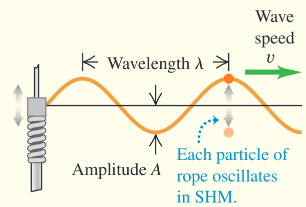
# CHAPTER 15 SUMMARY

**Waves and their properties:** A wave is any disturbance that propagates from one region to another. A mechanical wave travels within some material called the medium. The wave speed $v$ depends on the type of wave and the properties of the medium.

In a periodic wave, the motion of each point of the medium is periodic with frequency $f$ and period $T$. The wavelength $\lambda$ is the distance over which the wave pattern repeats, and the amplitude $A$ is the maximum displacement of a particle in the medium. The product of $\lambda$ and $f$ equals the wave speed. A sinusoidal wave is a special periodic wave in which each point moves in simple harmonic motion. (See Example 15.1.)

$$v = \lambda f \qquad (15.1)$$




**Wave functions and wave dynamics:** The wave function $y(x, t)$ describes the displacements of individual particles in the medium. Equations (15.3), (15.4), and (15.7) give the wave equation for a sinusoidal wave traveling in the $+x$-direction. If the wave is moving in the $-x$-direction, the minus signs in the cosine functions are replaced by plus signs. (See Example 15.2.)

The wave function obeys a partial differential equation called the wave equation, Eq. (15.12).

The speed of transverse waves on a string depends on the tension $F$ and mass per unit length $\mu$. (See Example 15.3.)

$$y(x, t) = A\cos\left[\omega\left(\frac{x}{v} - t\right)\right] \qquad (15.3)$$

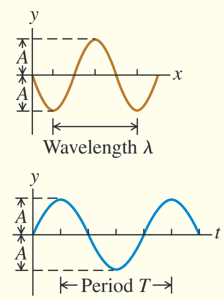
$$y(x, t) = A\cos 2\pi\left[\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right] \qquad (15.4)$$

$$y(x, t) = A\cos(kx - \omega t) \qquad (15.7)$$

where $k = 2\pi/\lambda$ and $\omega = 2\pi f = vk$

$$\frac{\partial^2 y(x, t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y(x, t)}{\partial t^2} \qquad (15.12)$$

$$v = \sqrt{\frac{F}{\mu}} \text{ (waves on a string)} \qquad (15.14)$$



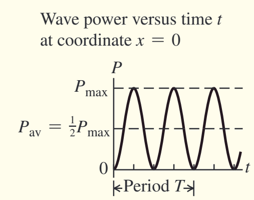

**Wave power:** Wave motion conveys energy from one region to another. For a sinusoidal mechanical wave, the average power $P_{av}$ is proportional to the square of the wave amplitude and the square of the frequency. For waves that spread out in three dimensions, the wave intensity $I$ is inversely proportional to the square of the distance from the source. (See Examples 15.4 and 15.5.)

$$P_{av} = \tfrac{1}{2}\sqrt{\mu F}\,\omega^2 A^2 \qquad (15.25)$$

(average power, sinusoidal wave)

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} \qquad (15.26)$$

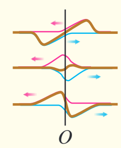
(inverse-square law for intensity)




**Wave superposition:** A wave reflects when it reaches a boundary of its medium. At any point where two or more waves overlap, the total displacement is the sum of the displacements of the individual waves (principle of superposition).

$$y(x, t) = y_1(x, t) + y_2(x, t) \qquad (15.27)$$

(principle of superposition)




**Standing waves on a string:** When a sinusoidal wave is reflected from a fixed or free end of a stretched string, the incident and reflected waves combine to form a standing sinusoidal wave with nodes and antinodes. Adjacent nodes are spaced a distance $\lambda/2$ apart, as are adjacent antinodes. (See Example 15.6.)

When both ends of a string with length $L$ are held fixed, standing waves can occur only when $L$ is an integer multiple of $\lambda/2$. Each frequency with its associated vibration pattern is called a normal mode. (See Examples 15.7 and 15.8.)

$$y(x, t) = (A_{SW}\sin kx)\sin \omega t \qquad (15.28)$$

(standing wave on a string, fixed end at $x = 0$)

$$f_n = n\frac{v}{2L} = nf_1 \quad (n = 1, 2, 3, \ldots) \qquad (15.33)$$

$$f_1 = \frac{1}{2L}\sqrt{\frac{F}{\mu}} \qquad (15.35)$$

(string fixed at both ends)

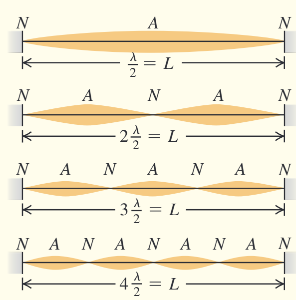
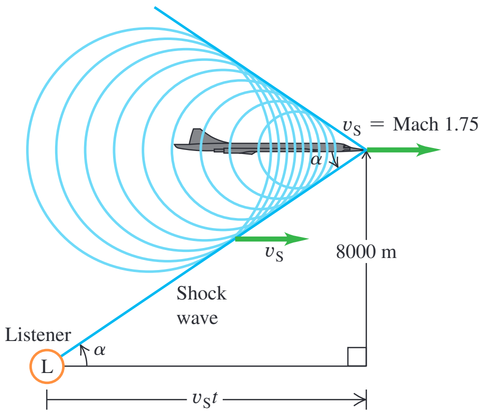


Figure **16.38** You hear a sonic boom when the shock wave reaches you at L (*not* just when the plane breaks the sound barrier). A listener to the right of L has not yet heard the sonic boom but will shortly; a listener to the left of L has already heard the sonic boom.




From Fig. 16.38 we have

$$\tan\alpha = \frac{8000\ \text{m}}{v_S t}$$

$$t = \frac{8000\ \text{m}}{(560\ \text{m/s})(\tan 34.8°)} = 20.5\ \text{s}$$

**EVALUATE** You hear the boom 20.5 s after the airplane passes overhead, at which time it has traveled $(560\ \text{m/s})(20.5\ \text{s}) = 11.5$ km since it passed overhead. We have assumed that the speed of sound is the same at all altitudes, so that $\alpha = \arcsin v/v_S$ is constant and the shock wave forms a perfect cone. In fact, the speed of sound decreases with increasing altitude. How would this affect the value of $t$?

**KEYCONCEPT** An object moving through the air faster than the speed of sound continuously produces a cone-shaped shock wave. The angle of the cone depends on the object's Mach number (the ratio of its speed to the speed of sound).

**TEST YOUR UNDERSTANDING OF SECTION 16.9** What would you hear if you were directly behind (to the left of) the supersonic airplane in Fig. 16.38? (i) A sonic boom; (ii) the sound of the airplane, Doppler-shifted to higher frequencies; (iii) the sound of the airplane, Doppler-shifted to lower frequencies; (iv) nothing.

**ANSWER** **(iii)** Figure 16.38 shows that there are sound waves inside the cone of the shock wave. Behind the airplane the wave crests are spread apart, just as they are behind the moving source in Fig. 16.28. Hence the waves that reach you have an increased wavelength and a lower frequency.

# CHAPTER 16 SUMMARY

**Sound waves:** Sound consists of longitudinal waves in a medium. A sinusoidal sound wave is characterized by its frequency $f$ and wavelength $\lambda$ (or angular frequency $\omega$ and wave number $k$) and by its displacement amplitude $A$. The pressure amplitude $p_{max}$ is directly proportional to the displacement amplitude, the wave number, and the bulk modulus $B$ of the wave medium. (See Examples 16.1 and 16.2.)

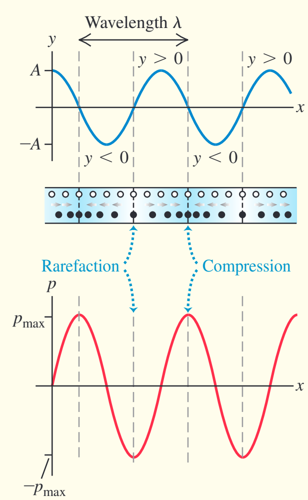
The speed of a sound wave in a fluid depends on the bulk modulus $B$ and density $\rho$. If the fluid is an ideal gas, the speed can be expressed in terms of the temperature $T$, molar mass $M$, and ratio of heat capacities $\gamma$ of the gas. The speed of longitudinal waves in a solid rod depends on the density and Young's modulus $Y$. (See Examples 16.3 and 16.4.)

$$p_{max} = BkA \tag{16.5}$$
(sinusoidal sound wave)

$$v = \sqrt{\frac{B}{\rho}} \tag{16.7}$$
(longitudinal wave in a fluid)

$$v = \sqrt{\frac{\gamma RT}{M}} \tag{16.10}$$
(sound wave in an ideal gas)

$$v = \sqrt{\frac{Y}{\rho}} \tag{16.8}$$
(longitudinal wave in a solid rod)



**Intensity and sound intensity level:** The intensity $I$ of a sound wave is the time average rate at which energy is transported by the wave, per unit area. For a sinusoidal wave, the intensity can be expressed in terms of the displacement amplitude $A$ or the pressure amplitude $p_{max}$. (See Examples 16.5–16.7.)

