 and 564 Hz, most of us cannot tell one from the other. However, if the sounds reach our ears simultaneously, what we hear is a sound whose frequency is 558 Hz, the average of the two combining frequencies. We also hear a striking variation in the intensity of this sound—it increases and decreases in slow, wavering beats that repeat at a frequency of 12 Hz, the difference between the two combining frequencies.

如果我們間隔幾分鐘聆聽頻率分別為 552 和 564 Hz 的兩種聲音，我們大多數人都無法分辨出一種和另一種。 但是，如果聲音同時到達我們的耳朵，我們聽到的是頻率為 558 Hz 的聲音，這是兩個組合頻率的平均值。 我們還聽到了這種聲音強度的顯著變化--它在緩慢、搖擺不定的節拍中增加和減少，以 12 Hz 的頻率重複，這是兩個組合頻率之間的差異。 圖顯示了這種節拍現象。

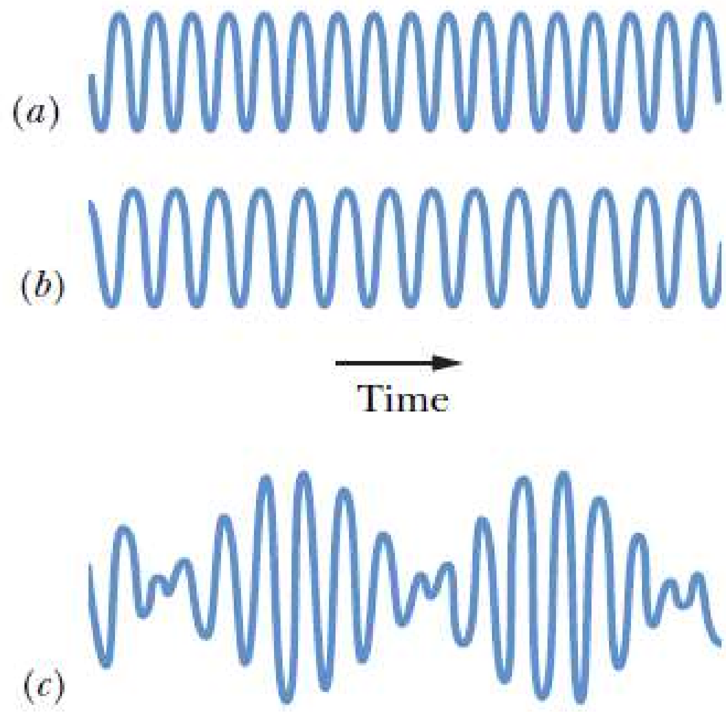
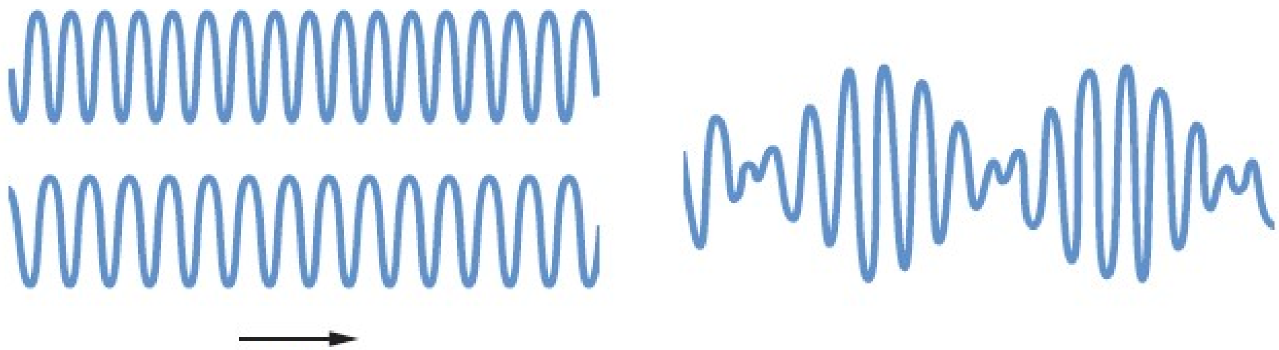


FIG. 17-18 (*a*, *b*) The pressure variations Δp of two sound waves as they would be detected separately. The frequencies of the waves are nearly equal. (*c*) The resultant pressure variation if the two waves are detected simultaneously.



