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FUNDAMENTALS OF PHYSICS

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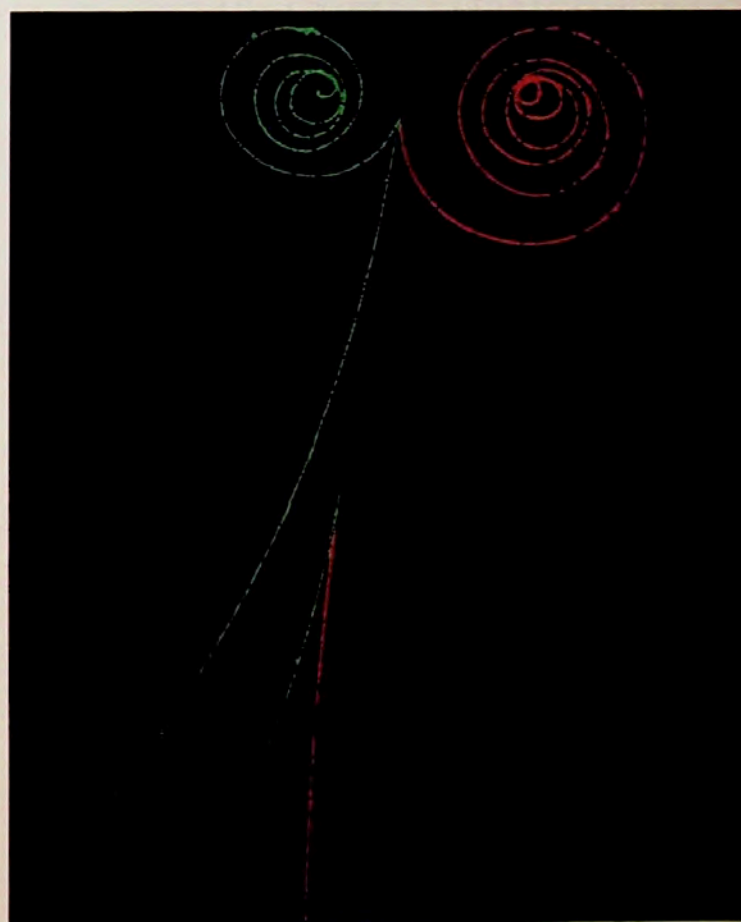
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ANSWERS TO CHECKPOINTS AND ODD-NUMBERED QUESTIONS, EXERCISES AND PROBLEMS AN1

INDEX II

on the square of its angular frequency is a general result, true for waves of all types.

SAMPLE PROBLEM 17-4

A string has a linear density μ of 525 g/m and is stretched with a tension τ of 45 N. A wave whose frequency f and amplitude y_m are 120 Hz and 8.5 mm, respectively, is traveling along the string. At what average rate is the wave transporting energy along the string?

SOLUTION: Before finding $\bar{P}$ from Eq. 17-35, we must calculate the angular frequency ω and the wave speed v . From Eq. 17-9,

$$\omega = 2\pi f = (2\pi)(120 \text{ Hz}) = 754 \text{ rad/s}.$$

From Eq. 17-24 we have

$$v = \sqrt{\frac{\tau}{\mu}} = \sqrt{\frac{45 \text{ N}}{0.525 \text{ kg/m}}} = 9.26 \text{ m/s}.$$

Equation 17-35 then yields

$$\begin{aligned} \bar{P} &= \frac{1}{2} \mu v \omega^2 y_m^2 \\ &= \frac{1}{2} (0.525 \text{ kg/m}) (9.26 \text{ m/s}) (754 \text{ rad/s})^2 (0.0085 \text{ m})^2 \\ &= 100 \text{ W}. \end{aligned} \quad (\text{Answer})$$

17-8 THE PRINCIPLE OF SUPERPOSITION FOR WAVES

It often happens that two or more waves pass simultaneously through the same region. When we listen to a concert, for example, sounds from many instruments fall simultaneously on our eardrums. The electrons in the antennas of our radio and TV receivers are set in motion by a whole array of signals from different broadcasting centers. The water of a lake or harbor may be churned up by the wakes of many boats.

Suppose that two waves travel simultaneously along the same stretched string. Let $y_1(x, t)$ and $y_2(x, t)$ be the displacements that the string would experience if each wave acted alone. The displacement of the string when both waves act is then

$$y'(x, t) = y_1(x, t) + y_2(x, t), \quad (17-36)$$

the sum being an algebraic sum. This summation of displacements along the string means

Overlapping waves algebraically add to produce a resultant wave.

