Chapter 10

Thermal Physics, Temperature and Heat

Some Vocabulary

Thermodynamics:
- Study of energy transfers (engines)
- Changes of state (solid, liquid, gas...)

Heat:
- Transfer of microscopic thermal energy

Thermal Equilibrium:
- Condition after two objects are in thermal contact and finish exchanging heat.

Zeroth Law of Thermodynamics

If A is in thermal equilibrium with B and B is in thermal equilibrium with C, A is in thermal equilibrium with C.

- allows definition of temperature
- objects at thermal equilibrium have same T
- Heat moves from high T to low T objects

Thermometers

Exploit temperature sensitivity of

- volume or length
- pressure
- electric resistance
- color
- average particle speeds

Temperature Scales

Celsius:

- **Water freezes at 0 °C, boils at 100 °C**

Farenheit:

- **Water freezes at 32 °F, boils at 212 °F**

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

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

Absolute Temperature

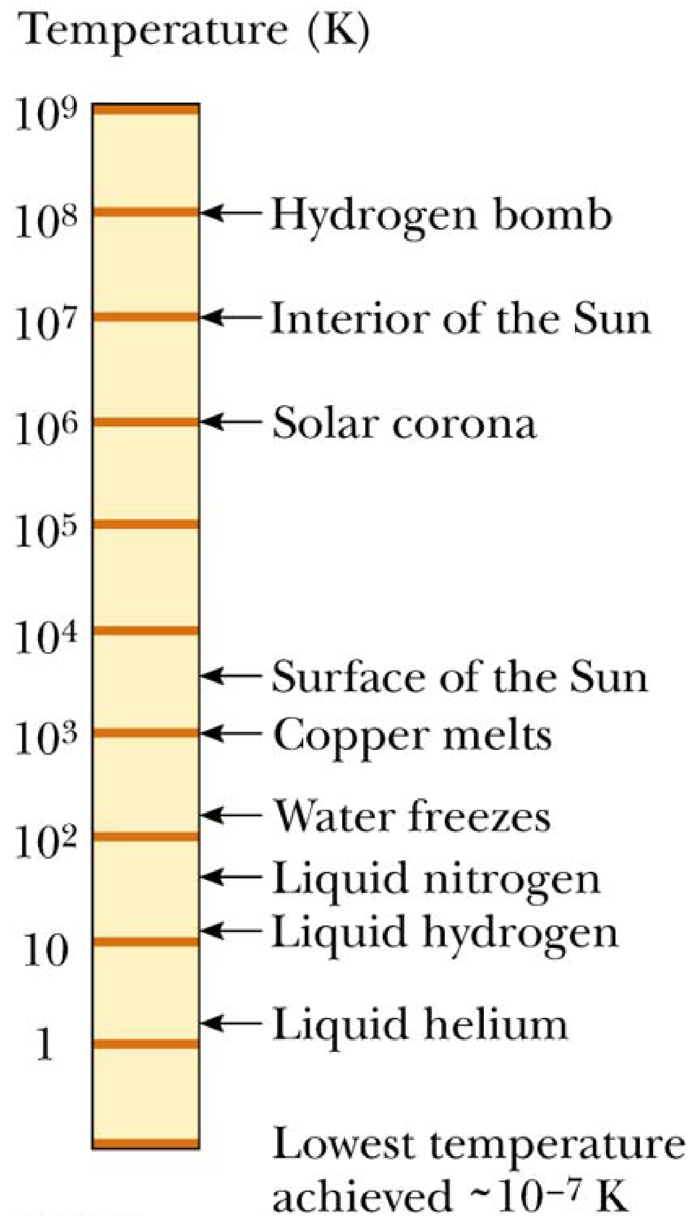
Kelvin Scale:

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

- **Lowest possible energy at T=0 °K**
- **Energy minimized at T=0**
- **Ideal gas law only makes sense for absolute scale**

