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PHYSICS

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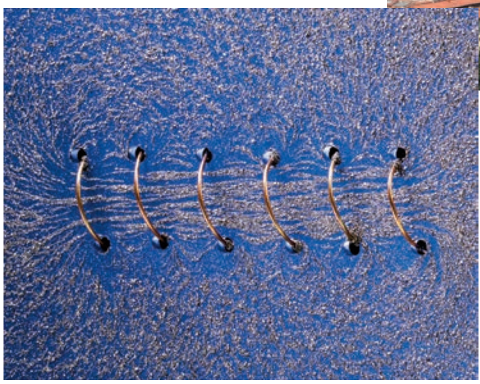
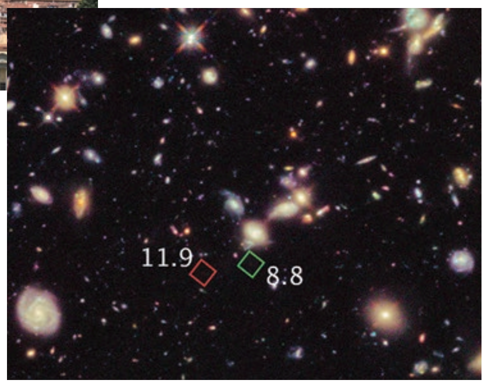
with Modern Physics





DOUGLAS
GIANCOLI

Fundamental Constants

Quantity	Symbol	Approximate Value	Current Best Value[†]
Speed of light in vacuum	c	3.00×10^8 m/s	2.99792458×10^8 m/s
Gravitational constant	G	$6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$	$6.67430(15) \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$
Avogadro's number	N_A	$6.02 \times 10^{23}\ \mathrm{mol^{-1}}$	$6.02214076 \times 10^{23}\ \mathrm{mol^{-1}}$
Gas constant	R	8.314 J/mol·K $= 1.99$ cal/mol·K $= 0.0821$ L·atm/mol·K	8.314462618 J/mol·K
Boltzmann's constant	k	1.38×10^{-23} J/K	1.380649×10^{-23} J/K
Charge on electron	e	1.60×10^{-19} C	$1.602176634 \times 10^{-19}$ C
Stefan-Boltzmann constant	σ	$5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$	$5.670374419 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$
Permittivity of free space	ϵ_0	$8.85 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2}$	$8.8541878128(13) \times 10^{-12}\ \mathrm{C^2/N \cdot m^2}$
Permeability of free space	μ_0	1.26×10^{-6} T·m/A	$1.25663706212(19) \times 10^{-6}$ T·m/A
Planck's constant	h	6.63×10^{-34} J·s	$6.62607015 \times 10^{-34}$ J·s
Electron rest mass	m_e	9.11×10^{-31} kg $= 0.000549$ u $= 0.511\ \mathrm{MeV}/c^2$	$9.1093837015(28) \times 10^{-31}$ kg $= 5.48579909065(16) \times 10^{-4}$ u
Proton rest mass	m_p	1.6726×10^{-27} kg $= 1.00728$ u $= 938.27\ \mathrm{MeV}/c^2$	$1.67262192369(51) \times 10^{-27}$ kg $= 1.007276466621(53)$ u
Neutron rest mass	m_n	1.6749×10^{-27} kg $= 1.008665$ u $= 939.57\ \mathrm{MeV}/c^2$	$1.67492749804(95) \times 10^{-27}$ kg $= 1.00866491595(49)$ u
Atomic mass unit (1 u)		1.6605×10^{-27} kg $= 931.49\ \mathrm{MeV}/c^2$	$1.66053906660(50) \times 10^{-27}$ kg $= 931.49410242(28)\ \mathrm{MeV}/c^2$

[†]Numbers in parentheses indicate one-standard-deviation experimental uncertainties in final digits (2019, new SI). Values without parentheses are exact (i.e., defined quantities).