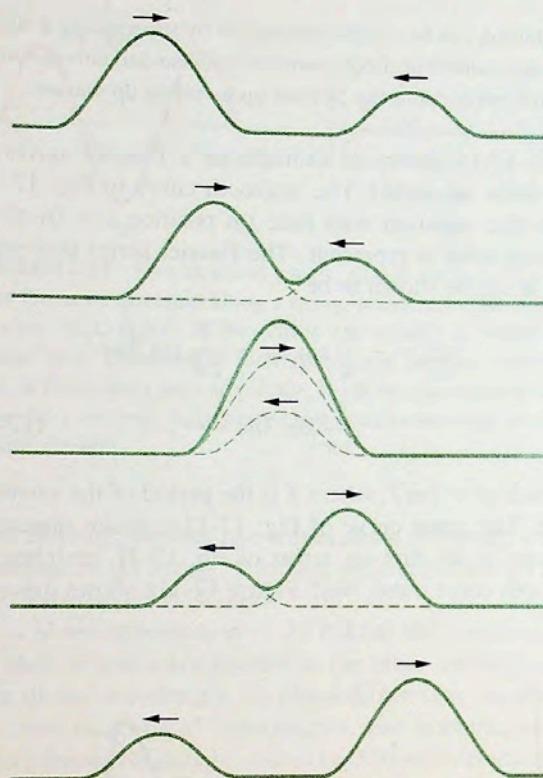


FIGURE 17-10 A series of snapshots that show two pulses traveling in opposite directions along a stretched string. The superposition principle applies as the pulses move through each other.

This is another example of the **principle of superposition**, which says that when several effects occur simultaneously, their net effect is the sum of the individual effects.

Figure 17-10 shows a sequence of snapshots of two pulses traveling in opposite directions on the same stretched string. When the pulses overlap, the resultant pulse is their sum. Moreover, each pulse moves through the other, as if the other were not present:

Overlapping waves do not in any way alter the travel of each other.

Fourier Analysis

French mathematician Jean Baptiste Fourier (1786–1830) explained how the principle of superposition can be used to analyze nonsinusoidal wave forms. He showed that any wave form can be represented as the sum of a large number of sinusoidal waves, of carefully chosen frequencies and amplitudes. English physicist Sir James Jeans expressed it well:

[Fourier's] theorem tells us that every curve, no matter what its nature may be, or in what way it was originally

obtained, can be exactly reproduced by superposing a sufficient number of simple harmonic [sinusoidal] curves—in brief, every curve can be built up by piling up waves.

Figure 17-11 shows an example of a *Fourier series*, as such sums are called. The sawtooth curve in Fig. 17-11a shows the variation with time (at position $x = 0$) of the wave we wish to represent. The Fourier series that represents it can be shown to be

$$y(t) = -\frac{1}{\pi} \sin \omega t - \frac{1}{2\pi} \sin 2\omega t - \frac{1}{3\pi} \sin 3\omega t \cdots, \quad (17-37)$$

in which $\omega = 2\pi/T$, where T is the period of the sawtooth curve. The green curve of Fig. 17-11a, which represents the sum of the first six terms of Eq. 17-37, matches the sawtooth curve rather well. Figure 17-11b shows these six

