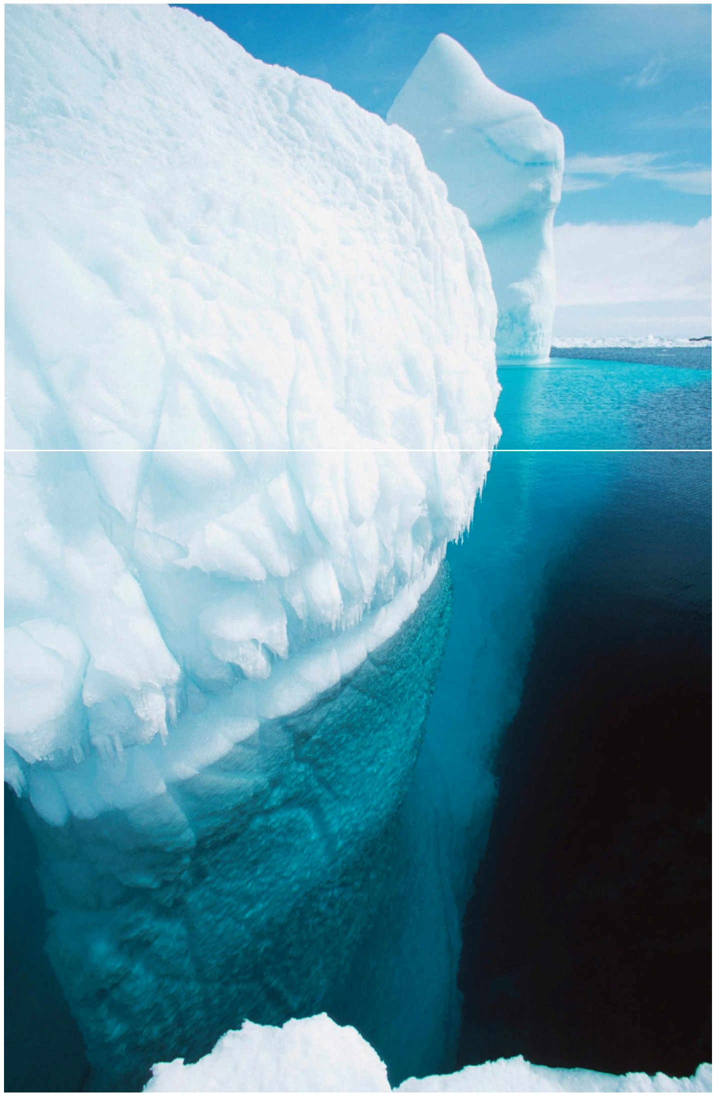
Chapter 16. A Macroscopic Description of Matter



Macroscopic systems are characterized as being either solid, liquid, or gas. These are called the phases of matter, and in this chapter we'll be interested in when and how a system changes from one phase to another.

Chapter Goal: To learn the characteristics of macroscopic systems.

Chapter 16. A Macroscopic Description of Matter

Topics:

- Solids, Liquids, and Gases
- Atoms and Moles
- Temperature
- Phase Changes
- Ideal Gases
- Ideal-Gas Processes

Chapter 16. Reading Quizzes

What is the SI unit of pressure?

A. The Nm^2 (Newton-meter-squared)
B. The atmosphere
C. The p.s.i.
D. The Pascal
E. The Archimedes

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✔ **D. The Pascal**
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The ideal gas model is valid if

A. the gas density and temperature are both low.
B. the gas density and temperature are both high.
C. the gas density is low and the temperature is high.
D. the gas density is high and the temperature is low.

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✔ **C. the gas density is low and the temperature is high.**

D. the gas density is high and the temperature is low.

An ideal-gas process in which the volume doesn't change is called

A. isobaric.
B. isothermal.
C. isochoric.
D. isentropic.

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B. isothermal.
✔ **C. isochoric.**
D. isentropic.

Chapter 16. Basic Content and Examples

Density

The ratio of a system's mass to its volume is called the **mass density**, or sometimes simply "the density."

$$\rho = \frac{M}{V} \qquad \text{(mass density)}$$

The SI units of mass density are kg/m^3. In this chapter we'll use an uppercase *M* for the system mass and lowercase *m* for the mass of an atom.

TABLE 16.1 Densities of materials

Substance	ρ (kg/m^3)
Air at STP*	1.3
Ethyl alcohol	790
Water (solid)	920
Water (liquid)	1000
Aluminum	2700
Copper	8920
Gold	19,300
Iron	7870
Lead	11,300
Mercury	13,600
Silicon	2330

*$T = 0°C$, $p = 1$ atm

EXAMPLE 16.1 The mass of a lead pipe

QUESTION:

EXAMPLE 16.1 The mass of a lead pipe

A project on which you are working uses a cylindrical lead pipe with outer and inner diameters of 4.0 cm and 3.5 cm, respectively, and a length of 50 cm. What is its mass?