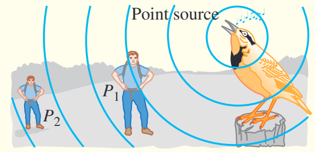
The sound intensity level $\beta$ of a sound wave is a logarithmic measure of its intensity. It is measured relative to $I_0$, an arbitrary intensity defined to be $10^{-12}\ \mathrm{W/m^2}$. Sound intensity levels are expressed in decibels (dB). (See Examples 16.8 and 16.9.)

$$I = \tfrac{1}{2}\sqrt{\rho B}\,\omega^2 A^2 = \frac{p_{max}{}^2}{2\rho v} = \frac{p_{max}{}^2}{2\sqrt{\rho B}} \qquad (16.12),\ (16.14)$$

(intensity of a sinusoidal sound wave in a fluid)

$$\beta = (10\ \mathrm{dB}) \log \frac{I}{I_0} \qquad (16.15)$$

(definition of sound intensity level)




**Standing sound waves:** Standing sound waves can be set up in a pipe or tube. A closed end is a displacement node and a pressure antinode; an open end is a displacement antinode and a pressure node. For a pipe of length $L$ open at both ends, the normal-mode frequencies are integer multiples of the sound speed divided by $2L$. For a stopped pipe (one that is open at only one end), the normal-mode frequencies are the odd multiples of the sound speed divided by $4L$. (See Examples 16.10 and 16.11.)

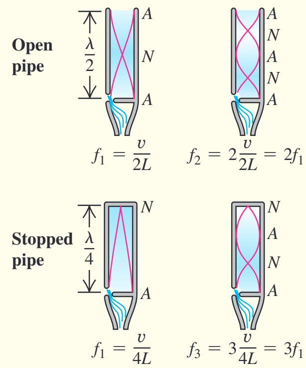
A pipe or other system with normal-mode frequencies can be driven to oscillate at any frequency. A maximum response, or resonance, occurs if the driving frequency is close to one of the normal-mode frequencies of the system. (See Example 16.12.)

$$f_n = \frac{nv}{2L} \qquad (n = 1, 2, 3, \ldots) \qquad (16.18)$$

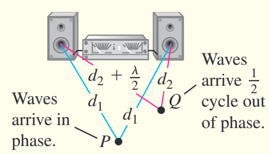
(open pipe)

$$f_n = \frac{nv}{4L} \qquad (n = 1, 3, 5, \ldots) \qquad (16.22)$$

(stopped pipe)



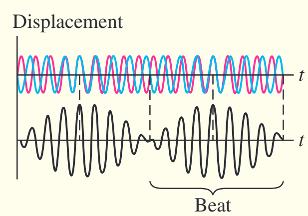

**Interference:** When two or more waves overlap in the same region of space, the resulting effects are called interference. The resulting amplitude can be either larger or smaller than the amplitude of each individual wave, depending on whether the waves are in phase (constructive interference) or out of phase (destructive interference). (See Example 16.13.)




**Beats:** Beats are heard when two tones with slightly different frequencies $f_a$ and $f_b$ are sounded together. The beat frequency $f_{beat}$ is the difference between $f_a$ and $f_b$.

$$f_{beat} = f_a - f_b \qquad (16.24)$$

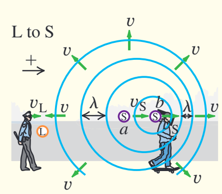
(beat frequency)




**Doppler effect:** The Doppler effect for sound is the frequency shift that occurs when there is motion of a source of sound, a listener, or both, relative to the medium. The source and listener frequencies $f_S$ and $f_L$ are related by the source and listener velocities $v_S$ and $v_L$ relative to the medium and to the speed of sound $v$. (See Examples 16.14–16.18.)

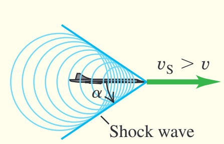
$$f_L = \frac{v + v_L}{v + v_S} f_S \qquad (16.29)$$

(Doppler effect, moving source and moving listener)




**Shock waves:** A sound source moving with a speed $v_S$ greater than the speed of sound $v$ creates a shock wave. The wave front is a cone with angle $\alpha$. (See Example 16.19.)

$$\sin\alpha = \frac{v}{v_S} \qquad \text{(shock wave)} \qquad (16.31)$$



# CHAPTER 17 SUMMARY

**Temperature and temperature scales:** Two objects in thermal equilibrium must have the same temperature. A conducting material between two objects permits them to interact and come to thermal equilibrium; an insulating material impedes this interaction.

The Celsius and Fahrenheit temperature scales are based on the freezing ($0°\text{C} = 32°\text{F}$) and boiling ($100°\text{C} = 212°\text{F}$) temperatures of water. One Celsius degree equals $\frac{9}{5}$ Fahrenheit degrees. (See Example 17.1.)

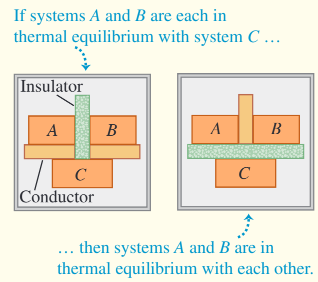
The Kelvin scale has its zero at the extrapolated zero-pressure temperature for a gas thermometer, $-273.15°\text{C} = 0\text{ K}$. In the gas-thermometer scale, the ratio of two temperatures $T_1$ and $T_2$ is defined to be equal to the ratio of the two corresponding gas-thermometer pressures $p_1$ and $p_2$.

$$T_F = \tfrac{9}{5}T_C + 32° \qquad (17.1)$$

$$T_C = \tfrac{5}{9}(T_F - 32°) \qquad (17.2)$$

$$T_K = T_C + 273.15 \qquad (17.3)$$

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \qquad (17.4)$$



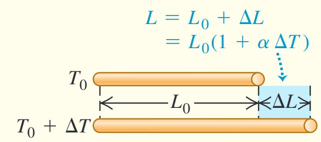

**Thermal expansion and thermal stress:** A temperature change $\Delta T$ causes a change in any linear dimension $L_0$ of a solid object. The change $\Delta L$ is approximately proportional to $L_0$ and $\Delta T$. Similarly, a temperature change causes a change $\Delta V$ in the volume $V_0$ of any solid or liquid; $\Delta V$ is approximately proportional to $V_0$ and $\Delta T$. The quantities $\alpha$ and $\beta$ are the coefficients of linear expansion and volume expansion, respectively. For solids, $\beta = 3\alpha$. (See Examples 17.2 and 17.3.)

When a material is cooled or heated and held so it cannot contract or expand, it is under a tensile stress $F/A$. (See Example 17.4.)

$$\Delta L = \alpha L_0 \,\Delta T \qquad (17.6)$$

$$\Delta V = \beta V_0 \,\Delta T \qquad (17.8)$$

$$\frac{F}{A} = -Y\alpha\,\Delta T \qquad (17.12)$$




**Heat, phase changes, and calorimetry:** Heat is energy in transit from one object to another as a result of a temperature difference. Equations (17.13) and (17.18) give the quantity of heat $Q$ required to cause a temperature change $\Delta T$ in a quantity of material with mass $m$ and specific heat $c$ (alternatively, with number of moles $n$ and molar heat capacity $C = Mc$, where $M$ is the molar mass and $m = nM$). When heat is added to an object, $Q$ is positive; when it is removed, $Q$ is negative. (See Examples 17.5 and 17.6.)

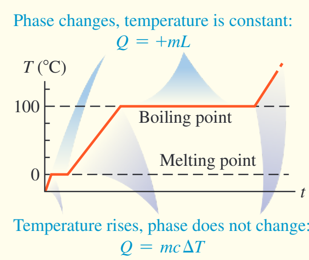
To change a mass $m$ of a material to a different phase at the same temperature (such as liquid to vapor), a quantity of heat given by Eq. (17.20) must be added or subtracted. Here $L$ is the heat of fusion, vaporization, or sublimation.

In an isolated system whose parts interact by heat exchange, the algebraic sum of the $Q$'s for all parts of the system must be zero. (See Examples 17.7–17.10.)

$$Q = mc\,\Delta T \qquad (17.13)$$

$$Q = nC\,\Delta T \qquad (17.18)$$

$$Q = \pm mL \qquad (17.20)$$




**Conduction, convection, and radiation:** Conduction is the transfer of heat within materials without bulk motion of the materials. The heat current $H$ depends on the area $A$ through which the heat flows, the length $L$ of the heat-flow path, the temperature difference $(T_H - T_C)$, and the thermal conductivity $k$ of the material. (See Examples 17.11–17.13.)