Other Useful Data

Joule equivalent (1 cal)		4.186 J
Absolute zero (0 K)		−273.15°C
Acceleration due to gravity at Earth's surface (avg.)		$9.80\ \mathrm{m/s^2}$ $(= g)$
Speed of sound in air (20°C)		343 m/s
Density of air (dry)		$1.29\ \mathrm{kg/m^3}$
Earth:	Mass	5.98×10^{24} kg
	Radius (mean)	6.38×10^3 km
Moon:	Mass	7.35×10^{22} kg
	Radius (mean)	1.74×10^3 km
Sun:	Mass	1.99×10^{30} kg
	Radius (mean)	6.96×10^5 km
Earth–Sun distance (mean)		149.60×10^6 km
Earth–Moon distance (mean)		384×10^3 km

The Greek Alphabet

Alpha	A	α	Nu	N	ν
Beta	B	β	Xi	Ξ	ξ
Gamma	Γ	γ	Omicron	O	o
Delta	Δ	δ	Pi	Π	π
Epsilon	E	ϵ, ε	Rho	P	ρ
Zeta	Z	ζ	Sigma	Σ	σ
Eta	H	η	Tau	T	τ
Theta	Θ	θ	Upsilon	Υ	υ
Iota	I	ι	Phi	Φ	ϕ, φ
Kappa	K	κ	Chi	X	χ
Lambda	Λ	λ	Psi	Ψ	ψ
Mu	M	μ	Omega	Ω	ω

Values of Some Numbers

$\pi = 3.1415927$	$\sqrt{2} = 1.4142136$	$\ln 2 = 0.6931472$	$\log_{10} e = 0.4342945$
$e = 2.7182818$	$\sqrt{3} = 1.7320508$	$\ln 10 = 2.3025851$	1 rad $= 57.2957795°$

Mathematical Signs and Symbols

$\propto$	is proportional to	$\leq$	is less than or equal to
$=$	is equal to	$\geq$	is greater than or equal to
$\approx$	is approximately equal to	Σ	sum of
$\neq$	is not equal to	$\bar{x}$	average value of x
$>$	is greater than	Δx	change in x
$\gg$	is much greater than	$\Delta x \to 0$	Δx approaches zero
$<$	is less than	$n!$	$n(n-1)(n-2) \ldots (1)$
$\ll$	is much less than		

Properties of Water

Density (4°C)	$1.000 \times 10^3\ \mathrm{kg/m^3}$
Heat of fusion (0°C)	334 kJ/kg (79.8 kcal/kg)
Heat of vaporization (100°C)	2260 kJ/kg (539.9 kcal/kg)
Specific heat (15°C)	4186 J/kg·C° (1.00 kcal/kg·C°)
Index of refraction	1.33

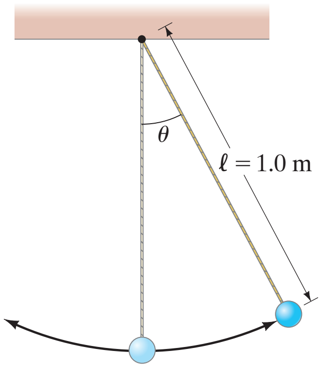


FIGURE 14–23 Example 14–14.

EXAMPLE 14–14 **Simple pendulum with damping** A simple pendulum has a length $\ell = 1.0\,\text{m}$ (Fig. 14–23). It is set swinging with small-amplitude oscillations. After 5.0 minutes, the amplitude is only 50% of what it was initially. (*a*) What is the value of γ for the motion? (*b*) By what factor does the frequency, f', differ from f, the undamped frequency?

APPROACH Lightly damped harmonic motion is described by (see Eqs. 14–16, 14–17, and 14–18)

$$x = Ae^{-\gamma t}\cos\omega' t, \quad \text{where} \quad \gamma = \frac{b}{2m} \quad \text{and} \quad \omega' = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}},$$

for damped motion of a mass on the end of a spring. For the simple pendulum without damping, we saw in Section 14–5 that, for small θ,

$$F = -mg\theta.$$

We start with $F = ma$, where a can be written in terms of the angular acceleration $\alpha = d^2\theta/dt^2$; that is, $a = \ell\alpha = \ell\, d^2\theta/dt^2$ so $F = ma = m\,\ell\, d^2\theta/dt^2$. Then, $F = ma$ means $ma - F = 0$ where $F = -mg\theta$, so (cancelling out m)

$$\ell\frac{d^2\theta}{dt^2} + g\theta = 0.$$

We introduce a damping term, $b(d\theta/dt)$, assuming the damping force is proportional to *angular* speed, $d\theta/dt$ (instead of plain v as before):

$$\ell\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} + g\theta = 0,$$

which is the same as Eq. 14–15 with θ replacing x, and ℓ and g replacing m and k.