EXAMPLE 16.1 The mass of a lead pipe

SOLVE The mass density of lead is $\rho_{\text{lead}} = 11{,}300\ \text{kg/m}^3$. The volume of a circular cylinder of length l is $V = \pi r^2 l$. In this case we need to find the volume of the outer cylinder, of radius r_2, *minus* the volume of air in the inner cylinder, of radius r_1. The volume of the pipe is

$$V = \pi r_2^2 l - \pi r_1^2 l = \pi (r_2^2 - r_1^2) l = 1.47 \times 10^{-4}\ \text{m}^3$$

Hence the pipe's mass is

$$M = \rho_{\text{lead}} V = 1.7\ \text{kg}$$

Atoms and Moles

• The mass of an atom is determined primarily by its most massive constituents, the protons and neutrons in its nucleus.

• The sum of the number of protons and neutrons is called the **atomic mass number** *A*.

• The **atomic mass** scale is established by defining the mass of ^{12}C to be exactly 12 u, where u is the symbol for the **atomic mass unit**.

• The conversion factor between atomic mass units and kilograms is

$$1\ \mathrm{u} = \frac{m(^{12}\mathrm{C})}{12} = 1.66 \times 10^{-27}\ \mathrm{kg}$$

Atoms and Moles

TABLE 16.2 Some atomic mass numbers

Element		A
^{1}H	Hydrogen	1
^{4}He	Helium	4
^{12}C	Carbon	12
^{14}N	Nitrogen	14
^{16}O	Oxygen	16
^{20}Ne	Neon	20
^{27}Al	Aluminum	27
^{40}Ar	Argon	40
^{207}Pb	Lead	207

Atoms and Moles

- By definition, one **mole** of matter, be it solid, liquid, or gas, is the amount of substance containing as many basic particles as there are atoms in 12 g of ^{12}C.
- The number of basic particles per mole of substance is called Avogadro's number, $N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$.
- The number of moles in a substance containing N basic particles is

$$n = \frac{N}{N_A}$$

Atoms and Moles

• If the atomic mass is specified in kilograms, the number of atoms in a system of mass *M* can be found from

$$N = \frac{M}{m}$$

• The **molar mass** of a substance is the mass *in grams* of 1 mol of substance. The molar mass, which we'll designate M_{mol}, has units g/mol.

• The number of moles in a system of mass *M* consisting of atoms or molecules with molar mass M_{mol} is

$$n = \frac{M \text{ (in grams)}}{M_{mol}}$$

EXAMPLE 16.2 Moles of oxygen

QUESTION:

EXAMPLE 16.2 Moles of oxygen

100 g of oxygen gas is how many moles of oxygen?

EXAMPLE 16.2 Moles of oxygen

SOLVE We can do the calculation two ways. First, let's determine the number of molecules in 100 g of oxygen. The diatomic oxygen molecule O_2 has molecular mass $m = 32$ u. Converting this to kg, we get the mass of one molecule:

$$m = 32\ \text{u} \times \frac{1.66 \times 10^{-27}\ \text{kg}}{1\ \text{u}} = 5.31 \times 10^{-26}\ \text{kg}$$

Thus the number of molecules in 100 g $= 0.10$ kg is

$$N = \frac{M}{m} = \frac{0.100\ \text{kg}}{5.31 \times 10^{-26}\ \text{kg}} = 1.88 \times 10^{24}$$

EXAMPLE 16.2 Moles of oxygen

Knowing the number of molecules gives us the number of moles:

$$n = \frac{N}{N_A} = 3.13 \text{ mol}$$

Alternatively, we can use Equation 16.5 to find

$$n = \frac{M \text{ (in grams)}}{M_{mol}} = \frac{100 \text{ g}}{32 \text{ g/mol}} = 3.13 \text{ mol}$$

Temperature

The *Celsius* temperature scale is defined by setting T_C=0 for the freezing point of pure water, and T_C=100 for the boiling point.

The *Kelvin* temperature scale has the same unit size as Celsius, with the zero point at absolute zero. The conversion between the Celsius scale and the Kelvin scale is

$$T_K = T_C + 273$$

The *Fahrenheit* scale, still widely used in the United States, is defined by its relation to the Celsius scale, as follows:

$$T_F = \frac{9}{5}T_C + 32°$$

Temperature

TABLE 16.4 Temperatures measured with different scales

Temperature	T (°C)	T (K)	T (°F)
Melting point of iron	1538	1811	2800
Boiling point of water	100	373	212
Normal body temperature	37.0	310	98.6
Room temperature	20	293	68
Freezing point of water	0	273	32
Boiling point of nitrogen	−196	77	−321
Absolute zero	−273	0	−460

Phase Changes

• The temperature at which a solid becomes a liquid or, if the thermal energy is reduced, a liquid becomes a solid is called the **melting point** or the **freezing point**. Melting and freezing are *phase changes*.