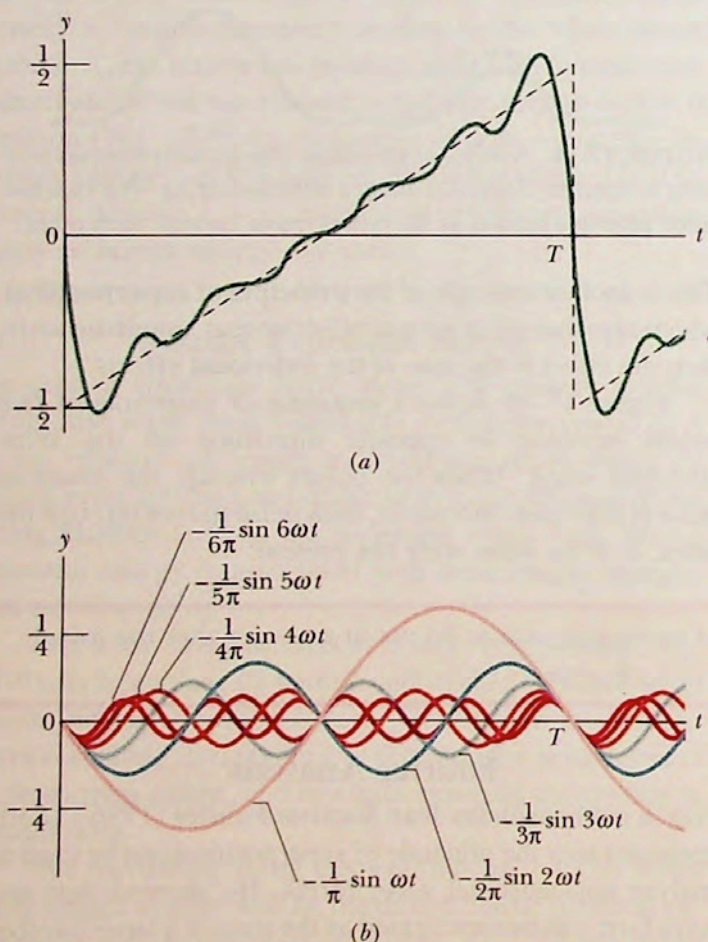


FIGURE 17-11 (a) The dashed sawtooth curve is approximated by the green curve, which is the result of evaluating the first six terms in the sum of Eq. 17-37. (Evaluating more terms would give closer approximations.) (b) Separate displays of the first six terms of that equation, each a sinusoidal function.

terms separately. By adding more terms, we can approximate the sawtooth curve as closely as we wish.

You can see now why we spent so much time analyzing the behavior of a sinusoidal wave. When we understand that, Fourier's theorem will open the door to all other wave shapes.

17-9 INTERFERENCE OF WAVES

Suppose we send two sinusoidal waves of the same wavelength and amplitude in the same direction along a stretched string. The superposition principle applies. What resultant wave does it predict for the string?

The resultant wave depends on the extent to which the waves are *in phase* (in step) with respect to each other, that is, how much one wave form is shifted from the other wave form. If the waves are exactly in phase (so that the peaks and valleys of one are exactly aligned with those of the other without any shift), they combine to double the displacement of either wave acting alone. If they are exactly out of phase (the peaks of one are exactly aligned with the valleys of the other), they cancel everywhere and the string remains straight. We call this phenomenon of combining and canceling of waves **interference**, and the waves are said to **interfere**. (These terms refer only to the displacements of the waves; the travel of the waves is unaffected.)

Let one wave traveling along a stretched string be given by

$$y_1(x, t) = y_m \sin(kx - \omega t) \quad (17-38)$$

and another, shifted from the first, by

$$y_2(x, t) = y_m \sin(kx - \omega t + \phi). \quad (17-39)$$

These waves have the same angular frequency ω (and thus the same frequency f), the same angular wave number k (and thus the same wavelength λ), and the same amplitude y_m . They travel in the same direction, that of increasing x , with the same speed, given by Eq. 17-24. They differ only by a constant angle ϕ , which we call the **phase constant**. These waves are said to be *out of phase* by ϕ or to have a *phase difference* of ϕ , or one wave is said to be *phase-shifted* from the other by ϕ .

From the principle of superposition (Eq. 17-36), the combined wave has displacement

$$y'(x, t) = y_1(x, t) + y_2(x, t) = y_m \sin(kx - \omega t) + y_m \sin(kx - \omega t + \phi). \quad (17-40)$$

In Appendix E we see that we can write the sum of the sines of two angles α and β as

$$\sin \alpha + \sin \beta = 2 \sin \frac{1}{2}(\alpha + \beta) \cos \frac{1}{2}(\alpha - \beta). \quad (17-41)$$

Applying this relation to Eq. 17-40 yields

$$y'(x, t) = [2y_m \cos \frac{1}{2}\phi] \sin(kx - \omega t + \frac{1}{2}\phi). \quad (17-42)$$

The resultant wave is thus also a sinusoidal wave traveling in the direction of increasing x . It is the only wave you would actually see on the string (you would *not* see the two combining waves of Eqs. 17-38 and 17-39).

If two sinusoidal waves of the same amplitude and wavelength travel in the *same* direction along a stretched string, they interfere to produce a resultant sinusoidal wave traveling in that direction.