SOLUTION (*a*) We compare Eq. 14–15 with our equation just above and see that Eq. 14–16, $x = Ae^{-\gamma t}\cos\omega' t$, becomes an equation for θ,

$$\theta = Ae^{-\gamma t}\cos\omega' t,$$

where

$$\gamma = \frac{b}{2\ell} \quad \text{and} \quad \omega' = \sqrt{\frac{g}{\ell} - \frac{b^2}{4\ell^2}}.$$

At $t = 0$,

$$\theta_0 = Ae^{-\gamma\cdot 0}\cos\omega'\cdot 0 = A.$$

Then at $t = 5.0\,\text{min} = 300\,\text{s}$, the amplitude θ has fallen to $0.50A$, so

$$0.50A = Ae^{-\gamma(300\,\text{s})}.$$

We solve this for γ and obtain $\gamma = \ln 2.0/(300\,\text{s}) = 2.3\times10^{-3}\,\text{s}^{-1}$. This means the oscillations fall to $1/e$ of their initial amplitude in a time $t = 1/\gamma = 1/(2.3\times10^{-3}\,\text{s}) = 430\,\text{s}$ or about 7 minutes.

(*b*) We have $\ell = 1.0\,\text{m}$, so $b = 2\gamma\ell = 2(2.3\times10^{-3}\,\text{s}^{-1})(1.0\,\text{m}) = 4.6\times10^{-3}\,\text{m/s}$. Thus $(b^2/4\ell^2)$ is very much less than $g/\ell\ (= 9.8\,\text{s}^{-2})$, and the angular frequency of the motion remains almost the same as that of the undamped motion. Specifically (see Eq. 14–20),

$$f' = \frac{1}{2\pi}\sqrt{\frac{g}{\ell}}\left[1 - \frac{\ell}{g}\left(\frac{b^2}{4\ell^2}\right)\right]^{\frac{1}{2}} \approx \frac{1}{2\pi}\sqrt{\frac{g}{\ell}}\left[1 - \frac{1}{2}\frac{\ell}{g}\left(\frac{b^2}{4\ell^2}\right)\right]$$

where we have used the binomial expansion (see Appendix A–2). Then, with $f = (1/2\pi)\sqrt{g/\ell}$ (Eq. 14–12b),

$$\frac{f - f'}{f} \approx \frac{1}{2}\frac{\ell}{g}\left(\frac{b^2}{4\ell^2}\right) = 2.7\times10^{-7}.$$

So f' differs from f by less than one part in a million.

*Showing $x = Ae^{-\gamma t}\cos\omega' t$ Is a Solution

We start with Eq. 14–16, to see if it is a solution to Eq. 14–15. First we take the first and second derivatives

$$\frac{dx}{dt} = -\gamma Ae^{-\gamma t}\cos\omega' t - \omega' Ae^{-\gamma t}\sin\omega' t$$

$$\frac{d^2x}{dt^2} = \gamma^2 Ae^{-\gamma t}\cos\omega' t + \gamma A\omega' e^{-\gamma t}\sin\omega' t + \omega'\gamma Ae^{-\gamma t}\sin\omega' t - \omega'^2 Ae^{-\gamma t}\cos\omega' t.$$

We next substitute these relations back into Eq. 14–15 and reorganize to obtain

$$Ae^{-\gamma t}\left[\left(m\gamma^2 - m\omega'^2 - b\gamma + k\right)\cos\omega' t + (2\omega'\gamma m - b\omega')\sin\omega' t\right] = 0. \qquad \textbf{(i)}$$

The left side of this equation must equal zero for all times t, because it is zero on the right. But this can only be so for certain values of γ and ω'. We choose two values of t that will make their evaluation easy. At $t = 0$, $\sin\omega' t = 0$, so the above relation reduces to $A\left(m\gamma^2 - m\omega'^2 - b\gamma + k\right) = 0$, which means† that

$$m\gamma^2 - m\omega'^2 - b\gamma + k = 0. \qquad \textbf{(ii)}$$

Then at $t = \pi/2\omega'$, $\cos\omega' t = 0$, so Eq. (i) can be valid only if

$$2\gamma m - b = 0, \quad \text{or} \quad \gamma = \frac{b}{2m}. \qquad [= \text{Eq. 14–17}]$$

From Eq. (ii)

$$\omega' = \sqrt{\gamma^2 - \frac{b\gamma}{m} + \frac{k}{m}} = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}. \qquad [= \text{Eq. 14–18}]$$

We see Eq. 14–16 is a solution to the equation of motion for damped harmonic motion as long as γ and ω' satisfy Eqs. 14–17 and 14–18.