Some Temperatures

- Lowest laboratory T ~ 10^{-7} °K
- At RHIC, T ~ 10^{13} °K
- In big bang,
  T ~ 10^{40} °K or more



Thermal Expansion

- At high T increased molecular vibration pushes molecules further apart

$$\frac{\Delta L}{L_0} = \alpha \, \Delta T$$

Coefficient of Linear Expansion

Property of Material

Area and Volume Expansion

Each dimension (length, width & height) stretch

$$\frac{\Delta L}{L_0} = \alpha \ \ \Delta T$$

$$\frac{\Delta A}{A_0} = \gamma \ \ \Delta T, \gamma = 2\alpha$$

$$\frac{\Delta V}{V_0} = \beta \ \ \Delta T, \beta = 3\alpha$$

Example 10.1

The coefficient of volume expansion of water at 20 °C is β=2.07x10^{-4} °K^{-1}. If the average depth of the ocean is 4000 m, by what height would the oceans rise due to thermal expansion if Earth's temperature rises by 2 °C?

1.65 m

If you live on a beach where the slope of the beach is one meter height per 100 meters, how much of your beach would disappear?

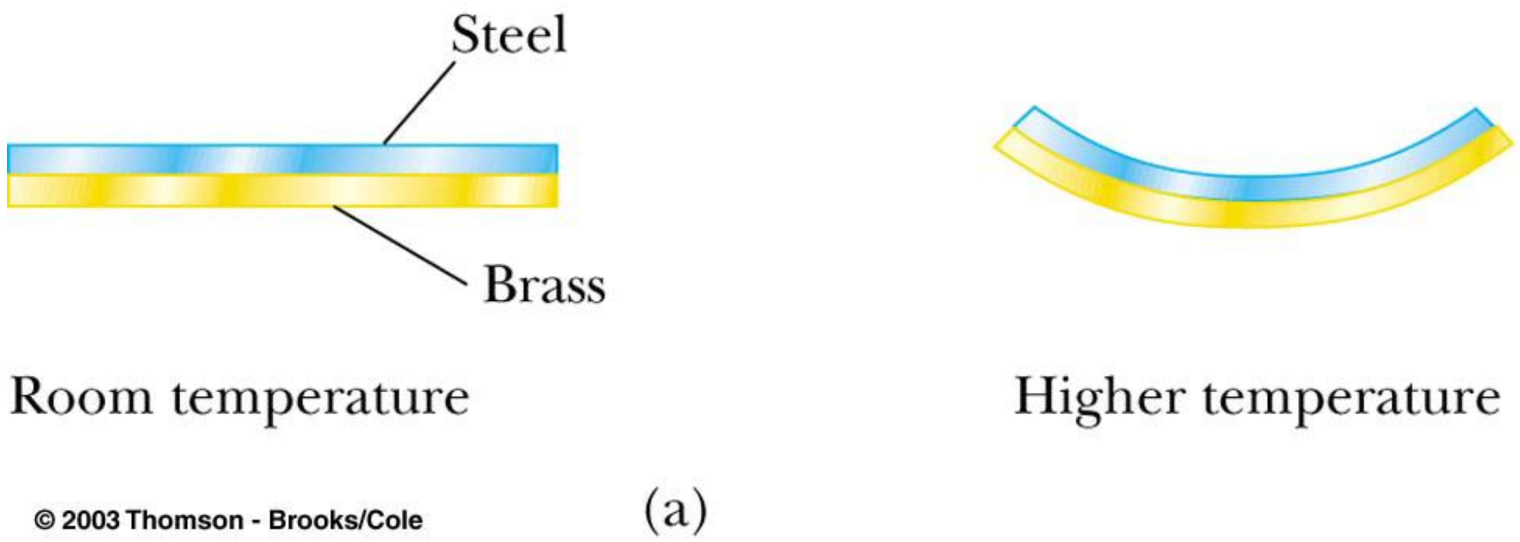
165 m
(warming doesn't go to all depths, land also expands)