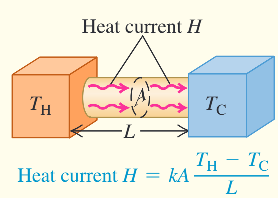
Convection is a complex heat-transfer process that involves mass motion from one region to another.

Radiation is energy transfer through electromagnetic radiation. The radiation heat current $H$ depends on the surface area $A$, the emissivity $e$ of the surface (a pure number between 0 and 1), and the Kelvin temperature $T$. Here $\sigma$ is the Stefan–Boltzmann constant. The *net* radiation heat current $H_{net}$ from an object at temperature $T$ to its surroundings at temperature $T_s$ depends on both $T$ and $T_s$. (See Examples 17.14 and 17.15.)

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L} \qquad (17.21)$$

$$H = Ae\sigma T^4 \qquad (17.25)$$

$$H_{net} = Ae\sigma(T^4 - T_s^4) \qquad (17.26)$$



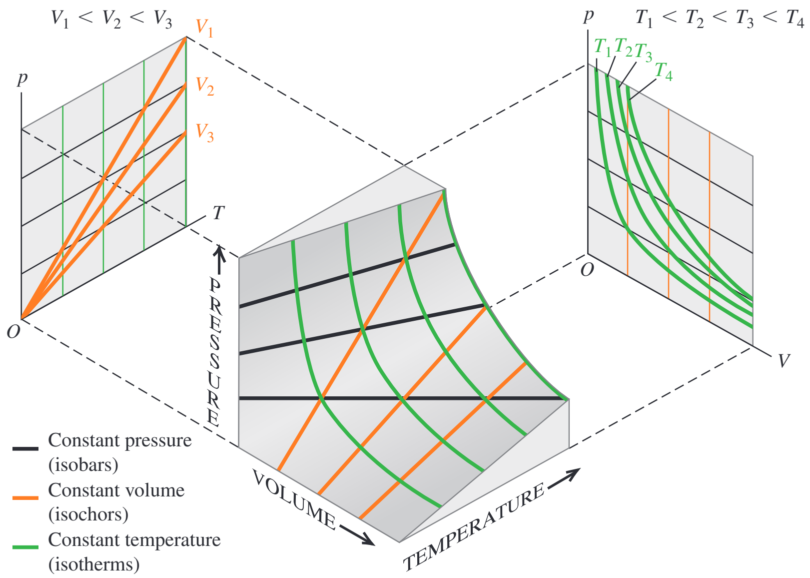



Figure 18.27 A $pVT$-surface for an ideal gas. At the left, each orange line corresponds to a certain constant volume; at the right, each green line corresponds to a certain constant temperature.

**Figure 18.27** shows the much simpler $pVT$-surface for a substance that obeys the ideal-gas equation of state under all conditions. The projections of the constant-temperature curves onto the $pV$-plane correspond to the curves of Fig. 18.6, and the projections of the constant-volume curves onto the $pT$-plane show that pressure is directly proportional to absolute temperature. Figure 18.27 also shows the *isobars* (curves of constant pressure) and *isochors* (curves of constant volume) for an ideal gas.

**TEST YOUR UNDERSTANDING OF SECTION 18.6** The average atmospheric pressure on Mars is $6.0 \times 10^2$ Pa. Could there be lakes of liquid water on the surface of Mars today? What about in the past, when the atmospheric pressure is thought to have been substantially greater?

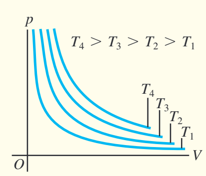
**ANSWER**

**no, yes** The triple-point pressure of water from Table 18.3 is $6.10 \times 10^2$ Pa. The present-day pressure on Mars is just less than this value, corresponding to the line labeled $p_s$ in Fig. 18.24. Hence liquid water cannot exist on the present-day Martian surface, and there are no rivers or lakes. Planetary scientists conclude that liquid water could have existed and almost certainly did exist on Mars in the past, when the atmosphere was thicker.

# CHAPTER 18 SUMMARY

**Equations of state:** The pressure $p$, volume $V$, and absolute temperature $T$ of a given quantity of a substance are related by an equation of state. This relationship applies only for equilibrium states, in which $p$ and $T$ are uniform throughout the system. The ideal-gas equation of state, Eq. (18.3), involves the number of moles $n$ and a constant $R$ that is the same for all gases. (See Examples 18.1–18.4.)

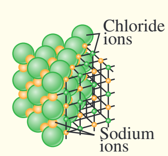
$$pV = nRT \quad (18.3)$$




**Molecular properties of matter:** The molar mass $M$ of a pure substance is the mass per mole. The mass $m_{total}$ of a quantity of substance equals $M$ multiplied by the number of moles $n$. Avogadro's number $N_A$ is the number of molecules in a mole. The mass $m$ of an individual molecule is $M$ divided by $N_A$. (See Example 18.5.)

$$m_{total} = nM \quad (18.2)$$

$$M = N_A m \quad (18.8)$$



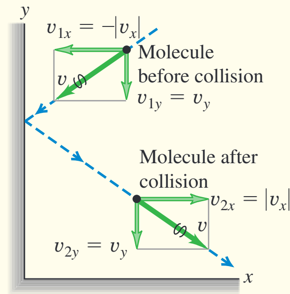
**Kinetic-molecular model of an ideal gas:** In an ideal gas, the total translational kinetic energy of the gas as a whole ($K_{tr}$) and the average translational kinetic energy per molecule $[\frac{1}{2}m(v^2)_{av}]$ are proportional to the absolute temperature $T$, and the root-mean-square speed of molecules is proportional to the square root of $T$. These expressions involve the Boltzmann constant $k = R/N_A$. (See Examples 18.6 and 18.7.) The mean free path $\lambda$ of molecules in an ideal gas depends on the number of molecules per volume $(N/V)$ and the molecular radius $r$. (See Example 18.8.)

$$K_{tr} = \tfrac{3}{2}nRT \qquad (18.14)$$

$$\tfrac{1}{2}m(v^2)_{av} = \tfrac{3}{2}kT \qquad (18.16)$$

$$v_{rms} = \sqrt{(v^2)_{av}} = \sqrt{\frac{3kT}{m}} \qquad (18.19)$$

$$\lambda = vt_{mean} = \frac{V}{4\pi\sqrt{2}r^2N} \qquad (18.21)$$

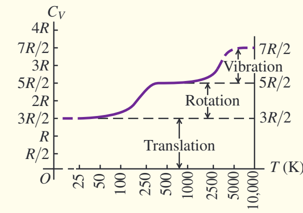



**Heat capacities:** The molar heat capacity at constant volume $C_V$ is a simple multiple of the gas constant $R$ for certain idealized cases: an ideal monatomic gas [Eq. (18.25)]; an ideal diatomic gas including rotational energy [Eq. (18.26)]; and an ideal monatomic solid [Eq. (18.28)]. Many real systems are approximated well by these idealizations.

$$C_V = \tfrac{3}{2}R \text{ (monatomic gas)} \qquad (18.25)$$

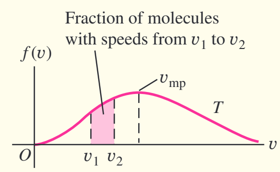
$$C_V = \tfrac{5}{2}R \text{ (diatomic gas)} \qquad (18.26)$$

$$C_V = 3R \text{ (monatomic solid)} \qquad (18.28)$$

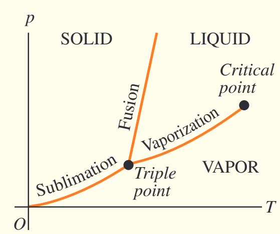



**Molecular speeds:** The speeds of molecules in an ideal gas are distributed according to the Maxwell–Boltzmann distribution $f(v)$. The quantity $f(v)\,dv$ describes what fraction of the molecules have speeds between $v$ and $v + dv$.

$$f(v) = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 e^{-mv^2/2kT} \qquad (18.32)$$




**Phases of matter:** Ordinary matter exists in the solid, liquid, and gas phases. A phase diagram shows conditions under which two phases can coexist in phase equilibrium. All three phases can coexist at the triple point. The vaporization curve ends at the critical point, above which the distinction between the liquid and gas phases disappears.




**Chapter 18 Media Assets**

## GUIDED PRACTICE

**For assigned homework and other learning materials, go to Mastering Physics.**

### KEY EXAMPLE VARIATION PROBLEMS

**Be sure to review EXAMPLES 18.1, 18.2, 18.3, and 18.4 (Section 18.1) before attempting these problems.**

**VP18.4.1** When the temperature is 30.0°C, the pressure of the air inside a bicycle tire of fixed volume $1.40 \times 10^{-3}$ m$^3$ is $5.00 \times 10^5$ Pa. (a) What will be the pressure inside the tire when the temperature drops to 10.0°C? (b) How many moles of air are inside the tire?