14–8 Forced Oscillations; Resonance

When an oscillating system is set into motion, it oscillates at its natural frequency $f = 1/2\pi\sqrt{k/m}$, Eq. 14–7a (or, for a simple pendulum, Eq. 14–12b). However, a system may have an external force applied to it that has its own particular frequency. Then we have a **forced oscillation**.

For example, we might pull the mass on the spring of Fig. 14–1 back and forth at an externally applied frequency f. The mass then oscillates at the external frequency f of the external force, even if this frequency is different from the **natural frequency** of the spring, which we will now denote by f_0, where (see Eq. 14–7a)

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

For a forced oscillation with only light damping, the amplitude of oscillation is found to depend on the difference between f and f_0, and is a maximum when the frequency of the external force equals the natural frequency of the system—that is, when $f = f_0$. The amplitude is plotted in Fig. 14–24 as a function of the external frequency f. Curve B represents light damping and curve C heavy damping. When the external driving frequency f is near the natural frequency, $f \approx f_0$, the amplitude can become large if the damping is small. This effect of increased amplitude at $f = f_0$ is known as **resonance**. The natural oscillation frequency f_0 of a system is also called its **resonant frequency**.

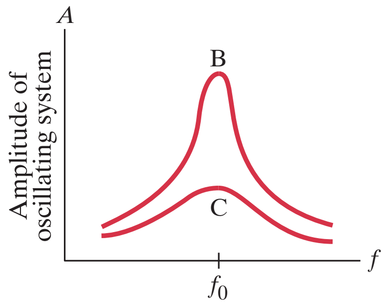


FIGURE 14–24 Amplitude as a function of driving frequency f, showing resonance for lightly damped (B) and heavily damped (C) systems.

PHYSICS APPLIED
Child on a swing

A simple illustration of resonance is pushing a child on a swing. A swing, like any pendulum, has a natural frequency of oscillation. If you push on the swing at a random frequency, the swing bounces around and reaches no great amplitude. But if you push with a frequency equal to the natural frequency of the swing, the amplitude increases greatly. At resonance, relatively little effort is required to obtain and maintain a large amplitude.

The great tenor Enrico Caruso was said to be able to shatter a crystal goblet by singing a note of just the right frequency at full voice. This is an example of resonance, for the sound waves emitted by the voice act as a forced oscillation on the glass. At resonance, the resulting oscillation of the goblet may be large enough in amplitude that the glass exceeds its elastic limit and breaks (Fig. 14–25).

FIGURE 14–25 A goblet breaks as it vibrates in resonance to a trumpet call.

†It would also be satisfied by $A = 0$, but this gives the trivial and uninteresting solution $x = 0$ for all t—that is, no oscillation.

(a)

(b)

FIGURE 14–26 (a) Large-amplitude oscillations of the Tacoma Narrows Bridge, due to gusty winds, led to its collapse (1940). (b) Collapse of a freeway in California, due to resonance in the soft ground below, caused by the 1989 earthquake.

Since material objects are, in general, elastic, resonance is an important phenomenon in a variety of situations. It is particularly important in structural engineering, although the effects are not always foreseen. For example, it has been reported that a railway bridge collapsed because a nick in one of the wheels of a crossing train set up a resonant oscillation in the bridge. Marching soldiers break step when crossing a bridge to avoid the possibility that their normal rhythmic march might match a resonant frequency of the bridge. The famous collapse of the Tacoma Narrows Bridge (Fig. 14–26a) in 1940 occurred (at least in part) as a result of winds gusting at just the right frequency, driving the span into large-amplitude oscillatory motion. The Oakland freeway collapse in the 1989 California earthquake (Fig. 14–26b) involved resonant oscillation of a section built on mudfill that readily transmitted that frequency.