Global Warming

http://www.ncdc.noaa.gov/oa/climate/globalwarming.html

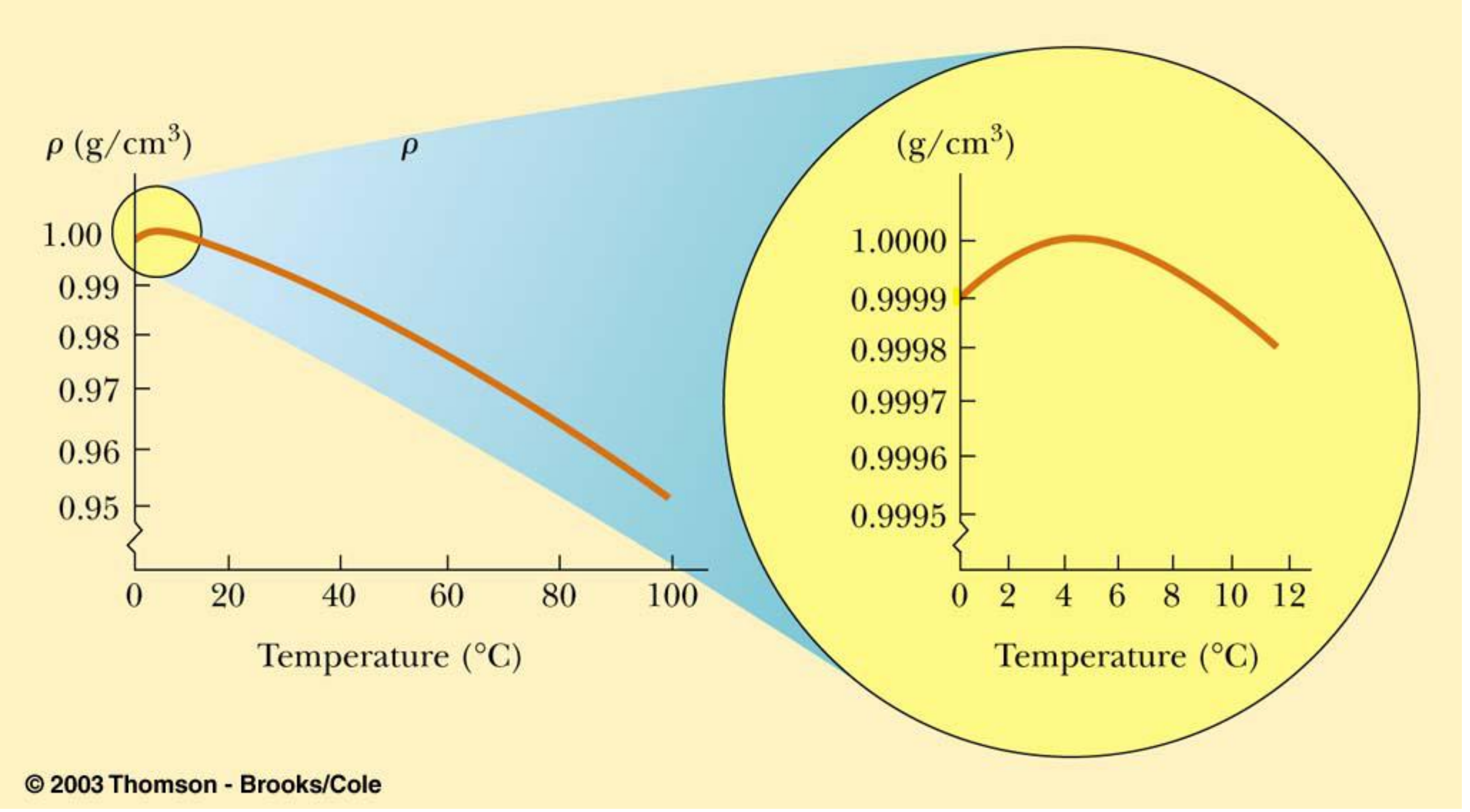
- T rose ~ 0.6 °C in last ~ 100 years
- T rose ~ 0.25 °C in last ~ 25 years
  Expected to rise from 1.5 to 4 °C by 2100 years
  Should rise higher in mid-upper latitudes
- Sea levels rise ~ 1-2 mm per year in last 100 years
  may rise from 10 cm to 90 cm by 2100
- Melting Antarctic ice caps are important