**VP18.4.2** When a research balloon is released at sea level, where the temperature is 15.0°C and the atmospheric pressure is $1.01 \times 10^5$ Pa, the helium in it has volume 13.0 m$^3$. (a) When the balloon reaches an altitude of 32.0 km, where the temperature is −44.5°C and the pressure is 868 Pa, what is the volume of the helium? (b) If this balloon is spherical, how many times larger is its radius at 32.0 km than at sea level?

**VP18.4.3** The dwarf planet Pluto has a very thin atmosphere made up almost entirely of nitrogen ($N_2$, molar mass $2.8 \times 10^{-2}$ kg/mol). At Pluto's surface the temperature is 42 K and the atmospheric pressure is 1.0 Pa. At the surface, (a) how many moles of gas are there per cubic meter of atmosphere, and (b) what is the density of the atmosphere in kg/m$^3$? (For comparison, the values are 42 mol/m$^3$ and 1.2 kg/m$^3$ at the earth's surface.)

**VP18.4.4** When the pressure on $n$ moles of helium gas is suddenly changed from an initial value of $p_1$ to a final value of $p_2$, the density of the gas changes from its initial value of $\rho_1$ to a final value of $\rho_2 = \rho_1(p_2/p_1)^{3/5}$. (a) If the initial absolute temperature of the gas is $T_1$, what is its final absolute temperature $T_2$ in terms of $T_1$, $p_1$, and $p_2$? (b) If the final pressure is 0.500 times the initial pressure, what are the ratio of the final density to the initial density and the ratio of the final temperature to the initial temperature? (c) Repeat part (b) if the final pressure is 2.00 times the initial pressure.

**Be sure to review EXAMPLES 18.6 and 18.7 (Section 18.3) before attempting these problems.**

**VP18.7.1** At what temperature (in °C) is the rms speed of helium atoms (molar mass 4.00 g/mol) the same as the rms speed of nitrogen molecules (molar mass 28.0 g/mol) at 20.0°C? (Note that helium remains a gas at temperatures above −269°C.)

*Continued*

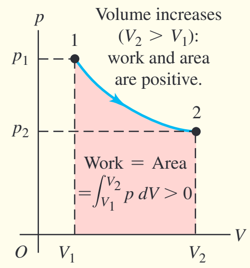
# CHAPTER 19 SUMMARY

**Heat and work in thermodynamic processes:** A thermodynamic system has the potential to exchange energy with its surroundings by heat transfer or by mechanical work. When a system at pressure $p$ changes volume from $V_1$ to $V_2$, it does an amount of work $W$ given by the integral of $p$ with respect to volume. If the pressure is constant, the work done is equal to $p$ times the change in volume. A negative value of $W$ means that work is done on the system. (See Example 19.1.)

In any thermodynamic process, the heat added to the system and the work done by the system depend not only on the initial and final states, but also on the path (the series of intermediate states through which the system passes).

$$W = \int_{V_1}^{V_2} p\, dV \qquad (19.2)$$

$$W = p(V_2 - V_1) \qquad (19.3)$$
(constant pressure only)

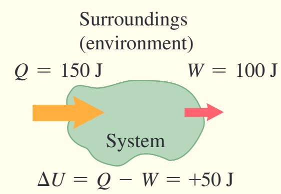



**The first law of thermodynamics:** The first law of thermodynamics states that when heat $Q$ is added to a system while the system does work $W$, the internal energy $U$ changes by an amount equal to $Q - W$. This law can also be expressed for an infinitesimal process. (See Examples 19.2, 19.3, and 19.5.)

The internal energy of any thermodynamic system depends only on its state. The change in internal energy in any process depends only on the initial and final states, not on the path. The internal energy of an isolated system is constant. (See Example 19.4.)

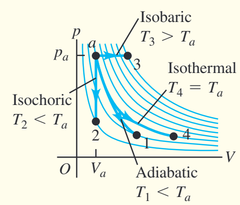
$$\Delta U = Q - W \qquad (19.4)$$

$$dU = dQ - dW \qquad (19.6)$$
(infinitesimal process)




**Important kinds of thermodynamic processes:**

- Adiabatic process: No heat transfer into or out of a system; $Q = 0$.
- Isochoric process: Constant volume; $W = 0$.
- Isobaric process: Constant pressure; $W = p(V_2 - V_1)$.
- Isothermal process: Constant temperature.

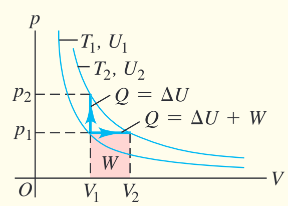



**Thermodynamics of ideal gases:** The internal energy of an ideal gas depends only on its temperature, not on its pressure or volume. For other substances the internal energy generally depends on both pressure and temperature.

The molar heat capacities $C_V$ and $C_p$ of an ideal gas differ by $R$, the ideal-gas constant. The dimensionless ratio of heat capacities, $C_p/C_V$, is denoted by $\gamma$. (See Example 19.6.)

$$C_p = C_V + R \qquad (19.17)$$

$$\gamma = \frac{C_p}{C_V} \qquad (19.18)$$

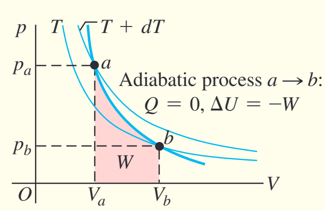



**Adiabatic processes in ideal gases:** For an adiabatic process for an ideal gas, the quantities $TV^{\gamma-1}$ and $pV^{\gamma}$ are constant. The work done by an ideal gas during an adiabatic expansion can be expressed in terms of the initial and final values of temperature, or in terms of the initial and final values of pressure and volume. (See Example 19.7.)

$$W = nC_V(T_1 - T_2) \qquad (19.25)$$

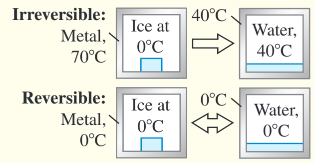
$$= \frac{C_V}{R}(p_1V_1 - p_2V_2)$$

$$= \frac{1}{\gamma - 1}(p_1V_1 - p_2V_2) \qquad (19.26)$$



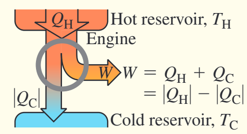
# CHAPTER 20 SUMMARY

**Reversible and irreversible processes:** A reversible process is one whose direction can be reversed by an infinitesimal change in the conditions of the process, and in which the system is always in or very close to thermal equilibrium. All other thermodynamic processes are irreversible.



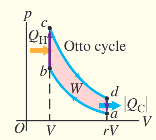

**Heat engines:** A heat engine takes heat $Q_H$ from a source, converts part of it to work $W$, and discards the remainder $|Q_C|$ at a lower temperature. The thermal efficiency $e$ of a heat engine measures how much of the absorbed heat is converted to work. (See Example 20.1.)

$$e = \frac{W}{Q_H} = 1 + \frac{Q_C}{Q_H} = 1 - \left|\frac{Q_C}{Q_H}\right| \qquad (20.4)$$



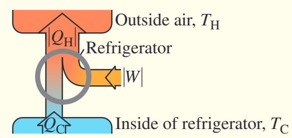

**The Otto cycle:** A gasoline engine operating on the Otto cycle has a theoretical maximum thermal efficiency $e$ that depends on the compression ratio $r$ and the ratio of heat capacities $\gamma$ of the working substance.

$$e = 1 - \frac{1}{r^{\gamma - 1}} \qquad (20.6)$$

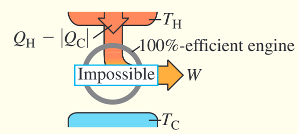



**Refrigerators:** A refrigerator takes heat $Q_C$ from a colder place, has a work input $|W|$, and discards heat $|Q_H|$ at a warmer place. The effectiveness of the refrigerator is given by its coefficient of performance $K$.

$$K = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|} \qquad (20.9)$$




**The second law of thermodynamics:** The second law of thermodynamics describes the directionality of natural thermodynamic processes. It can be stated in two equivalent forms. The *engine* statement is that no cyclic process can convert heat completely into work. The *refrigerator* statement is that no cyclic process can transfer heat from a colder place to a hotter place with no input of mechanical work.




**The Carnot cycle:** The Carnot cycle operates between two heat reservoirs at temperatures $T_H$ and $T_C$ and uses only reversible processes. Its thermal efficiency depends only on $T_H$ and $T_C$. An additional equivalent statement of the second law is that no engine operating between the same two temperatures can be more efficient than a Carnot engine. (See Examples 20.2
and 20.3.)