Resonance can be useful, too, and we will meet important examples later, such as in musical instruments and tuning a radio. We will also see that vibrating objects often have not one, but many resonant frequencies.

Equation of Motion and Its Solution

We now look at the equation of motion for a forced oscillation and its solution. Suppose the external force is sinusoidal and can be represented by

$$F_{\text{ext}} = F_0 \cos \omega t,$$

where $\omega = 2\pi f$ is the angular frequency applied externally to the oscillator. Then the equation of motion (with damping) is

$$ma = -kx - bv + F_0 \cos \omega t,$$

or

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F_0 \cos \omega t. \qquad \textbf{(14–21)}$$

The external force, on the right of the equation, is the only term that does not involve x or one of its derivatives. Problem 72 asks you to show that

$$x = A \sin(\omega t + \phi) \qquad \textbf{(14–22)}$$

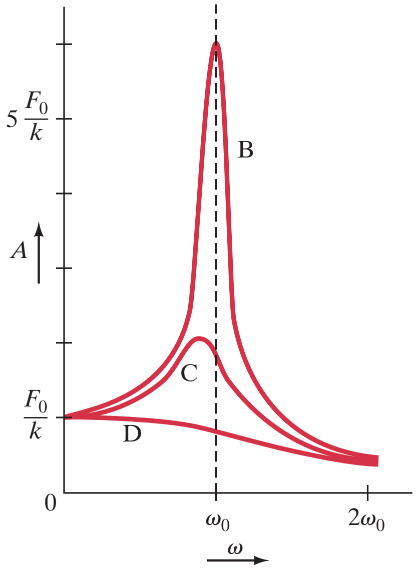
is a solution to Eq. 14–21, by direct substitution, where

$$A = \frac{F_0}{m\sqrt{(\omega^2 - \omega_0^2)^2 + b^2\omega^2/m^2}} \qquad \textbf{(14–23)}$$

and

$$\phi = \tan^{-1}\frac{\omega_0^2 - \omega^2}{\omega(b/m)}. \qquad \textbf{(14–24)}$$

FIGURE 14–27 Amplitude of a forced harmonic oscillator as a function of ω. Curves B, C, and D correspond to light, heavy, and overdamped systems, respectively $(Q = m\omega_0/b = 6, 2, 0.71)$.



Actually, the general solution to Eq. 14–21 is Eq. 14–22 plus another term of the form of Eq. 14–19 for the natural damped motion of an oscillator. This second term approaches zero in time, so let us concentrate on the long-term steady state solution, Eq. 14–22.

The amplitude of forced harmonic motion, A, depends strongly on the difference between the applied and the natural frequency. A plot of A (Eq. 14–23) as a function of the applied frequency, ω, is shown in Fig. 14–27 (a more detailed version of Fig. 14–24) for three specific values of the damping constant b. Curve B $\left(b = \frac{1}{6}m\omega_0\right)$ represents light damping, curve C $\left(b = \frac{1}{2}m\omega_0\right)$ fairly heavy damping, and curve D $\left(b = \sqrt{2}m\omega_0\right)$ overdamped motion. The amplitude can become large when the driving frequency is near the natural frequency, $\omega \approx \omega_0$, as long as the damping is not too large. When the damping is small, the increase in amplitude near $\omega = \omega_0$ is very large and, as we saw, is known as *resonance*. The natural oscillating frequency $f_0\ (= \omega_0/2\pi)$ of a system is its *resonant frequency*.†

†Sometimes the resonant frequency is defined as the actual value of ω at which the amplitude has its maximum value, and this depends somewhat on the damping constant. Except for very heavy damping, this value is quite close to ω_0.

If $b = 0$, resonance occurs at $\omega = \omega_0$ and the resonant peak (of A) becomes infinite; in such a case, energy is being continuously transferred into the system and none is dissipated. For real systems, b is never precisely zero, and the resonant peak is finite. The peak does not occur precisely at $\omega = \omega_0$ (because of the term $b^2\omega^2/m^2$ in the denominator of Eq. 14–23), although it is quite close to ω_0 unless the damping is very large. If the damping is large, there is little or no peak (curve D in Fig. 14–27).