$\omega_1 > \omega_2$. $s_1 = s_m \cos \omega_1 t$ and $s_2 = s_m \cos \omega_2 t$,

$$s = s_1 + s_2 = s_m(\cos \omega_1 t + \cos \omega_2 t).$$

$$\cos \alpha + \cos \beta = 2 \cos[\tfrac{1}{2}(\alpha - \beta)] \cos[\tfrac{1}{2}(\alpha + \beta)]$$

$$s = 2s_m \cos[\tfrac{1}{2}(\omega_1 - \omega_2)t] \cos[\tfrac{1}{2}(\omega_1 + \omega_2)t].$$

$$\omega' = \tfrac{1}{2}(\omega_1 - \omega_2) \quad \text{and} \quad \omega = \tfrac{1}{2}(\omega_1 + \omega_2),$$

$$s(t) = [2s_m \cos \omega' t] \cos \omega t.$$

$$\omega_{\text{beat}} = 2\omega' = (2)(\tfrac{1}{2})(\omega_1 - \omega_2) = \omega_1 - \omega_2.$$

$\omega = 2\pi f$,

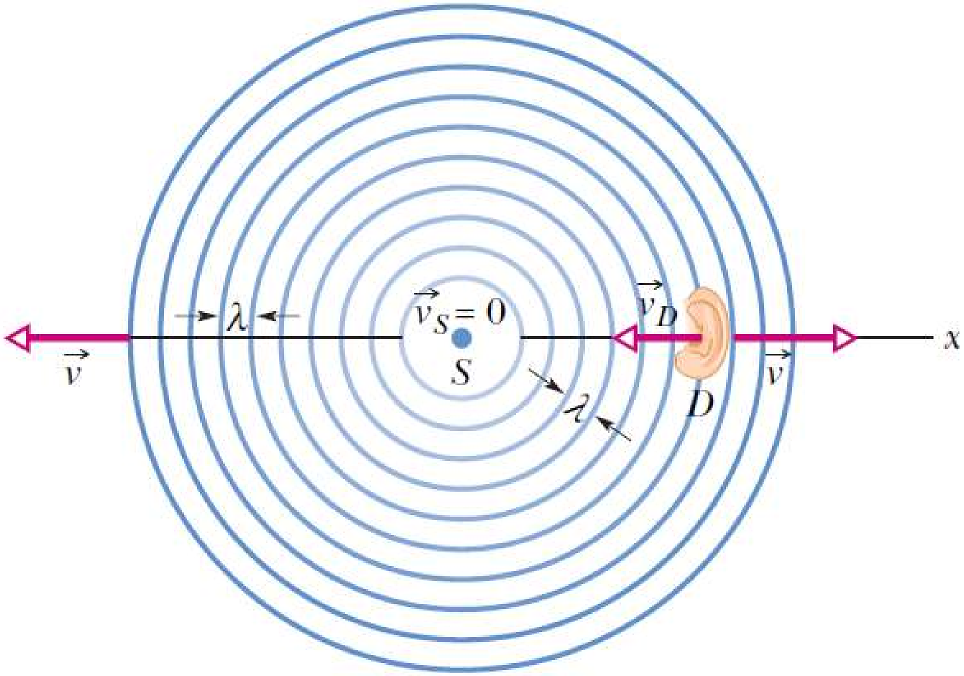
$$f_{\text{beat}} = f_1 - f_2 \quad \text{(beat frequency)}.$$