A Carnot engine run backward is a Carnot refrigerator. Its coefficient of performance depends on only $T_H$ and $T_C$. Another form of the second law states that no refrigerator operating between the same two temperatures can have a larger coefficient of performance than a Carnot refrigerator. (See Example 20.4.)

$$e_{\text{Carnot}} = 1 - \frac{T_C}{T_H} = \frac{T_H - T_C}{T_H} \qquad (20.14)$$

$$K_{\text{Carnot}} = \frac{T_C}{T_H - T_C} \qquad (20.15)$$

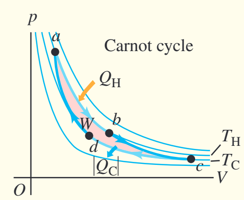
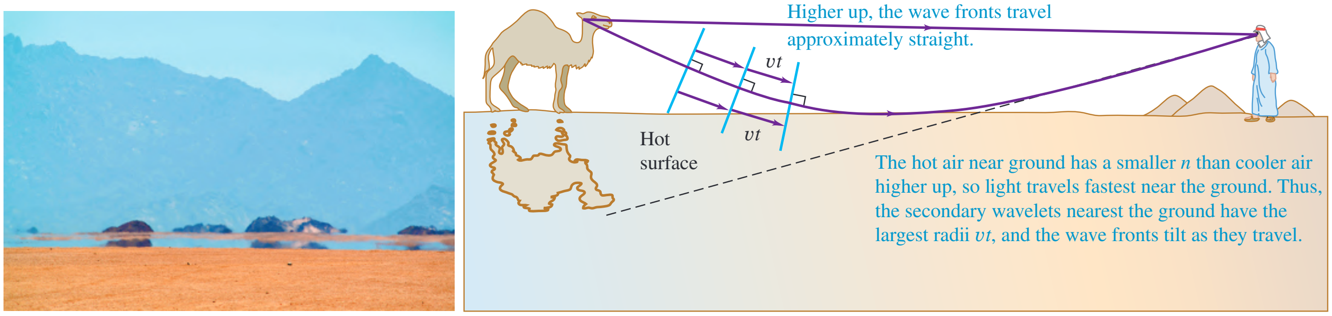


Figure 33.36 How mirages are formed.




**TEST YOUR UNDERSTANDING OF SECTION 33.7** Sound travels faster in warm air than in cold air. Imagine a weather front that runs north-south, with warm air to the west of the front and cold air to the east. A sound wave traveling in a northeast direction in the warm air encounters this front. How will the direction of this sound wave change when it passes into the cold air? (i) The wave direction will deflect toward the north; (ii) the wave direction will deflect toward the east; (iii) the wave direction will be unchanged.

**ANSWER**

**(ii)** Huygens's principle applies to waves of all kinds, including sound waves. Hence this situation is exactly like that shown in Fig. 33.35, with material $a$ representing the warm air, material $b$ representing the cold air in which the waves travel more slowly, and the interface between the materials representing the weather front. North is toward the top of the figure and east is toward the right, so Fig. 33.35 shows that the rays (which indicate the direction of propagation) deflect toward the east.

# CHAPTER 33 SUMMARY

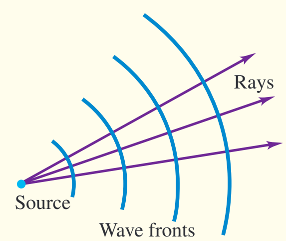
**Light and its properties:** Light is an electromagnetic wave. When emitted or absorbed, it also shows particle properties. It is emitted by accelerated electric charges.

A wave front is a surface of constant phase; wave fronts move with a speed equal to the propagation speed of the wave. A ray is a line along the direction of propagation, perpendicular to the wave fronts.

When light is transmitted from one material to another, the frequency of the light is unchanged, but the wavelength and wave speed can change. The index of refraction $n$ of a material is the ratio of the speed of light in vacuum $c$ to the speed $v$ in the material. If $\lambda_0$ is the wavelength in vacuum, the same wave has a shorter wavelength $\lambda$ in a medium with index of refraction $n$. (See Example 33.2.)

$$n = \frac{c}{v} \quad (33.1)$$

$$\lambda = \frac{\lambda_0}{n} \quad (33.5)$$



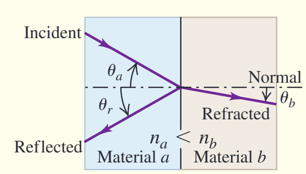

**Reflection and refraction:** At a smooth interface between two optical materials, the incident, reflected, and refracted rays and the normal to the interface all lie in a single plane called the plane of incidence. The law of reflection states that the angles of incidence and reflection are equal. The law of refraction relates the angles of incidence and refraction to the indexes of refraction of the materials. (See Examples 33.1 and 33.3.)

$$\theta_r = \theta_a \quad (33.2)$$

(law of reflection)

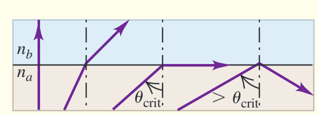
$$n_a \sin\theta_a = n_b \sin\theta_b \quad (33.4)$$

(law of refraction)




**Total internal reflection:** When a ray travels in a material of index of refraction $n_a$ toward a material of index $n_b < n_a$, total internal reflection occurs at the interface when the angle of incidence equals or exceeds a critical angle $\theta_{crit}$. (See Example 33.4.)

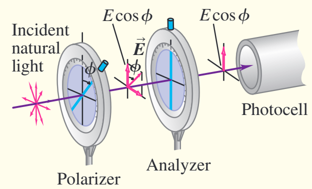
$$\sin\theta_{crit} = \frac{n_b}{n_a} \quad (33.6)$$



**Polarization of light:** The direction of polarization of a linearly polarized electromagnetic wave is the direction of the $\vec{E}$ field. A polarizing filter passes waves that are linearly polarized along its polarizing axis and blocks waves polarized perpendicularly to that axis. When polarized light of intensity $I_{max}$ is incident on a polarizing filter used as an analyzer, the intensity $I$ of the light transmitted through the analyzer depends on the angle $\phi$ between the polarization direction of the incident light and the polarizing axis of the analyzer. (See Example 33.5.)

$$I = I_{max} \cos^2 \phi \qquad (33.7)$$

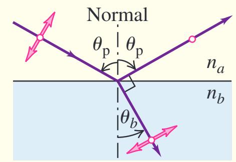
(Malus's law)



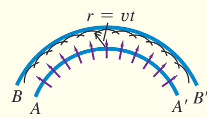

**Polarization by reflection:** When unpolarized light strikes an interface between two materials, Brewster's law states that the reflected light is completely polarized perpendicular to the plane of incidence (parallel to the interface) if the angle of incidence equals the polarizing angle $\theta_p$. (See Example 33.6.)

$$\tan \theta_p = \frac{n_b}{n_a} \qquad (33.8)$$

(Brewster's law)




**Huygens's principle:** Huygens's principle states that if the position of a wave front at one instant is known, then the position of the front at a later time can be constructed by imagining the front as a source of secondary wavelets. Huygens's principle can be used to derive the laws of reflection and refraction.




Chapter 33 Media Assets

## GUIDED PRACTICE

For assigned homework and other learning materials, go to Mastering Physics.

### KEY EXAMPLE VARIATION PROBLEMS

**Be sure to review EXAMPLES 33.1 and 33.2 (Section 33.2) before attempting these problems.**

**VP33.2.1** A block of glass with index of refraction 1.80 has a smooth surface. Light in air strikes this surface at an angle of incidence of 70.0° measured from the normal to the surface of the glass. Find the angles measured relative to this normal of (a) the reflected ray and (b) the refracted ray.

**VP33.2.2** A ray of light in water $(n = 1.33)$ strikes a submerged glass block at an angle of incidence of 55.0°. The angle of refraction for the light that enters the glass is 37.0°. Find (a) the index of refraction of the glass and (b) the speed of light in the glass.

**VP33.2.3** The light from a red laser pointer has wavelength 635 nm in air and 508 nm in a transparent liquid. You point the laser in air so that the beam strikes the surface of the liquid at an angle of 35.0° from the normal. Find (a) the index of refraction of the liquid, (b) the angle of refraction, (c) the frequency of the light in air, and (d) the frequency of the light in the liquid.

**VP33.2.4** A glass of ethanol $(n = 1.36)$ has an ice cube $(n = 1.309)$ floating in it. A light beam in the ethanol goes into the ice cube at an angle of refraction of 85.0°. Find (a) the angle of incidence in the ethanol and (b) the ratio of the wavelength of the light in ice to its wavelength in ethanol.

**Be sure to review EXAMPLE 33.5 (Section 33.5) before attempting these problems.**

**VP33.5.1** A polarized laser beam of intensity 255 W/m$^2$ shines on an ideal polarizer. The angle between the polarization direction of the laser beam and the polarizing axis of the polarizer is 15.0°. What is the intensity of the light that emerges from the polarizer?

**VP33.5.2** You shine unpolarized light with intensity 54.0 W/m$^2$ on an ideal polarizer, and then the light that emerges from this polarizer falls on a second ideal polarizer. The light that emerges from the second polarizer has intensity 19.0 W/m$^2$. Find (a) the intensity of the light that emerges from the first polarizer and (b) the angle between the polarizing axes of the two polarizers.