Q Value

The height and narrowness of a resonant peak is often specified by its **quality factor** or **Q value**, defined as

$$Q = \frac{m\omega_0}{b}. \qquad \textbf{(14–25)}$$

In Fig. 14–27, curve B has $Q = 6$, curve C has $Q = 2$, and curve D has $Q = 1/\sqrt{2}$. The smaller the damping constant b, the larger the Q value becomes, and the higher the resonance peak. The Q value is also a measure of the width of the peak. To see why, let us consider a graph like Fig. 14–27 but instead of the amplitude A on the vertical axis, we put A^2. The graphs will look a lot like Fig. 14–27, but now they will essentially be graphs of energy vs. ω (recall Eq. 14–10a, $E \propto A^2$). On these energy graphs, let ω_1 and ω_2 be the frequencies where the square of the amplitude A^2 has *half* its maximum value. Then $\Delta\omega = \omega_1 - \omega_2$, which is called the *width* of the resonance peak (or **full width at half maximum**, or FWHM), is related to Q by

$$\frac{\Delta\omega}{\omega_0} = \frac{1}{Q}. \qquad \textbf{(14–26)}$$

This relation is accurate only for weak damping. The larger the Q value, the narrower will be the resonance peak relative to its height. Thus a large Q value, representing a system of high quality, has a *high*, *narrow* resonance peak. To show the validity of Eq. 14–26, square Eq. 14–23 for A and determine ω_1 and ω_2 when A^2 is $\frac{1}{2}A^2_{max}$. Or wait and do it in Problem 73.

Summary

An oscillating (or vibrating) object undergoes **simple harmonic motion** (SHM) if the restoring force is proportional to the displacement,

$$F = -kx. \qquad \textbf{(14–1)}$$

The maximum displacement from equilibrium is called the **amplitude**.

The **period**, T, is the time required for one complete cycle (back and forth), and the **frequency**, f, is the number of cycles per second; they are related by

$$f = \frac{1}{T}. \qquad \textbf{(14–2)}$$

The period of oscillation for a mass m on the end of an ideal massless spring is given by

$$T = 2\pi\sqrt{\frac{m}{k}}. \qquad \textbf{(14–7b)}$$

SHM is **sinusoidal**, which means that the displacement as a function of time follows a sine or cosine curve. The general solution can be written

$$x = A\cos(\omega t + \phi) \qquad \textbf{(14–4)}$$

where A is the amplitude, ϕ is the **phase angle**, and

$$\omega = 2\pi f = \sqrt{\frac{k}{m}}. \qquad \textbf{(14–5)}$$

The values of A and ϕ depend on the **initial conditions** (x and v at $t = 0$).

During SHM, the total energy

$$E = \tfrac{1}{2}mv^2 + \tfrac{1}{2}kx^2$$

is continually changing from potential to kinetic and back again.

A **simple pendulum** of length ℓ approximates SHM if its amplitude is small and friction can be ignored. For small amplitudes, its period is given by

$$T = 2\pi\sqrt{\frac{\ell}{g}}, \qquad \textbf{(14–12c)}$$

where g is the acceleration of gravity.

When friction is present (for all real springs and pendulums), the motion is said to be **damped**. The maximum displacement decreases in time, and the mechanical energy is eventually all transformed to thermal energy. If the friction is very large, so no oscillations occur, the system is said to be **overdamped**. If the friction is small enough that oscillations occur, the system is **underdamped**, and the displacement is given by

$$x = Ae^{-\gamma t}\cos\omega' t, \qquad \textbf{(14–16)}$$

where γ and ω' are constants. For a **critically damped** system, no oscillations occur and equilibrium is reached in the shortest time.

If a varying force of frequency f is applied to a system capable of oscillating, the amplitude of oscillation can be very large if the frequency of the applied force is near the **natural** (or **resonant**) **frequency** of the oscillator. This is called **resonance**.

Questions

1. Give some examples of everyday vibrating objects. Which exhibit SHM, at least approximately?
2. Is the acceleration of a simple harmonic oscillator ever zero? If so, where?
3. Real springs have mass. Will the true period and frequency be larger or smaller than given by the equations for a mass oscillating on the end of an idealized massless spring? Explain.
4. How could you double the maximum speed of a simple harmonic oscillator (SHO)?
5. A 5.0-kg trout is attached to the hook of a vertical spring scale, and then is tugged and released. Describe the scale reading as a function of time.
6. If a pendulum clock is accurate at sea level, will it gain or lose time when taken to high altitude? Why?
7. A tire swing hanging from a branch reaches nearly to the ground (Fig. 14–28). How could you estimate the height of the branch using only a stopwatch?