• The temperature at which a gas becomes a liquid or, if the thermal energy is increased, a liquid becomes a gas is called the **condensation point** or the **boiling point**. Condensing and boiling are *phase changes*.

• The phase change in which a solid becomes a gas is called **sublimation**.

Ideal Gases

- The *ideal-gas model* is one in which we model atoms in a gas as being hard spheres. Such hard spheres fly through space and occasionally interact by bouncing off each other in perfectly elastic collisions.
- Experiments show that the ideal-gas model is quite good for gases if two conditions are met:

1. The density is low (i.e., the atoms occupy a volume much smaller than that of the container), and
2. The temperature is well above the condensation point.

The Ideal-Gas Law

The pressure p, the volume V, the number of moles n and the temperature T of an ideal gas are related by the ideal-gas law as follows:

$$pV = nRT \qquad \text{(ideal-gas law)}$$

where R is the universal gas constant, $R = 8.31$ J/mol K. The ideal gas law may also be written as

$$pV = Nk_B T \qquad \text{(ideal-gas law)}$$

where N is the number of molecules in the gas rather than the number of moles n. The Boltzmann's constant is $k_B = 1.38 \times 10^{-23}$ J/K.

EXAMPLE 16.3 Calculating a gas pressure

QUESTION:

EXAMPLE 16.3 Calculating a gas pressure

100 g of oxygen gas is distilled into an evacuated 600 cm^3 container. What is the gas pressure at a temperature of 150°C?

EXAMPLE 16.3 Calculating a gas pressure

MODEL The gas can be treated as an ideal gas. Oxygen is a diatomic gas of O_2 molecules.

EXAMPLE 16.3 Calculating a gas pressure

SOLVE From the ideal-gas law, the pressure is $p = nRT/V$. In Example 16.2 we calculated the number of moles in 100 g of O_2 and found $n = 3.13$ mol. Gas problems typically involve several conversions to get quantities into the proper units, and this example is no exception. The SI units of V and T are m^3 and K, respectively, thus

$$V = (600\ \text{cm}^3)\left(\frac{1\ \text{m}}{100\ \text{cm}}\right)^3 = 6.00 \times 10^{-4}\ \text{m}^3$$

$$T = (150 + 273)\ \text{K} = 423\ \text{K}$$

With this information, the pressure is

$$p = \frac{nRT}{V} = \frac{(3.13\ \text{mol})(8.31\ \text{J/mol K})(423\ \text{K})}{6.00 \times 10^{-4}\ \text{m}^3}$$

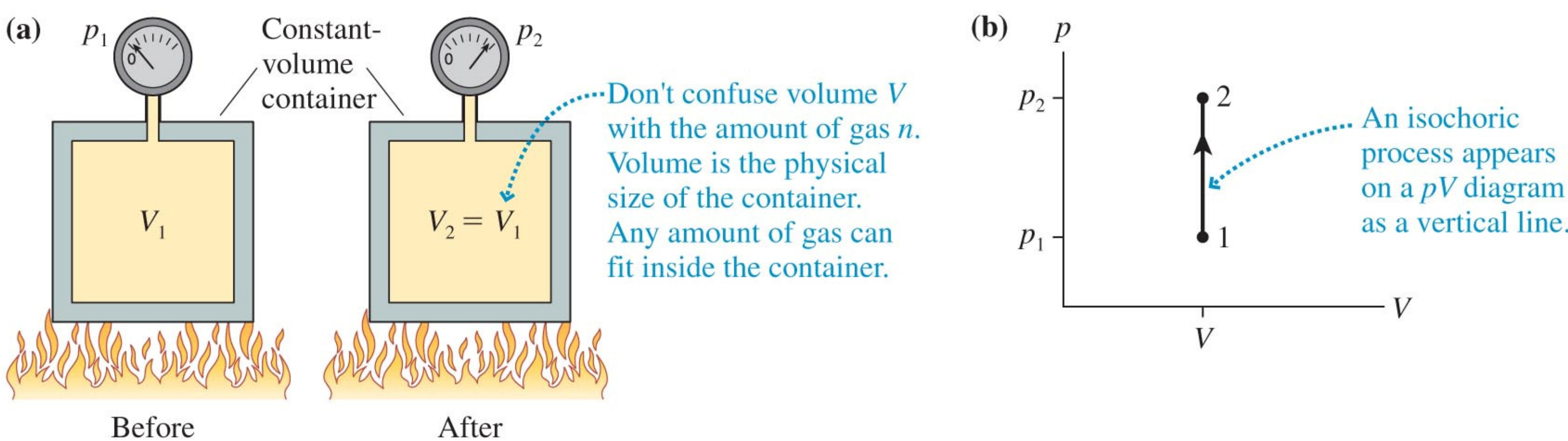
$$= 1.83 \times 10^{7}\ \text{Pa} = 181\ \text{atm}$$

Ideal-Gas Processes

Many important gas processes take place in a container of constant, unchanging volume. A constant-volume process is called an **isochoric process**.