**VP33.5.3** A beam of polarized light of intensity 60.0 W/m$^2$ propagates in the $+x$-direction. The light is polarized in the $+y$-direction. The beam strikes an ideal polarizer whose plane is parallel to the $yz$-plane and has its polarizing axis at 25.0° clockwise from the $y$-direction. Then the beam that emerges from this polarizer strikes a second ideal polarizer whose plane is also parallel to the $yz$-plane but has its polarizing axis at 50.0° clockwise from the $y$-direction. Find the intensity of the light that emerges (a) from the first polarizer, (b) from the second polarizer, and (b) from the second polarizer if the first polarizer is removed.

**VP33.5.4** You simultaneously shine two light beams, each of intensity $I_0$, on an ideal polarizer. One beam is unpolarized, and the other beam is polarized at an angle of exactly 30° to the polarizing axis of the polarizer. Find the intensity of the light that emerges from the polarizer.

**Be sure to review EXAMPLE 33.6 (Section 33.5) before attempting these problems.**

**VP33.6.1** Unpolarized sunlight in air shines on a block of a transparent solid with index of refraction 1.73. (a) For what angle of incidence is the reflected light completely polarized? (b) For this angle of incidence, is the light refracted into the solid completely polarized, partially polarized, or unpolarized?

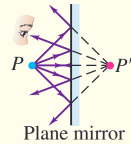
**VP33.6.2** You shine a beam of unpolarized light in air on a block of glass. You find that if the angle of incidence is 57.0°, the reflected light is completely polarized. Find (a) the index of refraction of the glass and (b) the angle of refraction.

**VP33.6.3** You shine a beam of *polarized* light in air on a piece of dense flint glass $(n = 1.66)$. (a) If the polarization direction is perpendicular to the plane of incidence, is there an angle of incidence for which no light is reflected from the glass? If so, what is this angle? (b) Repeat part (a) if the polarization direction is in the plane of incidence.

**VP33.6.4** A glass container holds water $(n = 1.33)$. If unpolarized light propagating in the glass strikes the glass–water interface, the light reflected back into the glass will be completely polarized if the angle of refraction is 53.5°. Find (a) the polarizing angle in this situation and (b) the index of refraction of the glass.

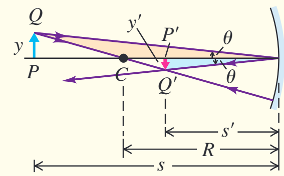
# CHAPTER 34 SUMMARY

**Reflection or refraction at a plane surface:** When rays diverge from an object point $P$ and are reflected or refracted, the directions of the outgoing rays are the same as though they had diverged from a point $P'$ called the image point. If they actually converge at $P'$ and diverge again beyond it, $P'$ is a real image of $P$; if they only appear to have diverged from $P'$, it is a virtual image. Images can be either erect or inverted.

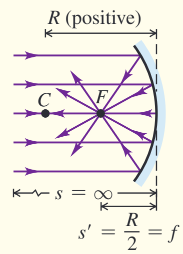



**Lateral magnification:** The lateral magnification $m$ in any reflecting or refracting situation is defined as the ratio of image height $y'$ to object height $y$. When $m$ is positive, the image is erect; when $m$ is negative, the image is inverted.

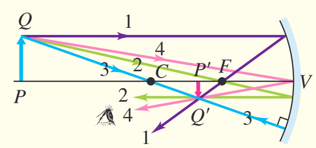
$$m = \frac{y'}{y} \tag{34.2}$$




**Focal point and focal length:** The focal point of a mirror is the point where parallel rays converge after reflection from a concave mirror, or the point from which they appear to diverge after reflection from a convex mirror. Rays diverging from the focal point of a concave mirror are parallel after reflection; rays converging toward the focal point of a convex mirror are parallel after reflection. The distance from the focal point to the vertex is called the focal length, denoted as $f$. The focal points of a lens are defined similarly.




**Relating object and image distances:** The formulas for object distance $s$ and image distance $s'$ for plane and spherical mirrors and single refracting surfaces are summarized in the table. The equation for a plane surface can be obtained from the corresponding equation for a spherical surface by setting $R = \infty$. (See Examples 34.1–34.7.)



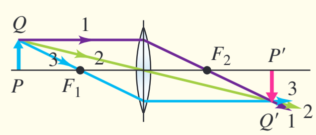

| | Plane Mirror | Spherical Mirror | Plane Refracting Surface | Spherical Refracting Surface |
|---|---|---|---|---|
| Object and image distances | $\frac{1}{s} + \frac{1}{s'} = 0$ | $\frac{1}{s} + \frac{1}{s'} = \frac{2}{R} = \frac{1}{f}$ | $\frac{n_a}{s} + \frac{n_b}{s'} = 0$ | $\frac{n_a}{s} + \frac{n_b}{s'} = \frac{n_b - n_a}{R}$ |
| Lateral magnification | $m = -\frac{s'}{s} = 1$ | $m = -\frac{s'}{s}$ | $m = -\frac{n_a s'}{n_b s} = 1$ | $m = -\frac{n_a s'}{n_b s}$ |

Object–image relationships derived in this chapter are valid for only rays close to and nearly parallel to the optic axis; these are called paraxial rays. Nonparaxial rays do not converge precisely to an image point. This effect is called spherical aberration.

**Thin lenses:** The object–image relationship, given by Eq. (34.16), is the same for a thin lens as for a spherical mirror. Equation (34.19), the lensmaker's equation, relates the focal length of a lens to its index of refraction and the radii of curvature of its surfaces. (See Examples 34.8–34.11.)

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \tag{34.16}$$

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \tag{34.19}$$

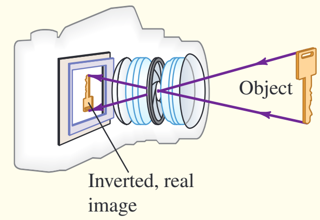



**Sign rules:** The following sign rules are used with all plane and spherical reflecting and refracting surfaces:

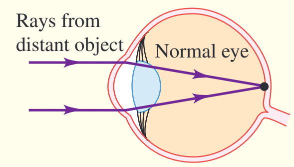
- $s > 0$ when the object is on the incoming side of the surface (a real object); $s < 0$ otherwise.
- $s' > 0$ when the image is on the outgoing side of the surface (a real image); $s' < 0$ otherwise.
- $R > 0$ when the center of curvature is on the outgoing side of the surface; $R < 0$ otherwise.
- $m > 0$ when the image is erect; $m < 0$ when inverted.

**Cameras:** A camera forms a real, inverted image of the object being photographed on a light-sensitive surface. The amount of light striking this surface is controlled by the shutter speed and the aperture. The intensity of this light is inversely proportional to the square of the $f$-number of the lens. (See Example 34.12.)

$$f\text{-number} = \frac{\text{Focal length}}{\text{Aperture diameter}} = \frac{f}{D} \qquad (34.20)$$

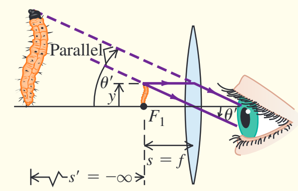



**The eye:** In the eye, refraction at the surface of the cornea forms a real image on the retina. Adjustment for various object distances is made by squeezing the lens, thereby making it bulge and decreasing its focal length. A nearsighted eye is too long for its lens; a farsighted eye is too short. The power of a corrective lens, in diopters, is the reciprocal of the focal length in meters. (See Examples 34.13 and 34.14.)

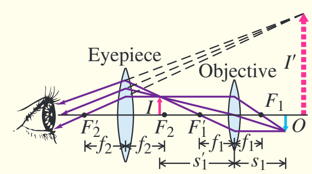



**The simple magnifier:** The simple magnifier creates a virtual image whose angular size $\theta'$ is larger than the angular size $\theta$ of the object itself at a distance of 25 cm, the nominal closest distance for comfortable viewing. The angular magnification $M$ of a simple magnifier is the ratio of the angular size of the virtual image to that of the object at this distance.

$$M = \frac{\theta'}{\theta} = \frac{25\text{ cm}}{f} \qquad (34.22)$$




**Microscopes and telescopes:** In a compound microscope, the objective lens forms a first image in the barrel of the instrument, and the eyepiece forms a final virtual image, often at infinity, of the first image. The telescope operates on the same principle, but the object is far away. In a reflecting telescope, the objective lens is replaced by a concave mirror, which eliminates chromatic aberrations.




Chapter 34 Media Assets

## GUIDED PRACTICE

For assigned homework and other learning materials, go to Mastering Physics.

### KEY EXAMPLE VARIATION PROBLEMS

**Be sure to review EXAMPLES 34.1, 34.3, and 34.4 (Section 34.2) before attempting these problems.**

**VP34.4.1** You place a light bulb 15.0 cm in front of a concave spherical mirror. The mirror forms an image of the bulb on a wall 4.50 m in front of the mirror. Find (a) the mirror's focal length, (b) the mirror's radius of curvature, and (c) the lateral magnification of the image.

