Chapter 11

...you create a transverse wave that
moves along the spring with speed v.

Each loop of the spring is displaced
transversely as the wave passes.

(a) Transverse wave

If you give a spring a back-and-forth twitch …

…you create a compression wave that
travels along the spring with speed v.

Each loop of the spring is displaced
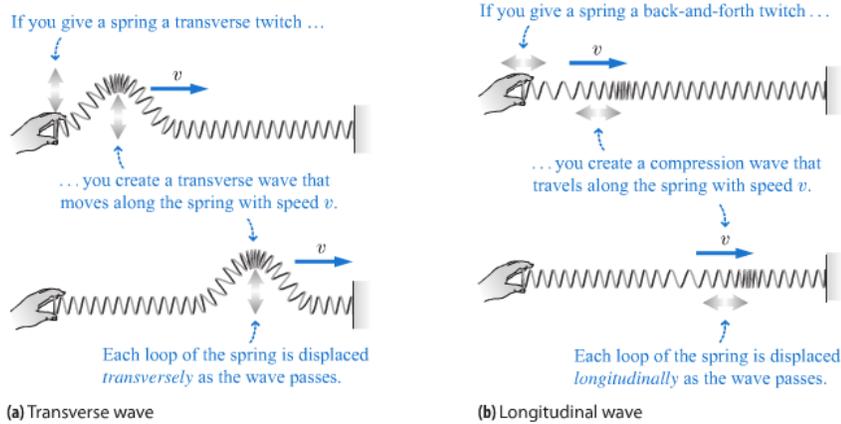*longitudinally* as the wave passes.

(b) Longitudinal wave

FIGURE 11.1 Transverse and longitudinal waves.

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Oscillator vibrates up and down in simple
harmonic motion with constant frequency,
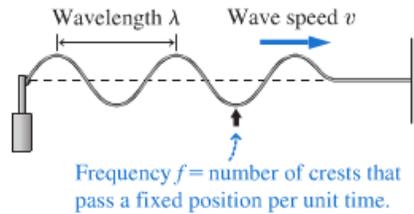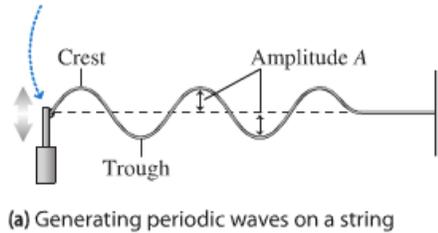generating periodic waves on the string.

Crest   Amplitude A

Trough

(a) Generating periodic waves on a string

Wavelength λ Wave speed v

Frequency f = number of crests that
pass a fixed position per unit time.

(b) Wavelength, wave speed, and frequency

FIGURE 11.3 Periodic waves.

Because $f = 1/T$, this means that the wave speed is

$$v = \lambda f \qquad \text{(Speed of a periodic wave; SI unit: m/s)} \qquad (11.1)$$

Equation 11.1 is a fundamental relationship for all periodic waves, linking wave speed, wavelength, and frequency.
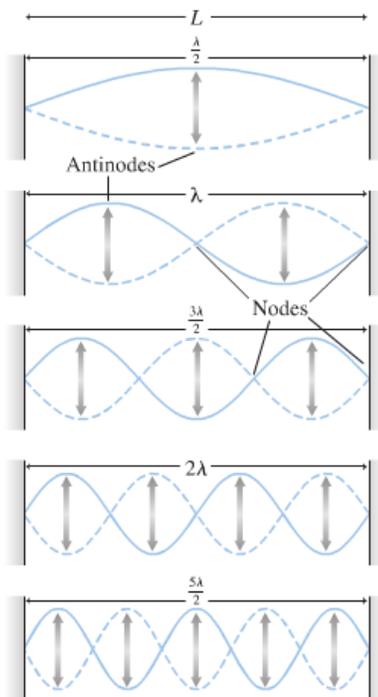
FIGURE 11.9 Standing waves on a string clamped at both ends; shown are the fundamental and four overtones. Note that the distance between antinodes is always $\lambda/2$.