Consider the gas in a closed, rigid container. Warming the gas with a flame will raise its pressure without changing its volume.

FIGURE 16.11 A constant-volume (isochoric) process.



Ideal-Gas Processes

Other gas processes take place at a constant, unchanging pressure. A constant-pressure process is called an **isobaric process**.

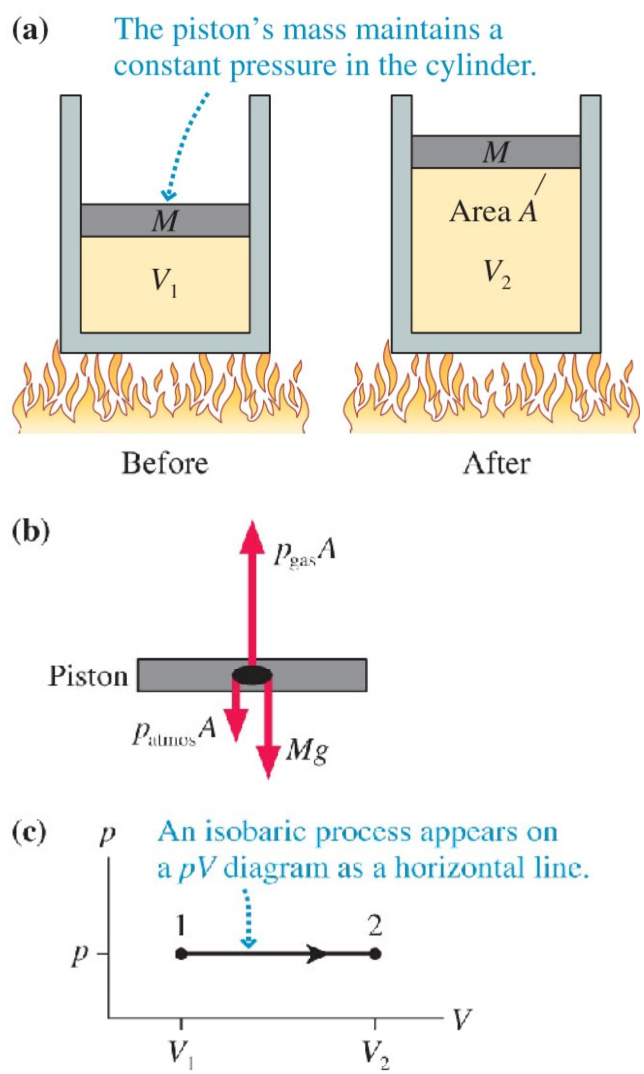
Consider a cylinder of gas with a tight-fitting piston of mass *M* that can slide up and down but seals the container so that no atoms enter or escape.

In equilibrium, the gas pressure inside the cylinder is

$$p = p_{\text{atmos}} + \frac{Mg}{A}$$

Isobaric Process

FIGURE 16.12 A constant-pressure (isobaric) process.



EXAMPLE 16.7 Comparing pressure

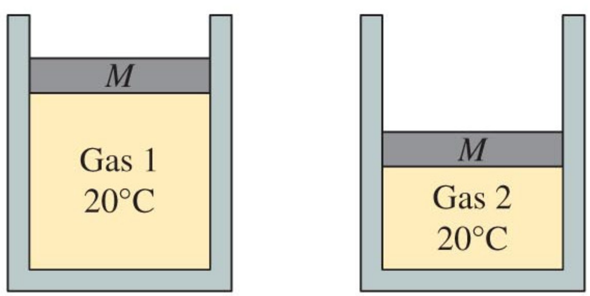
QUESTION:

EXAMPLE 16.7 Comparing pressure

The two cylinders in **FIGURE 16.13** contain ideal gases at 20°C. Each cylinder is sealed by a frictionless piston of mass M.

a. How does the pressure of gas 2 compare to that of gas 1? Is it larger, smaller, or the same?
b. Suppose gas 2 is warmed to 80°C. Describe what happens to the pressure and volume.

FIGURE 16.13 Compare the pressures of the two gases.



EXAMPLE 16.7 Comparing pressure

MODEL Treat the gases as ideal gases.

EXAMPLE 16.7 Comparing pressure

SOLVE a. The pressure in the gas is determined by the requirement that the piston be in mechanical equilibrium. The pressure of the gas inside pushes up on the piston; the air pressure and the weight of the piston press down. The gas pressure $p = p_{atmos} + Mg/A$ depends on the mass of the piston, but not at all on how high the piston is or what type of gas is inside the cylinder. Thus both pressures are the same.