**VP34.4.2** A concave spherical mirror has radius of curvature 37.0 cm. Find the image distance and lateral magnification for each of the following object distances. In each case state whether the image is real or virtual, whether it is erect or inverted, and whether it is larger or smaller than the object. (a) 11.0 cm; (b) 31.0 cm; (c) 55.0 cm.

**VP34.4.3** A spherical mirror has radius of curvature −44.0 cm. When you look at your eye in the mirror, your eye's reflection appears to be 18.0 cm behind the mirror's surface. (a) Is the mirror concave or convex? (b) How far is your eye from the mirror? (c) What is the lateral magnification of the image of your eye? Is the image real or virtual? Erect or inverted? Larger or smaller than your eye?

**VP34.4.4** A convex spherical mirror has radius of curvature −37.0 cm. Find the image distance and lateral magnification for each of the following object distances. In each case state whether the image is real or virtual, whether it is erect or inverted, and whether it is larger or smaller than the object. (a) 11.0 cm; (b) 31.0 cm; (c) 55.0 cm.

**Be sure to review EXAMPLE 34.8 (Section 34.4) before attempting these problems.**

**VP34.8.1** Both sides of a double convex thin lens have radii of curvature of the same magnitude. The lens is made of glass with index of refraction 1.65, and the focal length of the lens is +30.0 cm. Find the radius of curvature of (a) the front surface and (b) the back surface.

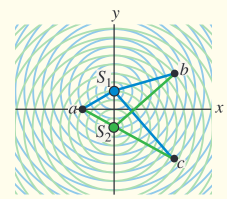
**VP34.8.2** The side of a thin lens that faces the object is convex and has radius of curvature 15.0 cm. The other side is concave and has radius of curvature 25.0 cm. The lens is made of glass with index of refraction 1.55. (a) Is this lens thicker at its center or at its edges? (b) What is the focal length of the lens? (c) Is the lens converging or diverging?

**VP34.8.3** The side of a thin lens that faces the object is convex and has radius of curvature 25.0 cm. The other side is concave and has radius of curvature 15.0 cm. The lens is made of glass with index of refraction 1.55. (a) Is this lens thicker at its center or at its edges? (b) What is the focal length of the lens? (c) Is the lens converging or diverging?

**VP34.8.4** You are designing a lens to be made of glass with index of refraction 1.70. The first surface (the surface toward the object) is to be convex with radius of curvature 28.0 cm, and the focal length of the lens is to be 14.0 cm. (a) What must be the radius of curvature of the second surface (the surface away from the object)? (b) Will the second surface be concave or convex?

# CHAPTER 35 SUMMARY

**Interference and coherent sources:** Monochromatic light is light with a single frequency. Coherence is a definite, unchanging phase relationship between two waves. The overlap of waves from two coherent sources of monochromatic light forms an interference pattern. The principle of superposition states that the total wave disturbance at any point is the sum of the disturbances from the separate waves.

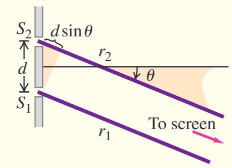



**Two-source interference of light:** When two sources are in phase, constructive interference occurs where the difference in path length from the two sources is zero or an integer number of wavelengths; destructive interference occurs where the path difference is a half-integer number of wavelengths. If two sources separated by a distance $d$ are both very far from a point $P$, and the line from the sources to $P$ makes an angle $\theta$ with the line perpendicular to the line of the sources, then the condition for constructive interference at $P$ is Eq. (35.4). The condition for destructive interference is Eq. (35.5). When $\theta$ is very small, the position $y_m$ of the $m$th bright fringe on a screen located a distance $R$ from the sources is given by Eq. (35.6). (See Examples 35.1 and 35.2.)

$$d\sin\theta = m\lambda \quad (m = 0, \pm 1, \pm 2, \ldots) \quad \text{(constructive interference)} \tag{35.4}$$

$$d\sin\theta = \left(m + \tfrac{1}{2}\right)\lambda \quad (m = 0, \pm 1, \pm 2, \ldots) \quad \text{(destructive interference)} \tag{35.5}$$

$$y_m = R\frac{m\lambda}{d} \quad (m = 0, \pm 1, \pm 2, \ldots) \quad \text{(bright fringes)} \tag{35.6}$$

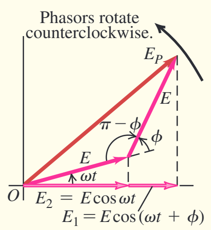



**Intensity in interference patterns:** When two sinusoidal waves with equal amplitude $E$ and phase difference $\phi$ are superimposed, the resultant amplitude $E_P$ and intensity $I$ are given by Eqs. (35.7) and (35.10), respectively. If the two sources emit in phase, the phase difference $\phi$ at a point $P$ (located a distance $r_1$ from source 1 and a distance $r_2$ from source 2) is directly proportional to the path difference $r_2 - r_1$. (See Example 35.3.)

$$E_P = 2E\left|\cos\frac{\phi}{2}\right| \tag{35.7}$$

$$I = I_0\cos^2\frac{\phi}{2} \tag{35.10}$$

$$\phi = \frac{2\pi}{\lambda}(r_2 - r_1) = k(r_2 - r_1) \tag{35.11}$$



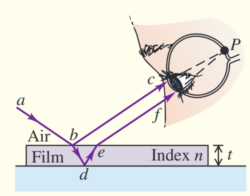

**Interference in thin films:** When light is reflected from both sides of a thin film of thickness $t$ and no phase shift occurs at either surface, constructive interference between the reflected waves occurs when $2t$ is equal to an integer number of wavelengths. If a half-cycle phase shift occurs at one surface, this is the condition for destructive interference. A half-cycle phase shift occurs during reflection whenever the index of refraction in the second material is greater than that in the first. (See Examples 35.4–35.7.)

$$2t = m\lambda \quad (m = 0, 1, 2, \ldots) \quad \text{(constructive reflection from thin film, no relative phase shift)} \tag{35.17a}$$

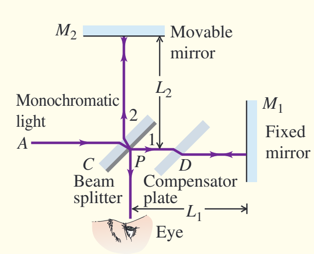
$$2t = \left(m + \tfrac{1}{2}\right)\lambda \quad (m = 0, 1, 2, \ldots) \quad \text{(destructive reflection from thin film, no relative phase shift)} \tag{35.17b}$$

$$2t = \left(m + \tfrac{1}{2}\right)\lambda \quad (m = 0, 1, 2, \ldots) \quad \text{(constructive reflection from thin film, half-cycle phase shift)} \tag{35.18a}$$

$$2t = m\lambda \quad (m = 0, 1, 2, \ldots) \quad \text{(destructive reflection from thin film, half-cycle phase shift)} \tag{35.18b}$$

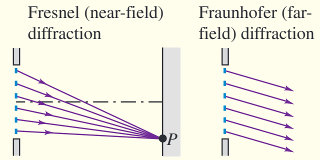



**Michelson interferometer:** The Michelson interferometer uses a monochromatic light source and can be used for high-precision measurements of wavelengths. Its original purpose was to detect motion of the earth relative to a hypothetical ether, the supposed medium for electromagnetic waves. The ether has never been detected, and the concept has been abandoned; the speed of light is the same relative to all observers. This is part of the foundation of the special theory of relativity.



# CHAPTER 36 SUMMARY

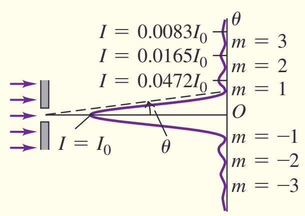
**Fresnel and Fraunhofer diffraction:** Diffraction occurs when light passes through an aperture or around an edge. When the source and the observer are so far away from the obstructing surface that the outgoing rays can be considered parallel, it is called Fraunhofer diffraction. When the source or the observer is relatively close to the obstructing surface, it is Fresnel diffraction.




**Single-slit diffraction:** Monochromatic light sent through a narrow slit of width $a$ produces a diffraction pattern on a distant screen. Equation (36.2) gives the condition for destructive interference (a dark fringe) at a point $P$ in the pattern at angle $\theta$. Equation (36.7) gives the intensity in the pattern as a function of $\theta$. (See Examples 36.1–36.3.)