FIGURE 14–28 Question 7.

8. For a simple harmonic oscillator, when (if ever) are the displacement and velocity vectors in the same direction? When are the displacement and acceleration vectors in the same direction?
9. Two equal masses are attached to separate identical springs next to one another. One mass is pulled so its spring stretches 20 cm and the other is pulled so its spring stretches only 10 cm. The masses are released simultaneously. Which mass reaches the equilibrium point first? Explain.
10. Does a car bounce on its springs more rapidly when it is empty or when it is fully loaded?
11. What happens to the period of a playground swing if you rise up from sitting and stand on the swing seat? Explain.

*12. A thin uniform rod of mass m is suspended from one end and oscillates with a frequency f. If a small sphere of mass $2m$ is attached to the other end, does the frequency increase or decrease? Explain.

13. What is the approximate natural period of your walking step?
14. A tuning fork of natural frequency 264 Hz sits on a table at the front of a room. At the back of the room, two tuning forks, one of natural frequency 260 Hz and one of 420 Hz are initially silent, but when the tuning fork at the front of the room is set into vibration, the 260-Hz fork spontaneously begins to vibrate but the 420-Hz fork does not. Explain.
15. Why can you make water slosh back and forth in a pan only if you shake the pan at a certain frequency?
16. Give several everyday examples of resonance.
17. Sometimes a car develops a pronounced *rattle* or vibration at a particular speed, especially if the road has regularly spaced bumps, as between slabs of concrete. Which of the following is a factor and, if so, how: underdamping, overdamping, critical damping, and forced resonance?
18. Over the years, buildings have been able to be built out of lighter and lighter materials. How has this affected the natural oscillation frequencies of buildings and the problems of resonance due to passing trucks, airplanes, or by wind and other natural sources of vibration?

MisConceptual Questions

1. A mass on a spring in SHM (Fig. 14–1) has amplitude A and period T. At what point in the motion is the velocity zero and the acceleration zero simultaneously?
   (*a*) $x = A$.
   (*b*) $x > 0$ but $x < A$.
   (*c*) $x = 0$.
   (*d*) $x < 0$.
   (*e*) None of the above.
2. An object oscillates back and forth on the end of a spring. Which of the following statements are true at some time during the course of the motion?
   (*a*) The object can have zero velocity and nonzero acceleration simultaneously.
   (*b*) The object can have zero velocity and zero acceleration simultaneously.
   (*c*) The object can have zero acceleration and nonzero velocity simultaneously.
   (*d*) The object can have nonzero velocity and nonzero acceleration simultaneously.
3. An object of mass M oscillates on the end of a spring. To double the period, replace the object with one of mass:
   (*a*) $2M$.
   (*b*) $M/2$.
   (*c*) $4M$.
   (*d*) $M/4$.
   (*e*) None of the above.
4. An object of mass m rests on a frictionless surface and is attached to a horizontal ideal spring with spring constant k. The system oscillates with amplitude A. The oscillation frequency of this system can be increased by
   (*a*) decreasing k.
   (*b*) decreasing m.
   (*c*) increasing A.
   (*d*) More than one of the above.
   (*e*) None of the above will work.

5. A block fastened to the end of a horizontal spring rests on a frictionless surface. When the block is pulled back a distance A from equilibrium, the spring–block system has energy E. If the block is pulled back a distance $2A$ from equilibrium, what is the energy of the spring–block system now?
(*a*) Still E, by energy conservation.
(*b*) Work was done on the block, increasing the energy to $2E$.
(*c*) Work was done by the block, decreasing the energy to $\frac{1}{2}E$.
(*d*) Work was done by the block, decreasing the energy to $\frac{1}{4}E$.
(*e*) Work was done on the block, increasing the energy to $4E$.

6. A 100-g mass hangs from a long cord forming a pendulum. The mass is pulled a short distance to one side and released from rest. The time to swing over and back is carefully measured to be 2.0 s. If the 100-g mass is replaced by a 200-g mass, which is then pulled over the same distance and released from rest, the time will be
(*a*) 1.0 s.
(*b*) 1.41 s.
(*c*) 2.0 s.
(*d*) 2.82 s.
(*e*) 4.0 s.