Figure 11.9 also shows that the distance between adjacent nodes is just half a wavelength, or $\lambda/2$. But we've just seen that the node spacing is L/n, so $L/n = \lambda/2$. Therefore, the allowed wavelengths for standing waves are

$$\lambda = \frac{2L}{n}$$
(Wavelength of standing waves on a string, with $n = 1, 2, 3, \ldots$; SI unit: m)
(11.2)

Wave Speed, Tension, and Density

You've seen how the fundamental frequency of a vibrating string depends on the wave speed. But what determines the speed of waves on a particular string? Both experimentally and through calculus, we find that two factors affect wave speed: the string's tension, T, and its linear mass density (mass per unit length), μ. The resulting wave speed is

$$v = \sqrt{\frac{T}{\mu}}$$
(11.3)

In SI units, tension is in N and linear mass density in kg/m. You can verify that this combination gives a speed in m/s.

As with any periodic wave, use the basic relation $v = \lambda f$ for sound.

Table 11.1 shows that the speed of sound in air increases with increasing temperature. For everyday temperatures, the dependence is approximately linear:
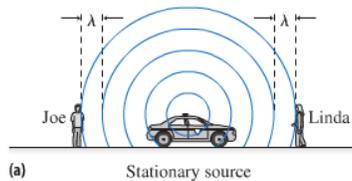
$$v(T) = 331 \text{ m/s} + 0.60T \tag{11.4}$$

with T in Celsius.

Sound intensity level where $I_o = 10^{-12}$ W/m^2

$$\beta \,(\text{in dB}) = 10 \log\left(\frac{I}{I_0}\right)$$

When source is stationary, wavelength and frequency are the same for both listeners.

λ λ

Joe   Linda

(a)   Stationary source

When source is moving to right, Joe hears a lower frequency (longer wavelength) than does Linda.

λ' λ'

Joe   Linda

v_s
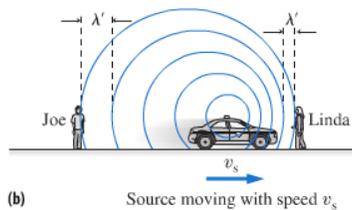
(b)   Source moving with speed v_s

FIGURE 11.17 The Doppler effect causes Joe and Linda to hear the sound at different frequencies.

$$f' = \frac{v}{\lambda'} = \frac{v}{(v - v_s)T} = \frac{v}{(v - v_s)}f$$

Dividing the numerator and denominator by v leads to

$$f' = \frac{f}{1 - v_s/v} \quad \text{(Doppler effect, source approaching; SI unit: Hz)} \tag{11.7}$$

When $v_s < v$, Equation 11.7 shows that the perceived frequency f' is greater than the source frequency f. Joe's situation is analogous, now with the wavelength *increased* by v_sT, giving a perceived frequency

$$f' = \frac{f}{1 + v_s/v} \quad \text{(Doppler effect, source receding; SI unit: Hz)} \tag{11.8}$$

Chapter 12

Temperature Scales

The **Fahrenheit temperature scale** (°F) is in everyday use in the United States. The German physicist Daniel Fahrenheit devised this scale in 1724, with 0°F set as the freezing point of a saturated solution of salt water and 32°F as the melting point of freshwater. Later the scale was adjusted, with 32°F kept as one reference point but water's boiling point, 212°F, used as the other. On this scale, normal body temperature is 98.6°F. The actual resting body temperature of a healthy human typically varies between 98.0°F and 98.6°F.