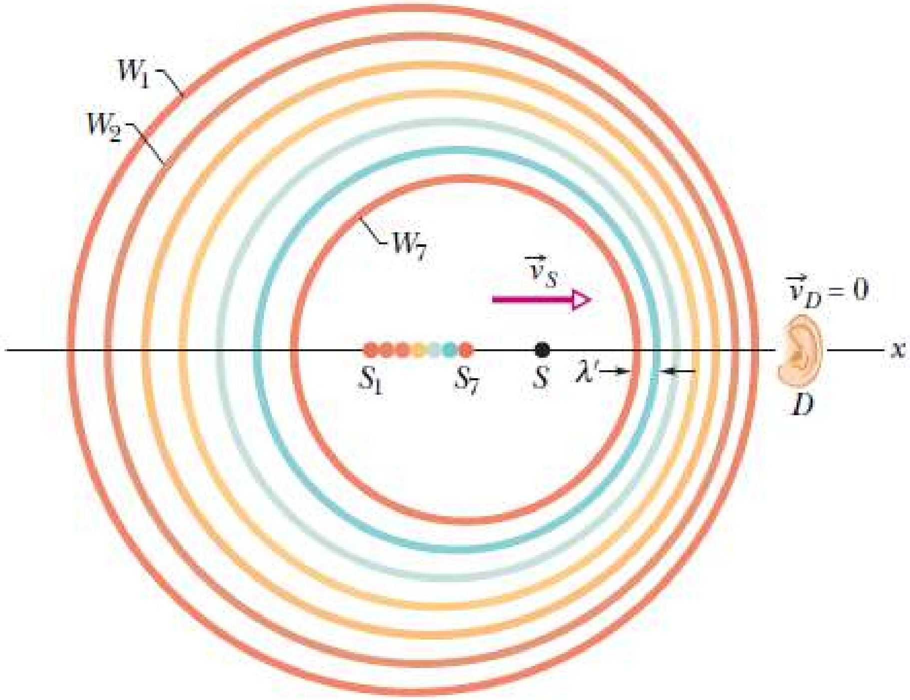
17-9 | The Doppler Effect

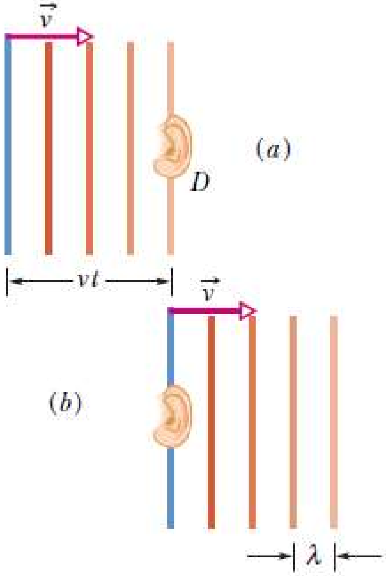
$$f' = f\frac{v \pm v_D}{v \pm v_S} \quad \text{(general Doppler effect)},$$

where v is the speed of sound through the air, v_D is the detector's speed relative to the air, and v_S is the source's speed relative to the air. The choice of plus or minus signs is set by this rule:

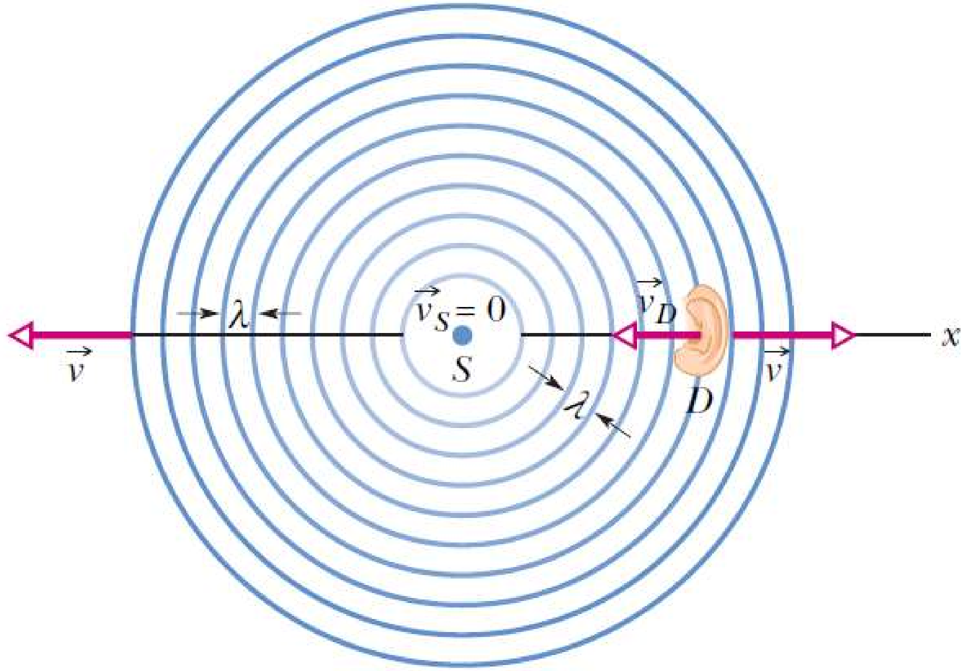
When the motion of detector or source is toward the other, the sign on its speed must give an upward shift in frequency. When the motion of detector or source is away from the other, the sign on its speed must give a downward shift in frequency.