EXAMPLE 16.7 Comparing pressure

b. Neither does the pressure depend on temperature. Warming the gas increases the temperature, but the pressure—determined by the mass and area of the piston—is unchanged. Because $pV/T =$ constant, and p is constant, it must be true that $V/T =$ constant. As T increases, the volume V also must increase to keep V/T unchanged. In other words, increasing the gas temperature causes the volume to expand—the piston goes up—but with no change in pressure. This is an isobaric process.

EXAMPLE 16.8 A constant-pressure compression

QUESTION:

EXAMPLE 16.8 A constant-pressure compression

A gas occupying 50.0 cm^3 at 50°C is cooled at constant pressure until the temperature is 10°C. What is its final volume?

EXAMPLE 16.8 A constant-pressure compression

MODEL The pressure of the gas doesn't change, so this is an isobaric process.

EXAMPLE 16.8 A constant-pressure compression

SOLVE By definition, $p_1/p_2 = 1$ for an isobaric process. Using the ideal-gas law for constant n, we have

$$V_2 = V_1 \frac{p_1}{p_2} \frac{T_2}{T_1} = V_1 \frac{T_2}{T_1}$$

Temperatures *must* be in kelvins to use the ideal-gas law. Thus

$$V_2 = (50.0 \text{ cm}^3) \frac{(10 + 273) \text{ K}}{(50 + 273) \text{ K}} = 43.8 \text{ cm}^3$$

EXAMPLE 16.8 A constant-pressure compression

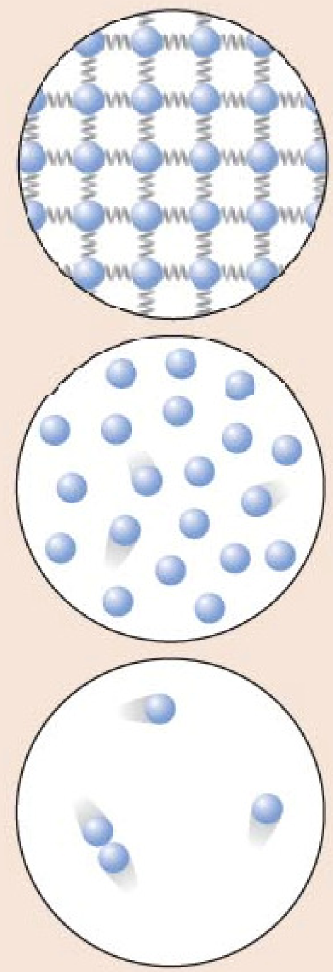
ASSESS As long as we use *ratios,* we do not need to convert volumes or pressures to SI units. That is because the conversion is a multiplicative factor that cancels. But the conversion of temperature is an *additive* factor that does *not* cancel. That is why you must always convert temperatures to kelvins in ideal-gas calculations.

Chapter 16. Summary Slides

General Principles

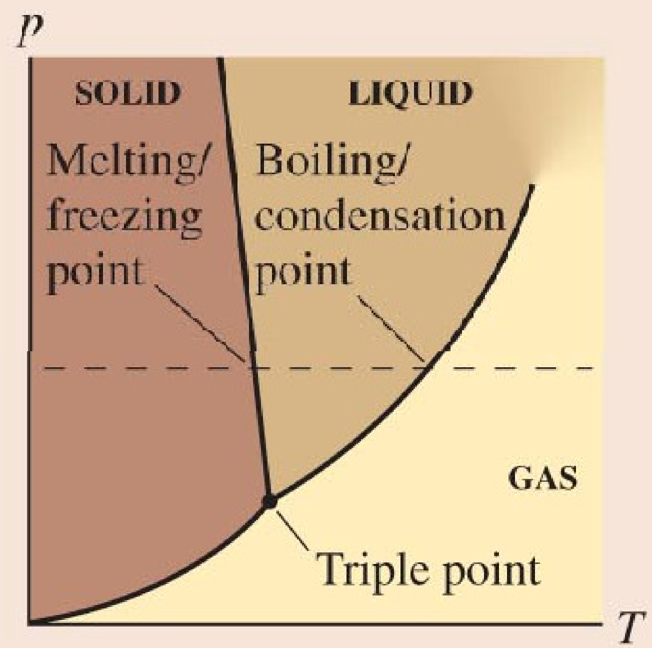
Three Phases of Matter

Solid	Rigid, definite shape. Nearly incompressible.
Liquid	Molecules loosely held together by molecular bonds, but able to move around. Nearly incompressible.
Gas	Molecules move freely through space. Compressible.