Scientists use the **Celsius temperature scale** (°C), with water's freezing and boiling points (under normal atmospheric pressure) at 0°C and 100°C, respectively. The conversion from Fahrenheit to Celsius is

$$T \text{ in } °C = \tfrac{5}{9}(T \text{ in } °F - 32°)$$

For example, on a warm 77°F day the Celsius temperature is

$$T \text{ in } °C = \tfrac{5}{9}(77° - 32°) = \tfrac{5}{9}(45°) = 25°C$$

Another important scale is the **Kelvin scale** (K). (That's the SI unit kelvin, *not* degrees kelvin or °K.) The kelvin and the Celsius degree are the same size, but the zero points differ by 273.15 K. Thus, the conversion between degrees Celsius and kelvins is

$$(T \text{ in } K) = (T \text{ in } °C) + 273.15$$

$$\frac{\Delta L}{L} = \alpha \Delta T \qquad \text{(Linear thermal expansion)}$$

$$\frac{\Delta V}{V} = \beta \Delta T \qquad \text{(Volume thermal expansion)}$$

Amount of gas

of moles n. Recall that one **mole** (mol) is Avogadro's number N_A of anything, where $N_A = 6.022 \times 10^{23}$. Therefore, N and n are related by $N = N_A n$. For example, the

Combining these results gives the **ideal-gas law**, a single equation relating all four variables:

$$PV = nRT \qquad \text{(Ideal-gas law)} \qquad (12.3)$$

The quantity R in Equation 12.3 is the **molar gas constant**. Its value, determined experimentally, is $R = 8.315 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$.

The quantity R/N_A defines **Boltzmann's constant**, $k_B = R/N_A$, so the ideal-gas law becomes

$$PV = Nk_BT \qquad \text{(Ideal-gas law, molecular version)} \qquad (12.4)$$

Numerically, Boltzmann's constant is $k_B = 1.38 \times 10^{-23}$ J/K. You can think of it as the **molecular gas constant**, which plays the same role in this version of the ideal-gas law as the molar gas constant R plays in the version $PV = nRT$.

$$P = \frac{Nm\overline{v^2}}{3V} \qquad \text{(Gas pressure; SI unit: Pa)} \qquad (12.5)$$

Here V is the container volume, N the number of gas molecules, and m the molecular mass. The quantity $\overline{v^2}$ is called the **mean-square speed**. As usual, the bar designates an average, and here it refers to the average of the squares of the molecular speeds—hence, *mean square.* The square root of $\overline{v^2}$ is called **root-mean-square speed** (or **rms speed**): $v_{\text{rms}} = \sqrt{\overline{v^2}}$. The root-mean-square speed is a typical speed for a gas molecule.

the **average molecular kinetic energy** $\overline{K}$, because $\overline{K} = \frac{1}{2}m\overline{v^2}$. Therefore, the average molecular kinetic energy is

$$\overline{K} = \tfrac{3}{2}k_BT \qquad \text{(Average molecular kinetic energy; SI unit: J)} \qquad (12.6)$$

Thermal energy for monoatomic gas

$$E_{\text{th}} = N\overline{K} = \tfrac{3}{2}Nk_BT \qquad \text{(Total thermal energy; SI unit: J)}$$

The Maxwell distribution is a function $F(v)$ that gives the relative probability of a molecule having a particular speed v:

$$F(v) = 4\pi\left(\frac{m}{2\pi k_BT}\right)^{3/2} v^2 e^{-\frac{mv^2}{2k_BT}} \qquad (12.8)$$

where m is the mass of a molecule in a gas at temperature T. The Maxwell distribution is mathematically complicated, so it's more instructive to graph it, as in Figure 12.11. The **most probable speed**, v^*, occurs at the peak of the distribution; its value is $v^* = \sqrt{2k_BT/m}$. But