The resultant wave differs from the original waves in two respects: (1) its phase constant is $\frac{1}{2}\phi$, and (2) its amplitude y'_m is the quantity in the brackets in Eq. 17-42:

$$y'_m = 2y_m \cos \frac{1}{2}\phi. \quad (17-43)$$

If $\phi = 0$ rad (or 0°), the two combining waves are exactly in phase (as in Fig. 17-12a). Then Eq. 17-42 reduces to

$$y'(x, t) = 2y_m \sin(kx - \omega t) \quad (\phi = 0). \quad (17-44)$$

Note that the amplitude of the resultant wave is twice the amplitude of either combining wave. This is the greatest amplitude the resultant wave can have, because the cosine term in Eq. 17-42 and Eq. 17-43 has its greatest value (unity) when $\phi = 0$. Interference that produces the greatest possible amplitude is called *fully constructive interference*.

If $\phi = \pi$ rad (or 180°), the combining waves are exactly out of phase (as in Fig. 17-12b). Then $\cos \frac{1}{2}\phi$ becomes $\cos \pi/2 = 0$, and the amplitude of the resultant wave (Eq. 17-43) is zero. We then have for all values of x and t ,

$$y'(x, t) = 0 \quad (\phi = \pi \text{ rad}). \quad (17-45)$$

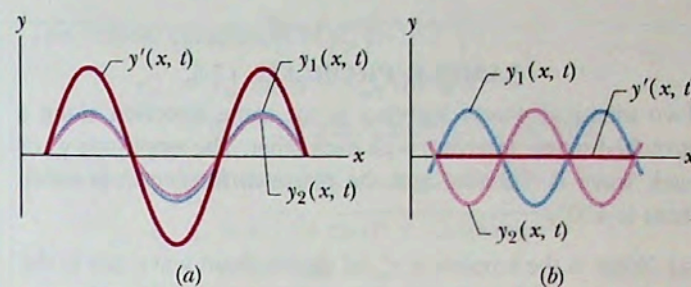


FIGURE 17-12 Two identical waves, $y_1(x, t)$ and $y_2(x, t)$, traveling in the same direction along a string, interfere to give a resultant wave $y'(x, t)$. (a) If the waves are exactly in phase, they undergo fully constructive interference and produce a resultant wave of twice their own amplitude. (b) If they are exactly out of phase, they undergo fully destructive interference and the string remains straight.

Now, although we sent two waves along the string, we see no motion of the string. This type of interference is called *fully destructive interference*.

A phase difference $\phi = 2\pi$ rad (or 360°) corresponds to a shift of one wave relative to the other wave by a distance of one wavelength. So phase differences can also be described in terms of wavelengths. For example, in Fig. 17-12b the waves may be said to be 0.50 wavelength out of phase. Table 17-1 shows some other examples of phase differences and the interference they produce. Note that when interference is neither fully constructive nor fully destructive, it is called *intermediate interference*. The amplitude of the resultant wave is then intermediate between 0 and $2y_m$.

Two waves with the same wavelength are in phase if their phase difference is zero or any integer number of wavelengths. Thus the integer part of any phase difference *expressed in wavelengths* may be discarded. For example, a phase difference of 0.40 wavelength is equivalent in every way to one of 2.40 wavelengths, and so the simpler of the two numbers can be used in computations.

TABLE 17-1 PHASE DIFFERENCES AND RESULTING INTERFERENCE TYPES^a

DEGREES	PHASE DIFFERENCE, IN		AMPLITUDE OF RESULTANT WAVE	TYPE OF INTERFERENCE
	RADIANS	WAVELENGTHS		
0	0	0	$2y_m$	Fully constructive
120	$2\pi/3$	0.33	y_m	Intermediate
180	π	0.50	0	Fully destructive
240	$4\pi/3$	0.67	y_m	Intermediate
360	2π	1.00	$2y_m$	Fully constructive
865	15.1	2.40	$0.60y_m$	Intermediate

^aThe phase difference is between two otherwise identical waves, with amplitude y_m , moving in the same direction.

SAMPLE PROBLEM 17-5

Two identical waves, moving in the same direction along a stretched string, interfere with each other. The amplitude y_m of each wave is 9.8 mm, and the phase difference ϕ between them is 100° .

(a) What is the amplitude y'_m of the resultant wave due to the interference of these two waves, and what type of interference occurs?

SOLUTION: From Eq. 17-43 we have for the amplitude

$$\begin{aligned} y'_m &= 2y_m \cos \frac{1}{2}\phi \\ &= (2)(9.8 \text{ mm}) \cos(100^\circ/2) \\ &= 13 \text{ mm.} \end{aligned} \quad (\text{Answer})$$

Because the phase difference is between 0 and 180° , the interference is intermediate.

(b) What phase difference, in radians and in wavelengths, will give the resultant wave an amplitude of 4.9 mm?