Application: Bimetallic Strip



- Used in thermostats

Water is Weird



- Density INCREASES between 0°C and 4 °C
- Maximum density of water is 1000 kg/m³ at 4 °C
- Density of ice = 917 kg/m³ .... Ice floats!

Ideal Gas Law

For sufficiently dilute gas,
pressure is:

- proportional to number
- proportional to temperature
- inversely proportional to volume

$$PV = nRT$$

pressure (P)
volume (V)
number of moles (n)
Ideal Gas Constant (R)
temperature (T)

Ideal Gas Law

$$PV = nRT$$

- One mole is N_A =6.023x10^{23} molecules (number of ^{12}C atoms in 12 g of ^{12}C)
- R=8.31 N·m/mole·°K

Microscopic Perspective

$$PV = Nk_B T$$

Boltzmann's constant
$k = 1.38 \times 10^{-23}$ N·m/°K

$= R/6.023 \times 10^{23}$

number of molecules

Example 10.2

Pure helium gas is admitted into a leak-proof cylinder containing a movable piston. The initial volume, pressure, and temperature of the gas are 15 L, 2.0 atm, and 300 K.

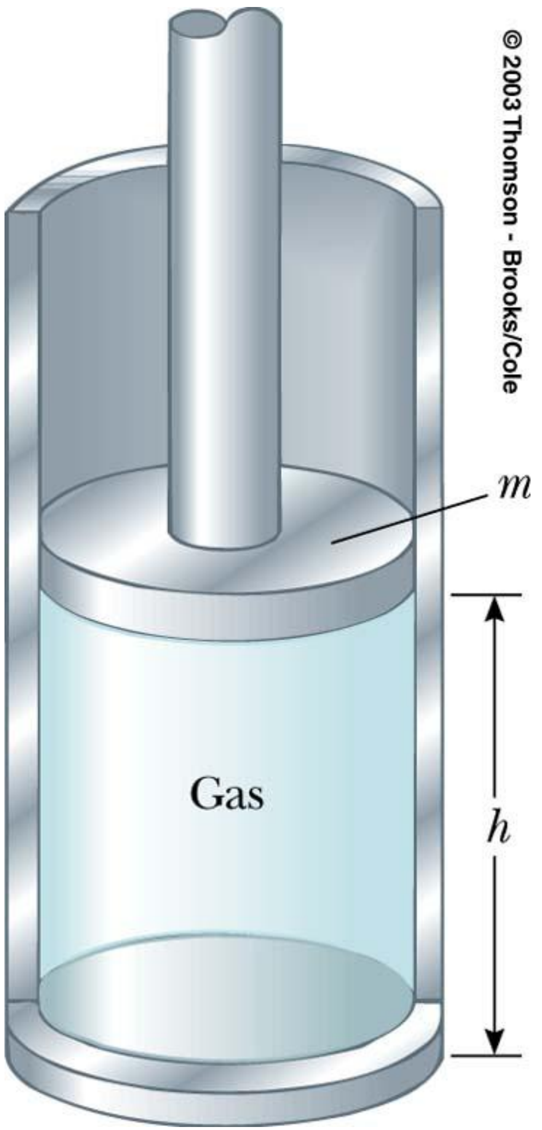
If the volume is decreased to 12 L and the pressure increased to 3.5 atm, find the final temperature of the gas. (Assume helium behaves as an ideal gas.)

420 °K

Example 10.3

A vertical cylinder of cross-sectional area 40 cm^2 is fitted with a tight-fitting, frictionless piston of mass 50.0 kg (see figure).