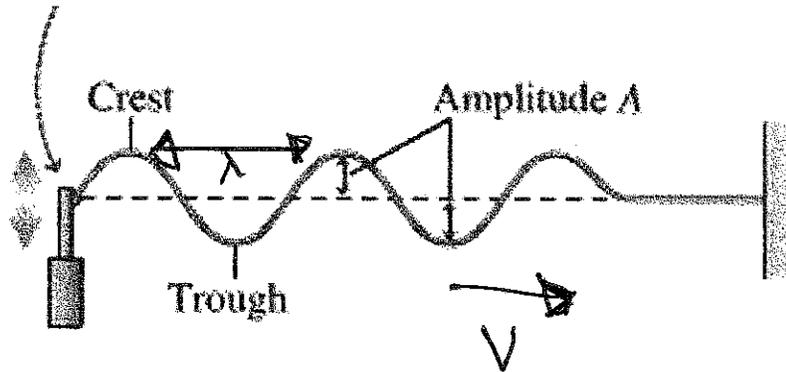Crests of Ocean waves pass a boat at rest every 10 sec. If the waves are moving at 4 m/s, what is their wavelength ?
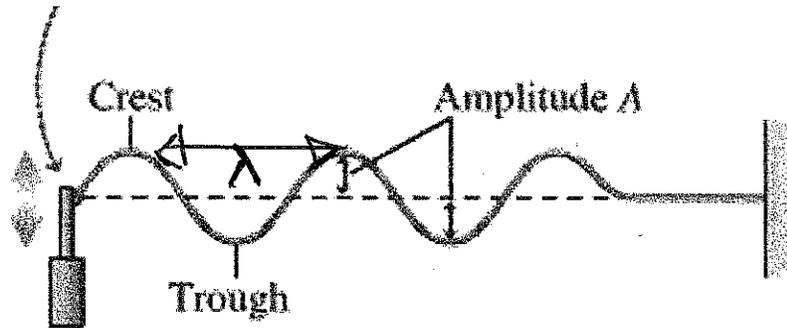
$$\lambda = v.T$$

where T = 10 sec and v = 4 m/s

then λ = (4 m/s).(10 sec) = 40 m

What is the speed of a wave with a wavelength of 15 cm and frequency of 2 kHz ?

$$\lambda = v.T$$

and T = 1/f

where f = 2 KHz = 2000 Hz

and λ = 15 cm = 0.15 m

then λ = v.T = v/f and v= λ.f = (0.15m).(2000 Hz) = 300 m/s

Ultrasound with f=4.8 MHz is used in medical imager. Find the wavelength in

  i)   Air where sound speed is 343 m/s
  ii)   In muscle tissues where sound speed is 1580 m/s

Answers:

i)

$$\lambda = V \cdot T = \frac{V}{f}$$

SOLVE   Plugging in values:

Part (a): Wavelength in air is $\lambda = \dfrac{343 \text{ m/s}}{4.8 \times 10^6 \text{ Hz}} = 71 \ \mu\text{m}.$

Part (b): Wavelength in muscle is $\lambda = \dfrac{1580 \text{ m/s}}{4.8 \times 10^6 \text{ Hz}} = 330 \ \mu\text{m}.$

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iii)

Transverse waves propagate at 30 m/s in a metal wire subjected to tension of 40 N. The wire is 10 m long. What is its mass?

(a)
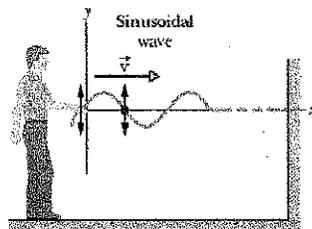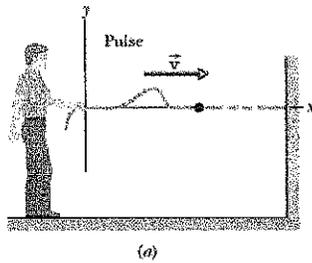
$V = \sqrt{\tau/\mu}$ and mass m = μ. Length $\quad V^2 = \tau/\mu$