SOLUTION: From Eq. 17-43 we have

$$\begin{aligned} y'_m &= 2y_m \cos \frac{1}{2}\phi, \\ \text{or} \quad 4.9 \text{ mm} &= (2)(9.8 \text{ mm}) \cos \frac{1}{2}\phi, \end{aligned}$$

which gives us (with a calculator in the radian mode)

$$\begin{aligned} \phi &= 2 \cos^{-1} \frac{4.9 \text{ mm}}{(2)(9.8 \text{ mm})} \\ &= \pm 2.636 \text{ rad} \approx \pm 2.6 \text{ rad.} \end{aligned} \quad (\text{Answer})$$

There are two solutions because we can obtain the same resultant wave by letting the first wave *lead* (travel ahead of) or *lag* (travel behind) the second wave by 2.6 rad. In wavelengths, the phase difference is

$$\begin{aligned} \frac{\phi}{2\pi \text{ rad/wavelength}} &= \frac{\pm 2.636 \text{ rad}}{2\pi \text{ rad/wavelength}} \\ &= \pm 0.42 \text{ wavelength.} \end{aligned} \quad (\text{Answer})$$

CHECKPOINT 4: Here are four other possible phase differences between the two waves of Sample Problem 17-5, expressed in wavelengths: 0.20, 0.45, 0.60, and 0.80. Rank them according to the amplitude of the resultant wave, greatest first.

17-10 PHASORS

We can represent a string wave (or any other type of wave) vectorially with a **phasor**. In essence, a phasor is a vector that has a magnitude equal to the amplitude of the wave and that rotates around an origin; the angular speed of the phasor is equal to the angular frequency ω of the wave. For

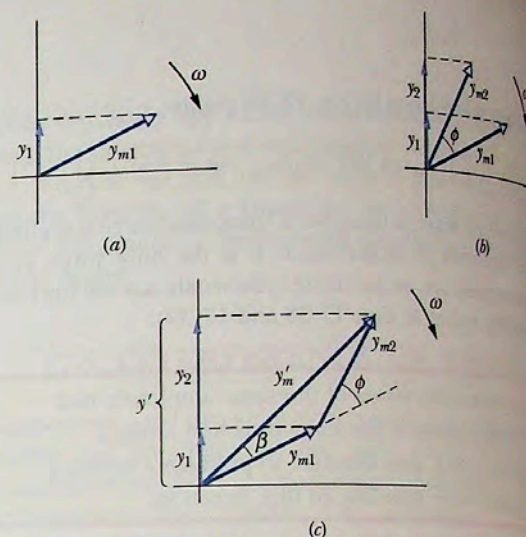


FIGURE 17-13 (a) A phasor of magnitude y_{m1} rotating about an origin at angular speed ω represents a sinusoidal wave. The phasor's projection y_1 on the vertical axis represents the displacement of a point through which the wave passes. (b) A second phasor, of magnitude y_{m2} and rotating at a constant angle ϕ to the first phasor, represents a second wave, with a phase constant ϕ . (c) The resultant wave of the two waves is represented by the vector sum y'_m of the two phasors. The projection y' on the vertical axis represents the displacement of a point as that resultant wave passes through it.

example, the wave

$$y_1(x, t) = y_{m1} \sin(kx - \omega t) \quad (17-46)$$

is represented by the phasor shown in Fig. 17-13a. The magnitude of the phasor is the amplitude y_{m1} of the wave. As the phasor rotates around the origin at angular speed ω , its projection y_1 on the vertical axis varies sinusoidally, from a maximum of y_{m1} through zero to a minimum of $-y_{m1}$. This variation corresponds to the sinusoidal variation in the displacement y_1 of any point along the string as the wave passes through it.

When two waves travel along the same string in the same direction, we can represent them and their resultant wave in a *phasor diagram*. The phasors in Fig. 17-13b represent the wave of Eq. 17-46 and a second wave given by

$$y_2(x, t) = y_{m2} \sin(kx - \omega t + \phi). \quad (17-47)$$

The angle between the two phasors in Fig. 17-13b is equal to the phase constant ϕ in Eq. 17-47. This angle is constant because the phasors rotate at the same angular speed ω , the angular frequency of the two waves.

Because waves y_1 and y_2 have the same angular wave number k and angular frequency ω , we know that their resultant is of the form

$$y'(x, t) = y'_m \sin(kx - \omega t + \beta), \quad (17-48)$$

where y'_m is the amplitude of the resultant wave and β is its phase constant. To find the values of y'_m and β , we write



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