If there is 0.15 mol of an ideal gas in the cylinder at 500 K, determine the height h at which the piston will be in equilibrium under its own weight.

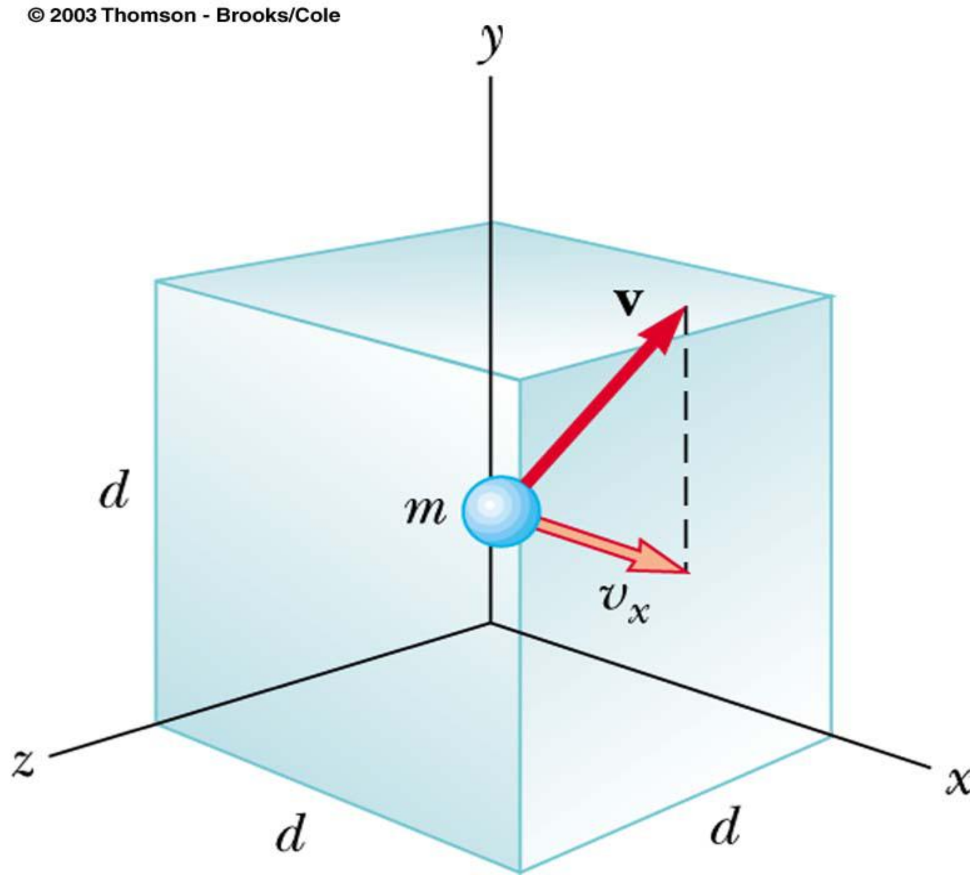


h=69.5 cm

Kinetic Theory of Gases

We wish to show:

$$\frac{3}{2}PV = E$$



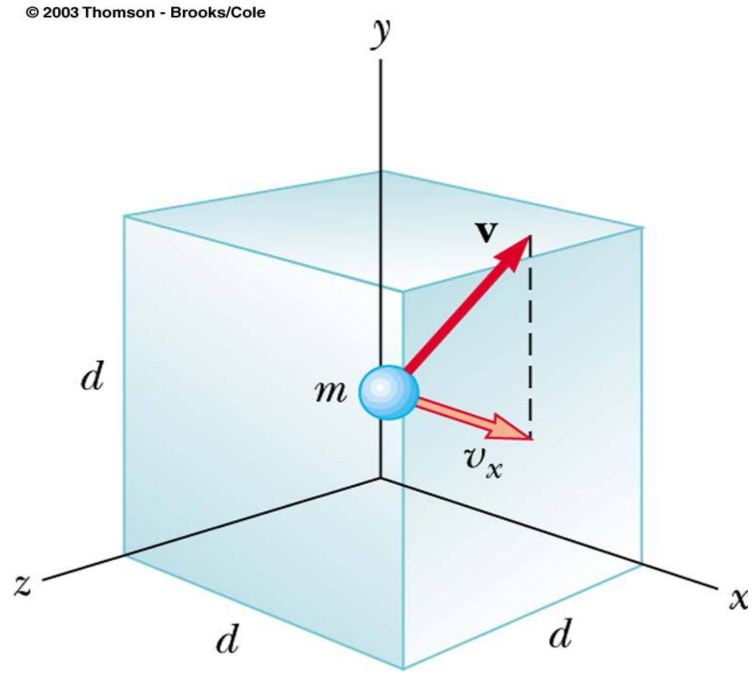
Derivation

$$P = \frac{N}{A}\frac{\Delta p_x}{\Delta t}$$

Area=d²

$$\Delta p_x = 2mv_x$$

$$\Delta t = \frac{2d}{v_x}$$



$$\frac{1}{A}\frac{\Delta p_x}{\Delta t} = m\frac{v_x^2}{dA} = mv_x^2\frac{1}{V} = \frac{2}{3V}KE_{one\ part}.$$

$$PV = \frac{2}{3}KE_{\mathrm{all\ part.s}}$$

Molecular Interpretation of Temperature

Using KE=(3/2)PV & PV=NkT,

$$KE = \frac{3}{2} N k_B T$$

$$\left\langle \frac{1}{2} m v^2 \right\rangle = \frac{3}{2} k_B T$$

$k_B = 1.38 \times 10^{-23}$ J/°K

- Temperature is proportional to the average kinetic energy of a single molecule:

Speed of Molecules

The *root-mean-square* (rms) speed of molecules is:

$$\left\langle \frac{1}{2} m v^2 \right\rangle = \frac{3}{2} k_B T$$

$$v_{rms} = \sqrt{\frac{3\, k_B\, T}{m}} = \sqrt{\frac{3\, R\, T}{M}}$$

Lighter molecules move faster

Internal Energy

- In a monatomic gas, the translational K.E. is the only type of energy the molecules can have

$$U = \frac{3}{2} nRT$$

- U is the *internal energy* of the gas.

- In a polyatomic gas, one also has rotational and vibrational energy & (3/2) --> bigger number

Example 10.4

A cylinder contains a mixture of helium (^4He) and argon (^{40}Ar) gas in equilibrium at a temperature of 150°C. DATA: $m_{proton}=1.67 \times 10^{-27}$ kg

(a) What is the average kinetic energy of each type of molecule?

8.76×10^{-21} J

(b) What is the rms speed of each type of molecule?