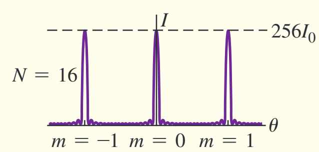
$$\sin\theta = \frac{m\lambda}{a} \quad (m = \pm 1, \pm 2, \pm 3, \ldots) \tag{36.2}$$

$$I = I_0\left\{\frac{\sin[\pi a(\sin\theta)/\lambda]}{\pi a(\sin\theta)/\lambda}\right\}^2 \tag{36.7}$$



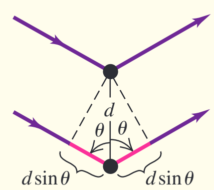

**Diffraction gratings:** A diffraction grating consists of a large number of thin parallel slits, spaced a distance $d$ apart. The condition for maximum intensity in the interference pattern is the same as for the two-source pattern, but the maxima for the grating are very sharp and narrow. (See Example 36.4.)

$$d\sin\theta = m\lambda \quad (m = 0, \pm 1, \pm 2, \pm 3, \ldots) \tag{36.13}$$



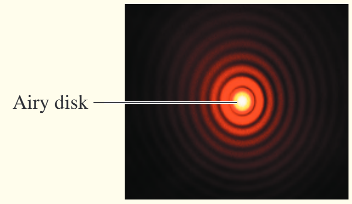

**X-ray diffraction:** A crystal serves as a three-dimensional diffraction grating for x rays with wavelengths of the same order of magnitude as the spacing between atoms in the crystal. For a set of crystal planes spaced a distance $d$ apart, constructive interference occurs when the angles of incidence and scattering (measured from the crystal planes) are equal and when the Bragg condition [Eq. (36.16)] is satisfied. (See Example 36.5.)

$$2d\sin\theta = m\lambda \quad (m = 1, 2, 3, \ldots) \tag{36.16}$$




**Circular apertures and resolving power:** The diffraction pattern from a circular aperture of diameter $D$ consists of a central bright spot, called the Airy disk, and a series of concentric dark and bright rings. Equation (36.17) gives the angular radius $\theta_1$ of the first dark ring, equal to the angular size of the Airy disk. Diffraction sets the ultimate limit on resolution (image sharpness) of optical instruments. According to Rayleigh's criterion, two point objects are just barely resolved when their angular separation $\theta$ is given by Eq. (36.17). (See Example 36.6.)

$$\sin\theta_1 = 1.22\frac{\lambda}{D} \tag{36.17}$$




Chapter 36 Media Assets

## GUIDED PRACTICE

For assigned homework and other learning materials, go to Mastering Physics.

### KEY EXAMPLE VARIATION PROBLEMS

**Be sure to review EXAMPLE 36.1 (Section 36.2) and EXAMPLES 36.2 and 36.3 (Section 36.3) before attempting these problems.**

**VP36.3.1** You pass laser light of wavelength 645 nm through a slit 0.250 mm in width and observe the diffraction pattern on a screen a large distance away. On the screen, the centers of the second minima on either side of the central bright fringe are 28.0 mm apart. (a) How far away is the screen? (b) What would the distance be between these minima if the wavelength were 525 nm?

**VP36.3.2** You shine a laser on a narrow slit 0.221 mm in width. In the diffraction pattern that appears on a screen 5.00 m from the slit, the third minimum is 45.7 mm from the middle of the central bright fringe. Find (a) the wavelength of the laser light and (b) the angle of a line from the center of the slit to the second dark fringe on the screen.

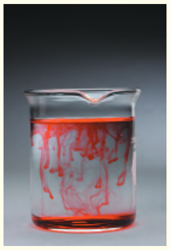
**VP36.3.3** At a certain point in a single-slit diffraction pattern there is a phase difference of 35.0 radians between wavelets arriving at the point from the two edges of the slit. The slit is 0.250 mm wide, and the light used has wavelength 545 nm. (a) What is the angle of a line from the center of the slit to this point in the diffraction pattern? (b) If the intensity at the center of the diffraction pattern is $I_0$, what is the intensity at this point?

**Entropy:** Entropy is a quantitative measure of the randomness of a system. The entropy change in any reversible process depends on the amount of heat flow and the absolute temperature $T$. Entropy depends only on the state of the system, and the change in entropy between given initial and final states is the same for all processes leading from one state to the other. This fact can be used to find the entropy change in an irreversible process. (See Examples 20.5–20.10.)

An important statement of the second law of thermodynamics is that the entropy of an isolated system may increase but can never decrease. When a system interacts with its surroundings, the total entropy change of system and surroundings can never decrease. When the interaction involves only reversible processes, the total entropy is constant and $\Delta S = 0$; when there is any irreversible process, the total entropy increases and $\Delta S > 0$.

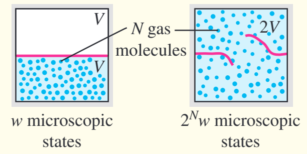
$$\Delta S = \int_1^2 \frac{dQ}{T} \qquad (20.19)$$

(reversible process)



**Entropy and microscopic states:** When a system is in a particular macroscopic state, the particles that make up the system may be in any of $w$ possible microscopic states. The greater the number $w$, the greater the entropy. (See Example 20.11.)

$$S = k \ln w \qquad (20.22)$$




Chapter 20 Media Assets

## GUIDED PRACTICE

For assigned homework and other learning materials, go to Mastering Physics.

### KEY EXAMPLE VARIATION PROBLEMS

**Be sure to review EXAMPLE 20.1 (Section 20.2) before attempting these problems.**

**VP20.1.1** A diesel engine has efficiency 0.180. (a) In order for this engine to do $1.24 \times 10^4$ J of work, how many joules of heat must it take in? (b) How many joules of this heat is discarded?

**VP20.1.2** In one cycle a heat engine absorbs $3.82 \times 10^4$ J of heat from the hot reservoir and rejects $3.16 \times 10^4$ J of heat to the cold reservoir. What is the efficiency of this engine?

**VP20.1.3** Measurements of a gasoline engine show that it has an efficiency of 0.196 and that it exhausts $4.96 \times 10^8$ J of heat during 20 minutes of operation. During that time, (a) how much heat does the engine take in and (b) how much work does the engine do?

**VP20.1.4** An aircraft piston engine that burns gasoline (heat of combustion $5.0 \times 10^7$ J/kg) has a power output of $1.10 \times 10^5$ W. (a) How much work does this engine do in 1.00 h? (b) This engine burns 34 kg of gasoline per hour. How much heat does the engine take in per hour? (c) What is the efficiency of the engine?

**Be sure to review EXAMPLES 20.2, 20.3 and 20.4 (Section 20.6) before attempting these problems.**

**VP20.4.1** In one cycle a Carnot engine takes in $8.00 \times 10^4$ J of heat and does $1.68 \times 10^4$ J of work. The temperature of the engine's cold reservoir is 25.0°C. (a) What is the efficiency of this engine? (b) How much heat does this engine exhaust per cycle? (c) What is the temperature (in °C) of the hot reservoir?

**VP20.4.2** For the Carnot cycle described in Example 20.3, you change the temperature of the cold reservoir from 27°C to −73°C. The initial pressure and volume at point $a$ are unchanged, the volume still doubles during the isothermal expansion $a \rightarrow b$, and the volume still decreases by one-half during the isothermal compression $c \rightarrow d$. For this modified cycle, calculate (a) the new efficiency of the cycle and (b) the amount of work done in each of the four steps of the cycle.

**VP20.4.3** A Carnot refrigerator has a cold reservoir at −10.0°C and a hot reservoir at 25.0°C. (a) What is its coefficient of performance? (b) How much work input does this refrigerator require to remove $4.00 \times 10^6$ J of heat from the cold reservoir?

**VP20.4.4** A Carnot engine uses the expansion and compression of $n$ moles of argon gas, for which $C_V = \frac{3}{2}R$. This engine operates between temperatures $T_C$ and $T_H$. During the isothermal expansion $a \rightarrow b$, the volume of the gas increases from $V_a$ to $V_b = 2V_a$. (a) Calculate the work $W_{ab}$ done during the isothermal expansion $a \rightarrow b$. Give your answer in terms of $n$, $R$, and $T_H$. (b) Calculate the work $W_{bc}$ done during the adiabatic expansion $b \rightarrow c$. Give your answer in terms of $n$, $R$, $T_C$ and $T_H$. (c) For this engine, $W_{ab} = W_{bc}$. Find the ratio $T_C/T_H$ and the efficiency of the engine.

**Be sure to review EXAMPLES 20.6, 20.7, 20.8, 20.9, and 20.10 (Section 20.7) before attempting these problems.**

**VP20.10.1** Ethanol melts at 159 K (heat of fusion $1.042 \times 10^5$ J/kg) and boils at 351 K (heat of vaporization $8.54 \times 10^5$ J/kg). Liquid ethanol has a specific heat of 2428 J/kg · K (which we assume does not depend on temperature). If you have 1.00 kg of ethanol originally in the solid state at 159 K, calculate the change in entropy of the ethanol when it (a) melts at 159 K, (b) increases in temperature as a liquid from 159 K to 351 K, and (c) boils at 351 K.

**VP20.10.2** Initially 5.00 mol of helium (which we can treat as an ideal gas) occupies volume 0.120 $m^3$ and is at temperature 20.0°C. You allow