Therefore, $\mu = \tau/V^2$ and $m = (\tau/V^2)$.Length

$m = (40 \text{ N}/30^2 \text{ m/s}).(10 \text{ m}) = 0.444 \text{ kg}$

A rope, 6 m in length, is fixed at both ends and tightened until the wave speed is 50 m/s. What is the frequency of the standing wave shown in the figure below ?
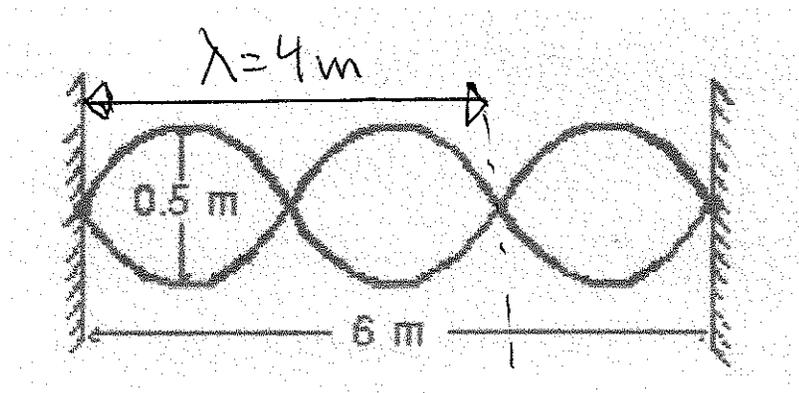
By definition λ = v.T and T = 1/f where f(Hz)

So λ = v/f.   Therefore, f = v/ λ = (50 m/s)/(4m) = 12.5 Hz

What is the intensity level in decibels of a sound wave whose intensity is 10^{-6} W/m^2 ?

By definition β (dB) = 10 log (I/I_o) where $I_o = 10^{-12}$ W/m^2 and $I = 10^{-6}$ W/m^2

So β (dB) = 10 log ($10^{-6} / 10^{-12}$) = 10 log (10^{+6}) = 10 . 6 = 60 dB

An cruise ship is approaching a harbor at a speed of 10 m/s. The captain sounds 100 Hz whistle. The air is still and the speed of sound in air is 343 m/s. What is the frequency of the ship whistle tone heard in the harbor ?

By definition $f' = f/(1 - v_s/v_a)$ where $v_s = 10$ m/s, $v_a = 343$ m/s and f = 100 Hz

Therefore f' = 100 Hz / (1- 10 / 343) = 100 / (0.97) = 103.1 Hz

The Four Basic Properties of Logs

1. $\log_b(xy) = \log_b x + \log_b y$.

2. $\log_b(x/y) = \log_b x - \log_b y$.

3. $\log_b(x^n) = n \log_b x$.

4. $\log_b x = \log_a x / \log_a b$.

43. A 200 cm open organ with one end open pipe is in resonance with a sound wave of wavelength 270 cm. The pipe is operating in its:

1) fundamental frequency
2) first overtone
3) second overtone
4) third overtone
5) fourth overtone

$L = 2m$ $f = ?$
$\lambda = 2.7m$

$L = 2m$
$\lambda = 2.7m$

$f = \frac{nV}{4L}$; $\lambda = \frac{4L}{n}$

$\frac{4L}{\lambda} = n = \frac{4 \times 2}{2.7} \approx 3$

$n = 1$ fundamental
$n = 3$ first

$\lambda = 1.33\,m$

Ans: 2

Outgoing waves

Radar gun

Reflected waves (higher frequency)