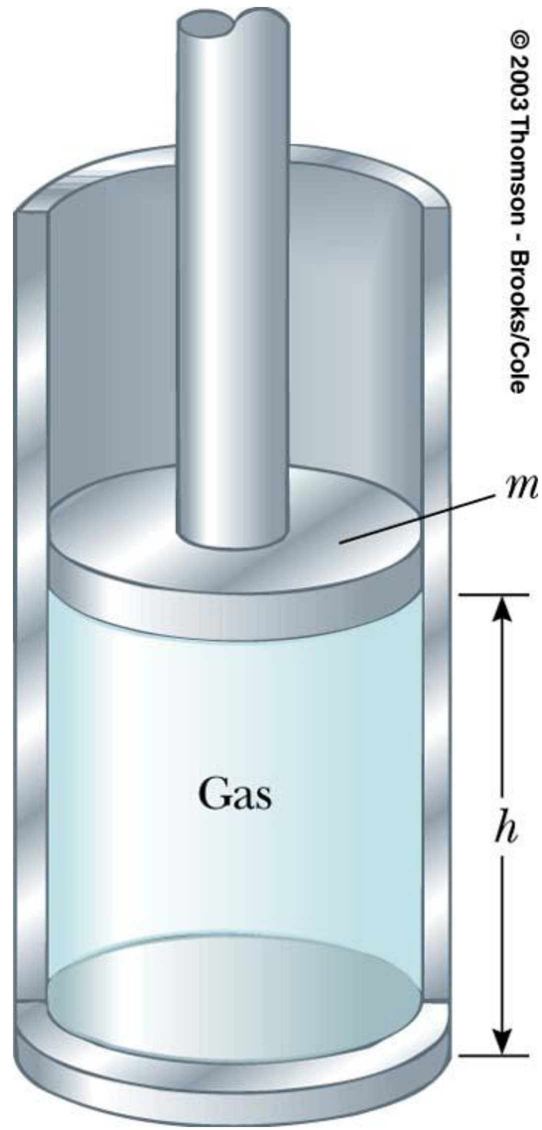
He: 1.62 km/s, Ar: 512 m/s

Example 10.5a

Consider the cylinder on the right which is filled with an ideal gas.

If P is doubled while maintaining the same volume, T must change by a factor of ________ .

a) 1/2
b) $2^{1/2}$
c) 2
d) 4
e) Can not determine

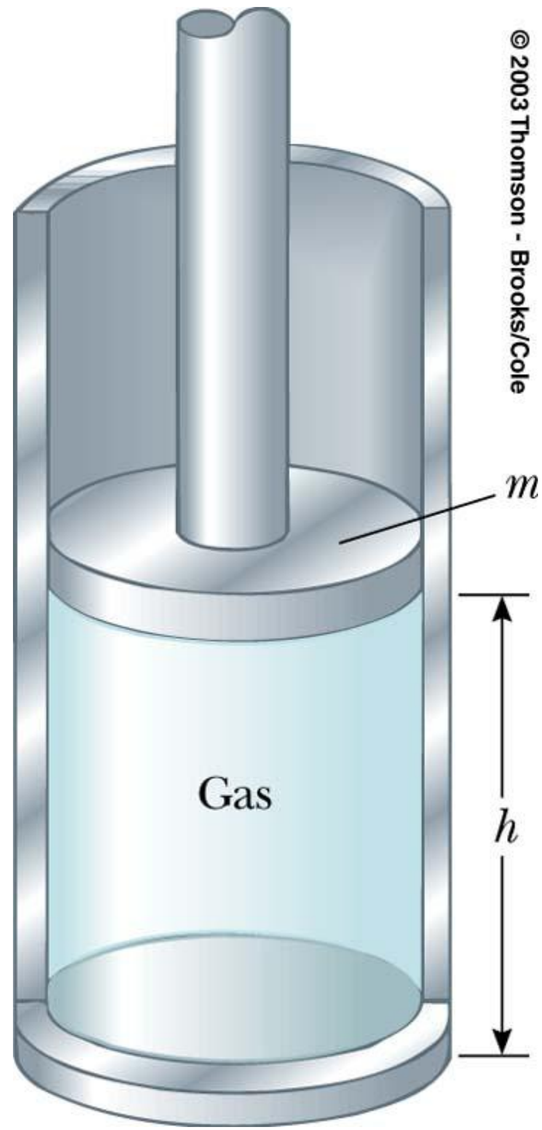


Example 10.5b

Consider the cylinder on the right which is filled with an ideal gas.

If P is doubled while maintaining the same volume, the r.m.s. speed of the molecules must change by a factor of ________ .

a) 1/2
b) $2^{1/2}$
c) 2
d) 4
e) Can not determine



Example 10.5c

Consider the cylinder on the right which is filled with an ideal gas.

If T is doubled while letting the piston slide freely, the volume will change by a factor of ________ .

a) 1/2
b) $2^{1/2}$
c) 2
d) 4
e) Can not determine