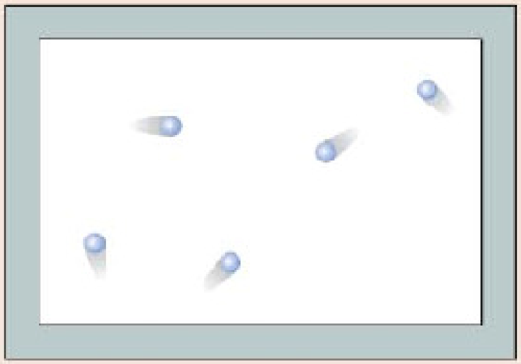
General Principles

The different phases exist for different conditions of temperature T and pressure p. The boundaries separating the regions of a phase diagram are lines of phase equilibrium. Any amounts of the two phases can coexist in equilibrium. The **triple point** is the one value of temperature and pressure at which all three phases can coexist in equilibrium.



Important Concepts

Ideal-Gas Model



- Atoms and molecules are small, hard spheres that travel freely through space except for occasional collisions with each other or the walls.
- The model is valid when the density is low and the temperature well above the condensation point.

Important Concepts

Ideal-Gas Law

The **state variables** of an ideal gas are related by the ideal-gas law

$$pV = nRT \quad \text{or} \quad pV = Nk_B T$$

where $R = 8.31$ J/mol K is the universal gas constant and $k_B = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant.

p, V, and *T must* be in SI units of Pa, m^3, and K. For a gas in a sealed container, with constant *n*:

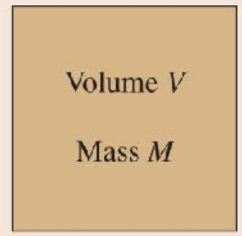
$$\frac{p_2 V_2}{T_2} = \frac{p_1 V_1}{T_1}$$

Important Concepts

Counting atoms and moles

A macroscopic sample of matter consists of N atoms (or molecules), each of mass m (the **atomic** or **molecular mass**):

$$N = \frac{M}{m}$$



Alternatively, we can state that the sample consists of n **moles:**

$$n = \frac{N}{N_A} \quad \text{or} \quad \frac{M(\text{in grams})}{M_{mol}}$$

$N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$ is **Avogadro's number.**

The numerical value of the molar mass M_{mol}, in g/mol, equals the numerical value of the atomic or molecular mass m in u. The atomic or molecular mass m, in atomic mass units u, is well approximated by the **atomic mass number** A:

$$1\ \text{u} = 1.66 \times 10^{-27}\ \text{kg}$$

The **number density** of the sample is $\frac{N}{V}$.

Applications

Temperature scales

$$T_F = \frac{9}{5}T_C + 32^\circ \qquad T_K = T_C + 273$$

The Kelvin temperature scale is based on:

- Absolute zero at $T_0 = 0$ K
- The triple point of water at $T_3 = 273.16$ K

Applications

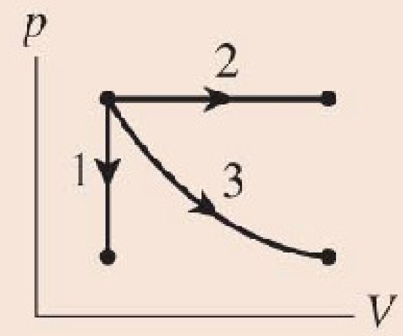
Three basic gas processes

1. **Isochoric,** or constant volume

2. **Isobaric,** or constant pressure

3. **Isothermal,** or constant temperature

pV diagram



Chapter 16. Questions

The pressure in a system is measured to be 60 kPa. At a later time the pressure is 40 kPa. The value of Δp is

A. –20 kPa.
B. –40 kPa.
C. 20 kPa.
D. 40 kPa.
E. 0 kPa.

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Which system contains more atoms: 5 mol of helium (A = 4) or 1 mol of neon (A = 20)?

A. They have the same number of atoms.
B. Helium
C. Neon

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✔ **B. Helium**

C. Neon

The temperature of a glass of water increases from 20°C to 30°C. What is ΔT?

A. 10 K

B. 283 K

C. 293 K

D. 303 K

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For which is there a sublimation temperature that is higher than a melting temperature?

A. Water
B. Carbon dioxide
C. Neither
D. Both

For which is there a sublimation temperature that is higher than a melting temperature?

✔ **A. Water**
B. Carbon dioxide
C. Neither
D. Both

You have two containers of equal volume. One is full of helium gas. The other holds an equal mass of nitrogen gas. Both gases have the same pressure. How does the temperature of the helium compare to the temperature of the nitrogen?