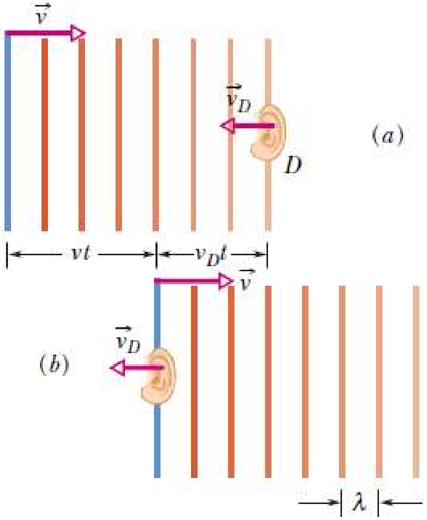






$$f = \frac{vt/\lambda}{t} = \frac{v}{\lambda}.$$





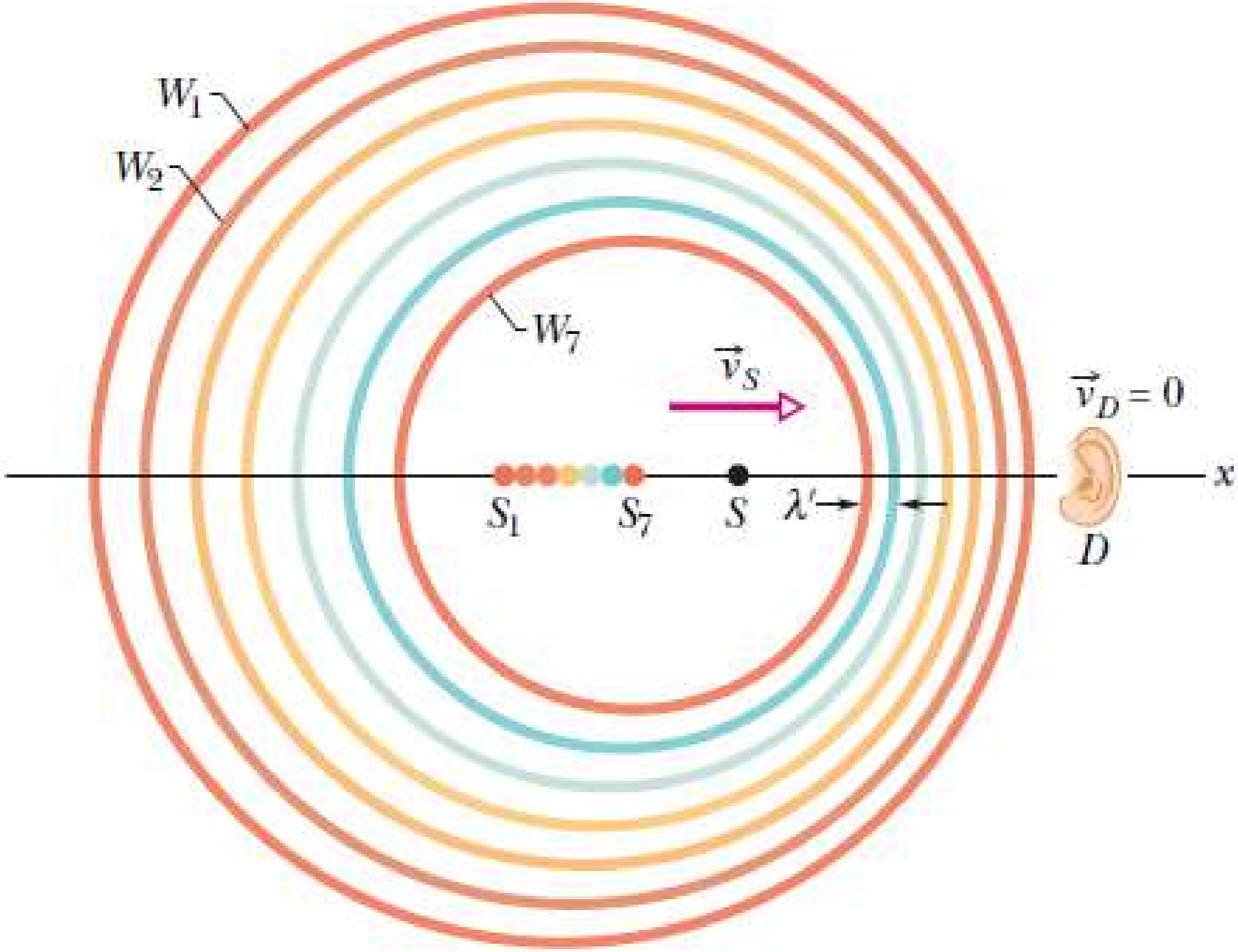
D moves in the direction opposite the wavefront velocity