Radar gun
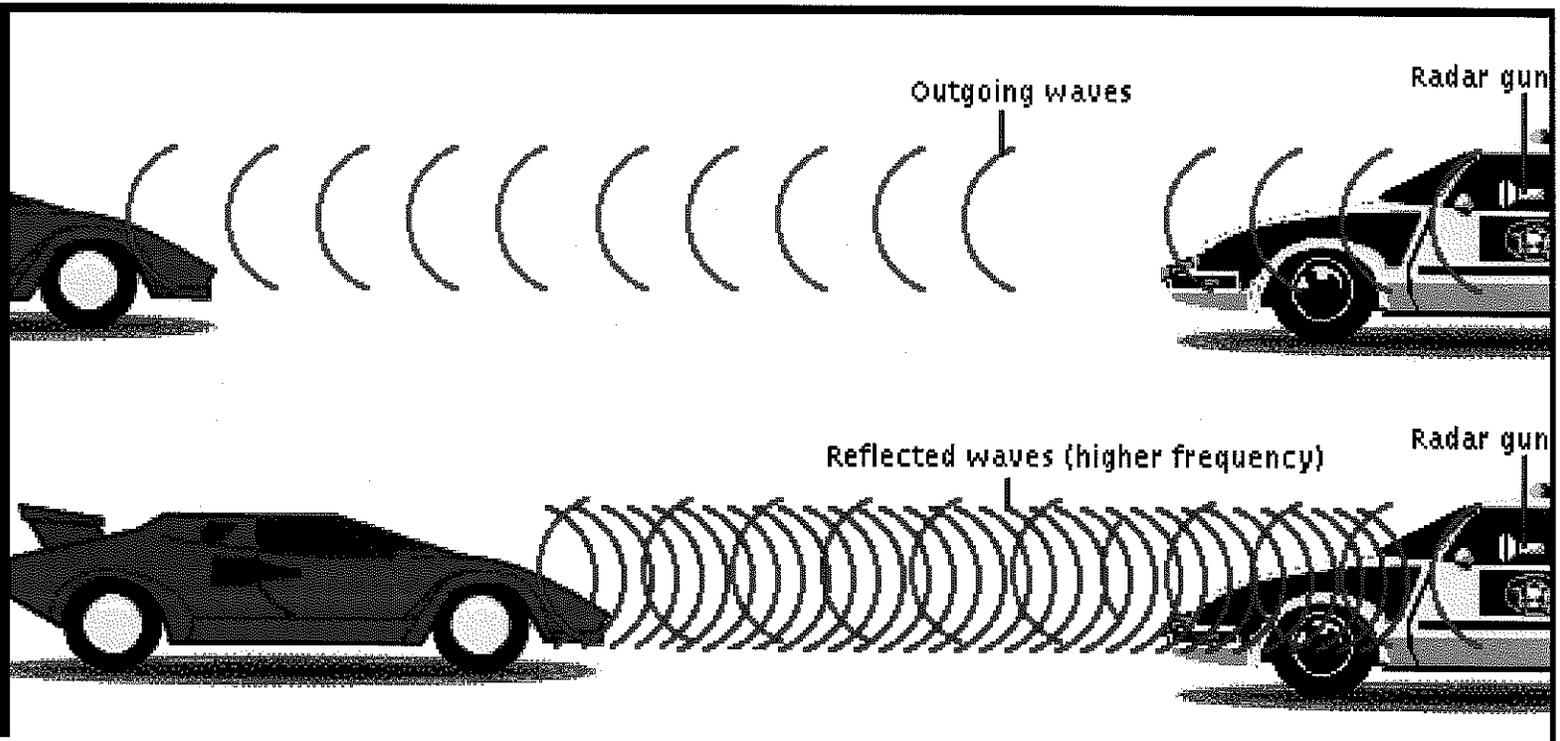
$T = 5°F, \quad T \to °C = ?$

25. **ORGANIZE AND PLAN** We convert °F to °C using:

$$T(°C) = \frac{5}{9}\left(T(°F) - 32°\right)$$

SOLVE $T(°C) = \frac{5}{9}\left(5°F - 32°\right) = -15°C$

REFLECT 32°F corresponds to 0°C, the temperature at which water freezes.

Temperature for storage of some delicate equipment is 78 K. Express this temperature in Celsius ?

$$T [K] = T\,^\circ C + 273.15$$

$$\text{So } T\,^\circ C = T [K] - 273.15 = -195.15\,^\circ C$$

38. **ORGANIZE AND PLAN**   We use the equation for linear expansion, $\frac{\Delta L}{L} = \alpha \Delta T$, solved for ΔL, and with the expansion coefficient of steel, α, from Table 12.1.

SOLVE $\Delta L = \alpha \Delta T L = \left(1.2 \times 10^{-5}\,^\circ C^{-1}\right) \times \left(60^\circ C\right) \times \left(246\text{ m}\right) = 0.177\text{ m}$

REFLECT   The building height differs by about 18 cm!

$$\beta = 9.5 \times 10^{-4}\ °C^{-1}$$

100-gallon $(378.5\ \ell) \rightarrow 12°C$; $V = ?$ at $39°C$

40. ORGANIZE AND PLAN We use the equation for volume thermal expansion, $\frac{\Delta V}{V} = \beta\ \Delta T$, and **solve** for the change in volume.