7. A mass m oscillates at the end of a spring with spring constant k_1. A second spring has the same amplitude but is twice as stiff $(k_2 = 2k_1)$ and the mass oscillating at its end is $2m$. Which quantities are the same for the two systems? (Choose all that apply.)
(*a*) The total energy.
(*b*) The period.
(*c*) The maximum speed of the mass.
(*d*) The maximum acceleration of the mass.
(*e*) None of the above.

8. When you use the approximation $\sin\theta \approx \theta$ for a pendulum, you must specify the angle θ in
(*a*) radians only.
(*b*) degrees only.
(*c*) revolutions or radians.
(*d*) degrees or radians.

9. At a playground, two young children are on identical swings. One child appears to be about twice as heavy as the other. If you pull them back together the same distance and release them to start them swinging, what will you notice about the oscillations of the two children?
(*a*) The heavier child swings with a period twice that of the lighter one.
(*b*) The lighter child swings with a period twice that of the heavier one.
(*c*) Both children swing with the same period.

10. A *grandfather clock* is "losing" time because its *pendulum* moves too slowly. Assume that the pendulum is a massive bob at the end of a string. The motion of this pendulum can be sped up by (list all that work):
(*a*) shortening the string.
(*b*) lengthening the string.
(*c*) increasing the mass of the bob.
(*d*) decreasing the mass of the bob.

11. Two simple pendulums swing at a small angle with the same period. The mass of one bob is twice the mass of the other. What can you say about the length of the pendulum with the heavier bob?
(*a*) It must be longer.
(*b*) It must be be shorter.
(*c*) It can be either longer or shorter as long as the amplitudes are adjusted appropriately.
(*d*) The lengths should be the same.

Problems

14–1 and 14–2 Simple Harmonic Motion

1. (I) If a particle undergoes SHM with amplitude 0.27 m, what is the total distance it travels in one period?

2. (I) The springs of a 1700-kg car compress 5.0 mm when its 72-kg driver gets into the driver's seat. If the car goes over a bump, what will be the frequency of oscillations? Ignore damping.

3. (I) (*a*) What is the equation describing the motion of a mass on the end of a spring which is stretched 7.8 cm from equilibrium and then released from rest, and whose period is 0.66 s? (*b*) What will be its displacement after 1.8 s?

4. (I) An elastic cord is 61 cm long when a weight of 68 N hangs from it but is 85 cm long when a weight of 210 N hangs from it. What is the "spring" constant k of this elastic cord?

5. (II) Estimate the spring constant in a child's pogo stick if the child has a mass of 32 kg and bounces once every 1.6 seconds.

6. (II) A fisherman's scale stretches 3.2 cm when a 2.4-kg fish hangs from it. (*a*) What is the spring constant and (*b*) what will be the amplitude and frequency of oscillation if the fish is pulled down 2.1 cm more and released so that it oscillates up and down?

7. (II) A small fly of mass 0.28 g is caught in a spider's web. The web oscillates predominantly with a frequency of 4.0 Hz. (*a*) Estimate the value of the effective force constant k for the web. (*b*) At what frequency would you expect the web to oscillate if an insect of mass 0.46 g is trapped?

8. (II) Construct a Table indicating the position x of the mass in Fig. 14–2 at times $t = 0, \frac{1}{4}T, \frac{1}{2}T, \frac{3}{4}T, T,$ and $\frac{5}{4}T$, where T is the period of oscillation. On a graph of x vs. t, plot these six points. Now connect these points with a smooth curve. Based on these simple considerations, does your curve resemble that of a cosine or sine wave?

9. (II) A mass m at the end of a spring oscillates with a frequency of 0.83 Hz. When an additional 830-g mass is added to m, the frequency is 0.60 Hz. What is the value of m?

10. (II) A wood block of mass 52 g floats on a lake, bobbing up and down at a frequency of 3.5 Hz. (*a*) Estimate the effective force constant of this motion. (*b*) A partially filled water bottle of mass 0.28 kg and almost the same size and shape of the wood block is tossed into the water. At what frequency would you expect the bottle to bob up and down? Assume SHM.