$$f' = \frac{(vt + v_D t)/\lambda}{t} = \frac{v + v_D}{\lambda}.$$

$$f' = \frac{v + v_D}{v/f} = f\frac{v + v_D}{v}.$$

detector moving, source stationary

$$f' = f\frac{v \pm v_D}{v}$$



$$f' = f\frac{v}{v \pm v_S} \qquad \text{(source moving, detector stationary).}$$

Sample Problem 17-8 Build your skill

Bats navigate and search out prey by emitting, and then detecting reflections of, ultrasonic waves, which are sound waves with frequencies greater than can be heard by a human. Suppose a bat emits ultrasound at frequency $f_{be} = 82.52$ kHz while flying with velocity $\vec{v}_b = (9.00\text{ m/s})\hat{\text{i}}$ as it chases a moth that flies with velocity $\vec{v}_m = (8.00\text{ m/s})\hat{\text{i}}$. What frequency f_{md} does the moth detect? What frequency f_{bd} does the bat detect in the returning echo from the moth?

the emitted frequency f is the bat's emission frequency f_{be} 82.52 kHz, the speed of sound is v 343 m/s, the speed v_D of the detector is the moth's speed v_m 8.00 m/s, and the speed v_S of the source is the bat's speed v_b 9.00 m/s.

$$f_{md} = f_{be}\frac{v - v_m}{v - v_b}$$

$$= (82.52\text{ kHz})\frac{343\text{ m/s} - 8.00\text{ m/s}}{343\text{ m/s} - 9.00\text{ m/s}}$$

$$= 82.767\text{ kHz} \approx 82.8\text{ kHz}.$$

$$f_{bd} = f_{md}\frac{v + v_b}{v + v_m}$$

$$= (82.767\text{ kHz})\frac{343\text{ m/s} + 9.00\text{ m/s}}{343\text{ m/s} + 8.00\text{ m/s}}$$

$$= 83.00\text{ kHz} \approx 83.0\text{ kHz}.$$

Bat to Moth

Detector	Source
moth	bat
speed $v_D = v_m$	speed $v_S = v_b$
away	toward
shift down	shift up
numerator	denominator
minus	minus

Echo Back to Bat

Detector	Source
bat	moth
speed $v_D = v_b$	speed $v_S = v_m$
toward	away
shift up	shift down
numerator	denominator
plus	plus