A. $T_{\text{helium}} > T_{\text{nitrogen}}$

B. $T_{\text{helium}} < T_{\text{nitrogen}}$

C. $T_{\text{helium}} = T_{\text{nitrogen}}$

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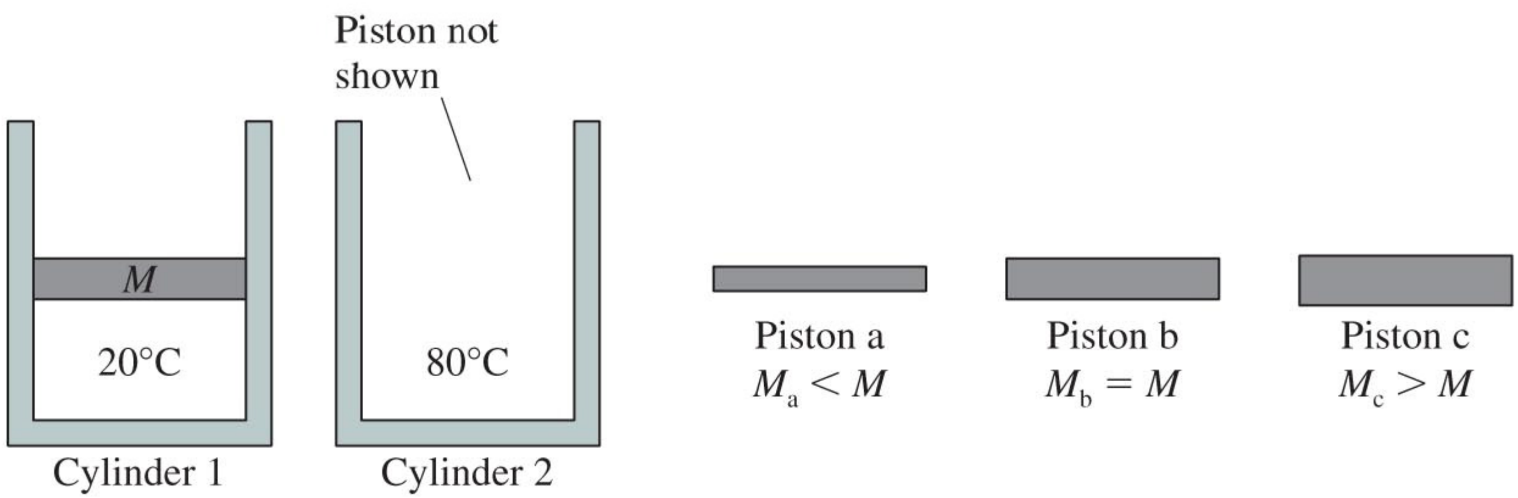
✔ **B.** $\boldsymbol{T_{\text{helium}} < T_{\text{nitrogen}}}$

C. $T_{\text{helium}} = T_{\text{nitrogen}}$

Two cylinders contain the same number of moles of the same ideal gas. Each cylinder is sealed by a frictionless piston. To have the same pressure in both cylinders, which piston would you use in cylinder 2?