SOLVE $\Delta V = \beta\ \Delta TV = (9.5 \times 10^{-4}\ °C^{-1}) \times (39°C - 12°C) \times (378.5\ L) = 9.7\ L$

REFLECT The gasoline expanded by about 2.5%, making the expansion tank absolutely necessary.

$12°C$ $39°C$

(100-gallon 378.5 ℓ)

$? ($
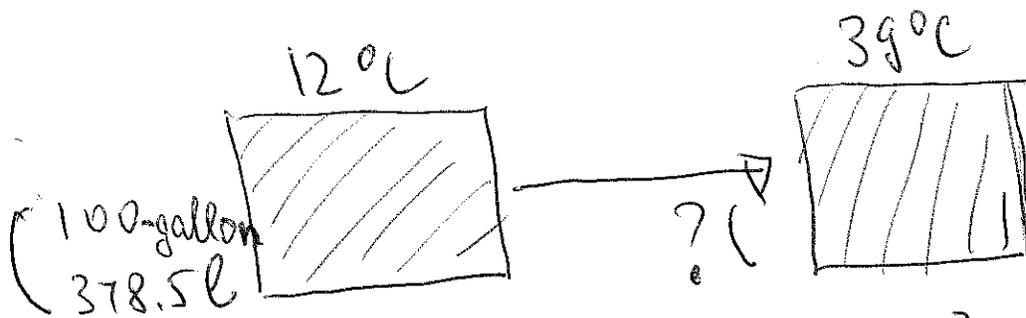
1 gallon = 3.785 ℓ ; 1 liter = $10^{-3}\ m^3$

β — from tabulated values

$\beta = 9.5 \times 10^{-4}\ C^{-1}$

$$\frac{9.7\ \ell}{378\ \ell} = 0.0257 \approx 2.5\%$$

The amount of gas:

1 mol $6.022 \times 10^{23} = N_A$

$N = N_A \cdot n$

$2.85 \ mol = (6.022 \times 10^{23})(2.85) = 1.72 \times 10^{24} \ molecules$

$M_{molar}(O_2) = 32g = 16_{(O)} + 16_{(O)} = 32 \ O_2$

$$1\ mol \longrightarrow 6.022 \times 10^{23} \overset{\underset{N_A}{\uparrow}}{} molecules$$

$$N = n \cdot N_A$$

$g \cdot mol^{-1}$

Chart Key:

element name
atomic number
symbol
atomic weight

solid	liquid	gas	synth
C	Br	He	Tc

Alkali Metals
Alkaline Earth Metals
Transition Metals
Other Metals
Non-metals
Noble Gases
Lanthanoids
Actinoids

1 mol Ar   1.5 mol UF$_6$

0.25 mol CO$_2$

2.6 mol Ne

49. ORGANIZE AND PLAN   First, we determine the molecular weights of the atoms and molecules under questions. Then we use $m = Mn,$ where M is the molecular weight and n is the number of moles.

SOLVE

(a) $m(\text{Ar}) = M(\text{Ar})\ n = (40 \text{ g mol}^{-1}) \times (1 \text{ mol}) = 40 \text{ g}$

(b) $m(\text{CO}_2) = M(\text{CO}_2)\ n = (44 \text{ g mol}^{-1}) \times (0.25 \text{ mol}) = 11 \text{ g}$ $C(12) + O(16) + O(16) \approx 44$

(c) $m(\text{Ne}) = M(\text{Ne})\ n = (20 \text{ g mol}^{-1}) \times (2.6 \text{ mol}) = 52 \text{ g}$

(d) $m(\text{UF}_6) = M(\text{UF}_6)\ n = (352 \text{ g mol}^{-1}) \times (1.5 \text{ mol}) = 528 \text{ g}$ $U(238) + 6 * (18) \approx 352$

A 10 liter tank contains ideal gas at 30 °C and a pressure of 15 atm. How many moles of gas are in the tank ?