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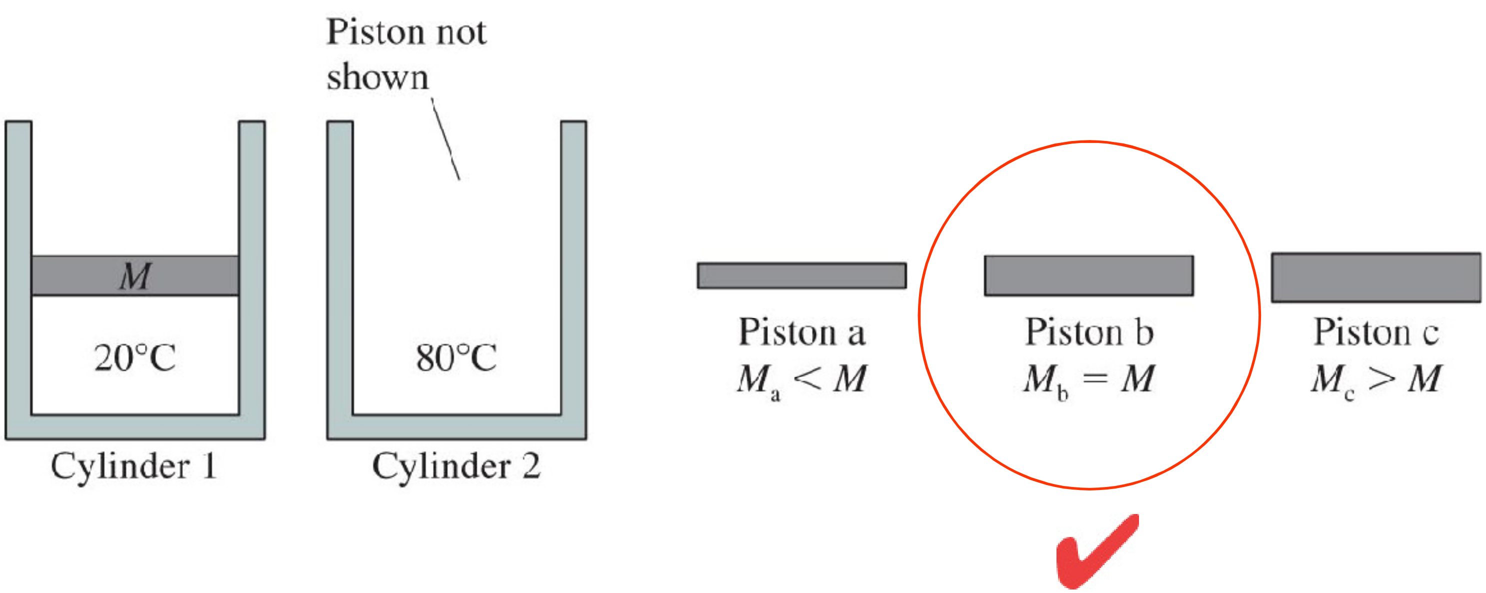
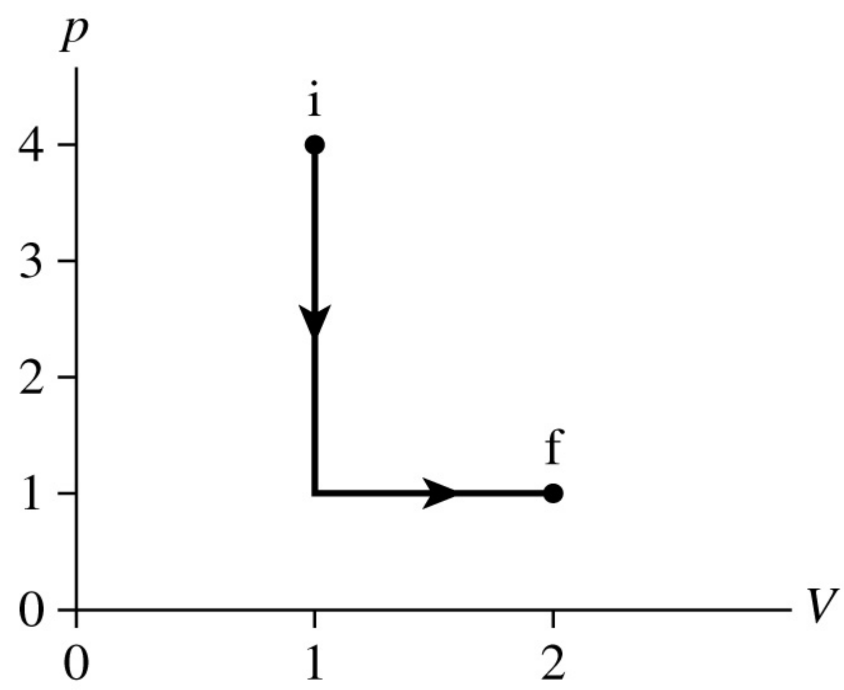


What is the ratio T_f/T_i for this process?



A. $\frac{1}{2}$

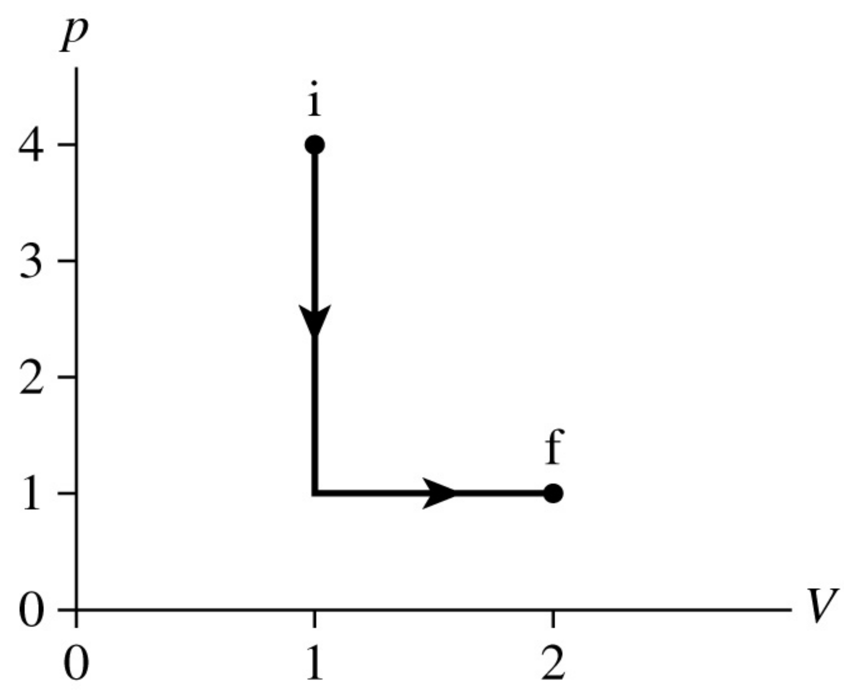
B. $\frac{1}{4}$

C. 4

D. 2

E. 1 (no change)

What is the ratio T_f/T_i for this process?



✔ **A.** $\frac{1}{2}$

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C. 4

D. 2

E. 1 (no change)