Equation of state for ideal gas: $p.V = n.R.T$ so $n = (P_i V) / (R_g T)$

Where p – pressure in Pa, V – volume in m^3, n – number of moles, R – gas constant = 8.31 $J.mol^{-1} K^{-1}$

and T – temperature in "K". Note $T [K] = T °C + 273 = 303 K$. Also, note 1 atm = 1.013×10^5 Pa and

1 liter = $10^{-3} m^3$

Then $n = (15 \times 1.013 \times 10^5 [Pa] \times 10 [liters] \times 10^{-3} [m^3]) / (8.31 [J.mol^{-1} K^{-1}] \times 303 [K]) = 6$ moles

Ideal gas is in a closed metal cylinder. If its pressure is 1000 Pa initially, and its temperature is 293 K, what is its pressure after its temperature is raised to 333 K ?

Equation of state (atomic) for ideal gas: $p.V = n.R.T$

So for the initial state: $p_1.V_1 = N.k_B.T_1$ Note: $V_1 = V_2$
And for the final state: $P_2.V_2 = N.k_B.T_2$

Therefore, $(p_1)/(p_2) = T_1/T_2$

and isolating $p_2 = (p_1 \times T_2)/T_1$

$p_2 = (1000 [Pa] \times 333 [K])/(293 [K])$

$p_2 = 1137 Pa$

A container fitted with a movable lid contains ideal gas at 50 °C, pressure of 5 atm and volume of 2 m^3. What would be the final temperature if the gas is compressed to 1 m^3 and the pressure rises to 10 atm ?

Equation of state for ideal gas: $p.V = n.R.T$

So for the initial state: $p_1.V_1 = n.R.T_1$ Note, $T_1 [K] = T °C + 273 = 323$ K.
And for the final state: $P_2.V_2 = n.R.T_2$

Therefore, $(p_1.V_1)/(p_2.V_2) = T_1 / T_2$

and isolating $T_2 = (p_2.V_2)xT_1 / (p_1.V_1)$

$T_2 = (p_2.V_2)xT_1 / (p_1.V_1) = (10x1.013x10^5 [Pa] x1 m^3 x 323 [K]) / (5x1.013x10^5 [Pa] x2 m^3)$

$T_2 = 327$ K

Sample Problem 19-3

Here are five numbers: 5, 11, 32, 67, and 89.

(a) What is the average value of these numbers?

$$n_{avg} = \frac{5+11+32+67+89}{5} = 40.8$$

(b) What is the *rms* value n_{rms} of these numbers?

$$n_{rms} = \sqrt{\frac{5^2 + 11^2 + 32^2 + 67^2 + 89^2}{5}} = 52.1$$

$\underbrace{}_{\sqrt{}}$

Find the thermal energy of 3.5 mol of monoatomic gas at 293 K and 1. Note the molar gas constant $R = 8.315 \text{ J/(mol.K)}$

By definition $E_{th} = (3/2).N.k_B.T$

where $N = N_A.n$

Here "N_A" is so-called Avogardro's number and "n" – number of moles.

Also, $k_B = R/N_A$, therefore $E_{th} = (3/2).N.k_B.T = (3/2).(N_A .n)(R/N_A) .T$

$= (3/2).n. R .T$

In our case $E_{th} = (3/2).(3.5). (8.315).(293) = 12.8 \text{ kJ}$

At what temperature would the average thermal/most probable speed of oxygen molecules be 33 m/s ? The mass of O_2 molecule is 5.312 x10^{-26} kg.

Average thermal/most probable speed is $v^* = \sqrt{2k_\mathrm{B}T/m}$.

Therefore, $(v^*)^2 = 2k_BT/m$ and so T = $(v^*)^2$ x m(O_2)/(2 x k_B)

$\qquad\qquad\qquad\qquad$ = $(33 \text{ m/s})^2$ x 5.312 x10^{-26} kg/(2 x 1.38 x 10^{-23} J/K)

$\qquad\qquad\qquad\qquad$ = 2.1 K

Find the average kinetic energy of a molecule of ideal gas at 654 K. The value of Boltzmann's constant $k_B = 1.38 \times 10^{-23}$ J/K.

By definition the average kinetic energy of a molecule is $K = (3/2) . K_B . T$

Therefore, in our case, $K = (3/2) . (1.38 \times 10^{-23}) . (654) = 1.35 \times 10^{-20}$ J